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An evidence-based review on the likely economic and environmental impact of genetically modified cereals and oilseeds for UK agriculture

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CONTENTS

1. Abstract

An evidence-based review of the potential impact that the introduction of genetically-modified (GM) cereal and oilseed crops could have for the UK was carried out. The inter-disciplinary research project addressed the key research questions using scenarios for the uptake, or not, of GM technologies. This was followed by an extensive literature review, stakeholder consultation and financial modelling.

The world area of canola, oilseed rape (OSR) low in both erucic acid in the oil and glucosinolates in the meal, was 34M ha in 2012 of which 27% was GM; Canada is the lead producer but it is also grown in the USA, Australia and Chile. Farm level effects of adopting GM OSR include: lower production costs; higher yields and profits; and ease of farm management. Growing GM OSR instead of conventional OSR reduces both herbicide usage and environmental impact.

Some 170M ha of maize was grown in the world in 2011 of which 28% was GM; the main producers are the USA, China and Brazil. Spain is the main EU producer of GM maize although it is also grown widely in Portugal. Insect resistant (IR) and herbicide tolerant (HT) are the GM maize traits currently available commercially. Farm level benefits of adopting GM maize are lower costs of production through reduced use of pesticides and higher profits. GM maize adoption results in less pesticide usage than on conventional counterpart crops leading to less residues in food and animal feed and allowing increasing diversity of bees and other pollinators. In the EU, well-tried coexistence measures for growing GM crops in the proximity of conventional crops have avoided gene flow issues.

Scientific evidence so far seems to indicate that there has been no environmental damage from growing GM crops. They may possibly even be beneficial to the environment as they result in less pesticides and herbicides being applied and improved carbon sequestration from less tillage.

A review of work on GM cereals relevant for the UK found input trait work on: herbicide and pathogen tolerance; abiotic stress such as from drought or salinity; and yield traits under different field conditions. For output traits, work has mainly focussed on modifying the nutritional components of cereals and in connection with various enzymes, diagnostics and vaccines.

Scrutiny of applications submitted for field trial testing of GM cereals found around 9000 applications in the USA, 15 in Australia and 10 in the EU since 1996. There have also been many patent applications and granted patents for GM cereals in the USA for both input and output traits;

an indication of the scale of such work is the fact that in a 6 week period in the spring of 2013, 12 patents were granted relating to GM cereals.

A dynamic financial model has enabled us to better understand and examine the likely performance of Bt maize and HT OSR for the south of the UK, if cultivation is permitted in the future. It was found that for continuous growing of Bt maize and HT OSR, unless there was pest pressure for the former and weed pressure for the latter, the seed premia and likely coexistence costs for a buffer zone between other crops would reduce the financial returns for the GM crops compared with their conventional counterparts. When modelling HT OSR in a four crop rotation, it was found that gross margins increased significantly at the higher levels of such pest or weed pressure, particularly for farm businesses with larger fields where coexistence costs would be scaled down.

The impact of the supply of UK-produced GM crops on the wider supply chain was examined through an extensive literature review and widespread stakeholder consultation with the feed supply chain.

The animal feed sector would benefit from cheaper supplies of raw materials if GM crops were grown and, in the future, they might also benefit from crops with enhanced nutritional profile (such as having higher protein levels) becoming available. This would also be beneficial to livestock producers enabling lower production costs and higher margins. Whilst coexistence measures would result in increased costs, it is unlikely that these would cause substantial changes in the feed chain structure. Retailers were not concerned about a future increase in the amount of animal feed coming from GM crops.

To conclude, we (the project team) feel that the adoption of currently available and appropriate GM crops in the UK in the years ahead would benefit farmers, consumers and the feed chain without causing environmental damage. Furthermore, unless British farmers are allowed to grow GM crops in the future, the competitiveness of farming in the UK is likely to decline relative to that globally.

2. Introduction

2.1. Overview

This document reports on a desk-based review of the potential economic and environmental impact that GM cereal and oilseed crops could have for UK agriculture. The research was carried out by seven highly experienced inter-disciplinary economists and scientists from the University of Reading's world-renowned School of Agriculture, Policy and Development, an institution that has been serving UK agriculture for over 125 years.

A methodological approach was taken to address the key research questions using, as a framework, a set of scenarios for the uptake, or not, of GM technologies in the UK. Once the scenarios were defined, both qualitative and quantitative approaches were used to elaborate the various outcomes associated with each set of scenario provisions.

The project used varying combinations of a literature review, evidence transfer, stakeholder consultation and modelling to achieve this.

2.2. Aims and objectives

The aims of the project were to conduct an evidence-based review of the potential economic and environmental impact that GM cereal and oilseed crops could have for UK agriculture. The objectives of the project were to:

- (i) compare GM crop adoption and non-adoption scenarios relevant to UK agriculture;
- (ii) consider both on and off-farm economic and financial impacts of GM crop adoption;
- (iii) consider both on and off-farm environmental/agronomic impacts of GM crop adoption;
- (iv) propose which traits could have a positive impact on production economics and the environment and where these traits may benefit the consumer; and
- (v) consider all implications of coexistence measures throughout the supply chain.

2.3. Methodology

2.3.1. Overview

The methodological approach was to address the key research questions using, as a framework, a set of 'futures', or scenarios, which were defined and developed over the course of the project. The scenarios for the uptake of GM technologies in the UK were based on certain key parameters, such as: crop type; type of trait introduced; time-scale of official approval; time-scale and extent of uptake; and required coexistence measures etc. Having defined the scenarios, various approaches were used, some quantitative, some qualitative, to elaborate the various outcomes associated with each set of scenario provisions.

The work programme was broken down into six work packages, each of which, in terms of methodological approaches, used various combinations of literature review and data mining, evidence transfer, stakeholder consultation, and modelling (both quantitative and qualitative) to define the scenarios and elaborate them with outcomes data. The stakeholder consultation used a small group of experts drawn from various stakeholder groups, including farmers' representatives, food chain organisations and academic commentators. This group of experts was recruited during the course of the project as particular expertise was needed.

2.3.2. Literature review

A systematic review of relevant literature was undertaken guided by the five specific objectives of the project including previous reviews of the literature and a review of international patent databases, the experience of the project team and advice from expert stakeholders. In terms of methodology, this systematic review identified a set of selection criteria by which to identify a core of appropriate studies from the very large body of literature that is available. This was designed to reduce the scale of the review task by screening out less relevant and unreliable studies. Two types of selection criteria were used, both qualitative and quantitative.

The literature review informed the design of subsequent work packages and generated data for use in the scenario design and economic and environmental modelling work packages.

2.3.3. Scenario design

These scenarios were based on a number of agreed parameters, such as:

- type of GM technologies;
- different crops and traits;
- timescale and future date of approval;
- length of time required for widespread uptake; and
- coexistence measures adopted at the levels of the farm and the wider supply chain.

A suite of scenarios was designed, capturing a range of parameter settings. Scenario formulation was undertaken by the project team, informed by the literature review and guided by a panel of expert stakeholders. In the selection of coexistence measures, reference was made to Defra requirements and an EU FP7 project undertaken by some members of the project team - *PRactical Implementation of Coexistence in Europe* (PRICE - KBBE-2011-5-289157).

The first stage of the process of elaborating these scenarios was through the use of the literature, which will be used to add outcomes/impacts data, supplemented with expert judgement where necessary. As there is little in the way of data derived from UK trials of GM crops, this involved evidence transfer from other geographical settings.

2.3.4. Financial modelling of impacts on agriculture

The data from the literature review, supplemented by expert judgement where needed, was used to construct spreadsheet-based financial models of the crop types. This modelling involved the construction of baseline models reflecting no-adoption of GM which acts as a baseline comparator for a suite of scenario runs. This modelling captured impacts of GM adoption on:

- crop yields;
- cost(s) of production (including coexistence costs);
- market returns; and
- enterprise gross and net margins.

The outputs of the financial modelling exercise was then used to further elaborate the scenario narratives in terms of specific agronomic and financial outcomes.

2.3.5. Economic modelling of impacts on the wider supply chain

The process of elaborating the scenario narratives continued with the addition of qualitative and quantitative data on the impacts of GM adoption on the wider supply chain. The nature of the data derived was necessarily largely qualitative due to the heterogeneity of supply chain businesses, the difficulty of obtaining baseline economic data for these businesses, the relative scarcity of studies on the impacts of GM adoption on feed chain businesses and uncertainty over likely business responses to the presence of market demand for, and domestic supply of, GM products. Data acquisition was informed by:

- the literature review
- the outputs of the modelling of primary production (including GM trait, supply and price effects); and
- the opinions of feed chain stakeholders.

The particular outcomes addressed in this exercise included:

- coexistence measures and compliance costs;
- capital investment requirements;
- the role of retailers;
- price transmission effects from primary producers; and
- food chain business margins and competitiveness.

2.3.6. Land use and environmental impacts

The final stage in the elaboration of the scenarios focussed on the land use and environmental impacts using data collected that was both qualitative and narrative in nature and derived from:

- the scenario parameters (e.g. traits; assumptions about levels of uptake etc.);
- the literature review;
- the outputs of the modelling of primary production (input use etc.); and
- expert consultation.

3. Literature review of GM oilseed rape

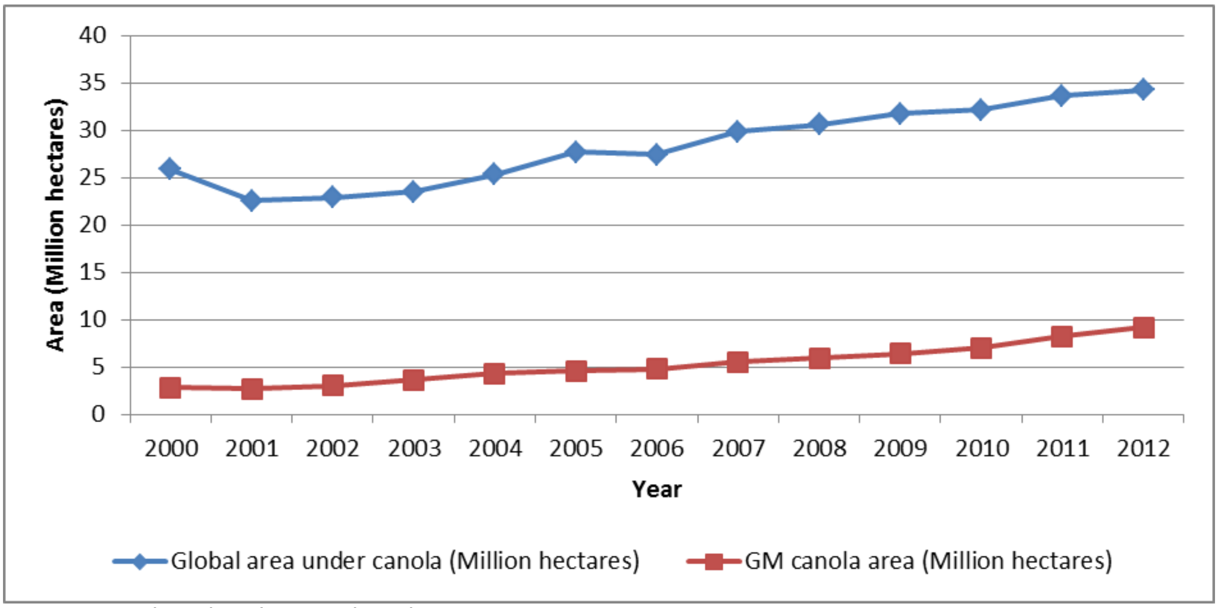
3.1. Status of the OSR crop

The global production of OSR has expanded rapidly since the 1980s making it the second largest oilseed crop (FAO, 2013). OSR accounts for around 15% of world vegetable oil production and is the third largest contributor to world vegetable oil production after soybean oil and palm oil. Rapeseed is also the second largest feed meal after soybean meal. Strong growth in the demand for OSR is expected in the coming decade based on the increasing use of vegetable oils in China and India and OSR-based biodiesel use in the EU (USDA, 2013a). The rapid growth in production has been facilitated by plant breeding breakthroughs which have enabled production of rapeseed oil low both in erucic acid content in the oil and glucosinolates in the meal (the so-called 'double-low' varieties).

The term 'canola' was established after the licensing of the first 'double-low' variety in Canada in 1974. The success of these varieties in North America has made the term 'canola' almost synonymous with OSR. The term 'canola' generally refers to edible varieties of OSR. European breeders have also developed low-erucic acid rapeseed varieties which have been termed as 'double-zero' varieties or 'canola equivalents'. In this report, the term OSR will be used throughout to refer to both edible and non-edible varieties of oilseed rape.

The OSR crop is highly susceptible to weed pressures in the early stages of seedling growth. Genetic modification in OSR has aimed at the development of herbicide tolerant (HT) varieties that would allow more efficient weed control and easier prevention of weed resistance to herbicides. GM varieties of HT OSR were first commercialised in Canada in 1995. The development of GM HT OSR varieties has centred on glyphosate-tolerant varieties, glufosinate-tolerant varieties and, more recently, on bromoxynil/ioxynil-tolerant varieties using the agrobacterium *Thuringiensis* transformation (Phillips, 2003). Non-GM HT varieties tolerant to triazine (a commonly used herbicide in North America and Australia) were developed in the mid-1980s in Canada but these varieties were first commercialised in Australia in the early 1990s. In 1995, non-GM imidazolinone-tolerant ('Clearfield' varieties) were developed using mutagenesis.

The total worldwide area under all types of OSR was estimated at 34.2M ha in 2012 of which 8.2M ha was estimated to be under GM OSR varieties (James, 2012). Figure 3.1 shows the rapid growth in the area under GM OSR with the share of GM OSR increasing from 11% in 2000 to 27% in 2012 (James, 2012). Only four countries currently grow GM OSR – Canada, USA, Australia and Chile. Canada is the leading producer of OSR accounting for 8.4% of the global area. The share of GM OSR in the Canadian area of OSR increased to 97.5% by 2012 (James, 2012). In the USA, over 90% of the OSR area is under GM OSR. However, the USA accounts for only 4.5% of the global GM OSR area and has witnessed a modest decrease in area in the last 2–4 years. In the UK, OSR is an important crop which accounts for nearly 10% of the arable area, but GM OSR varieties have not been approved for commercial use (Defra, 2013).



Source: FAO (2013) and James (2012).

Figure 3.1. The growth in global and GM OSR area (2000–2012).

3.2. Economic impact assessments of GM OSR

3.2.1. Introduction

GM OSR varieties were among the first genetically modified varieties to be commercialised. Despite the substantial area under GM OSR and high rates of adoption (in Canada and the USA), empirical assessments of the economic impacts of adoption have been limited (Gomez-Barbero and Rodriguez-Cerezo, 2006; Hall *et al.*, 2012). This may possibly be due to the high concentration of GM OSR in a single country – Canada – where adoption levels are close to 100%, perhaps reducing the interest in comparative assessment of impacts with alternative conventionally bred varieties. Most of the empirical studies have focused on Canada and have examined farm-level impacts. A few studies (Phillips, 2003; Brookes and Barfoot, 2012) have attempted to assess the aggregate economic welfare impacts of GM OSR adoption and the distribution of welfare gains between innovating companies, farm producers and consumers. A small number of *ex-ante* assessments of adoption impacts have also been attempted for the EU (e.g. Demont *et al*., 2007).

3.2.2. Farm level impacts studies

Farm-level impacts of GM OSR adoption may arise on account of:

(i) Yield effects: yield effects of HT varieties may arise on account of reduction in 'knock-back', improved reliability of yield due to better weed control, improved hybrid vigour in some varieties on account of the use of the HT characteristic in the seed production process, or improvements in effective yield on account of reduced 'dockage' by buyers as deductions for weight reductions for weed seeds and other foreign material for cleaner crops.

(ii) Effects on costs of production, particularly lower crop protection expenditures and higher seed costs, whilst leading to a net gain overall.

(iii) Effects on farm profits resulting from yield and cost effects.

(iv) Effects on crop quality and crop rotations (feasibility of planting additional crops in a given production cycle).

(v) Non-economic effects such as convenience, flexibility in farm management practices and risk management.

(vi) Impact on overall production levels of the crop as a result of adoption of GM HT varieties which may have resulted in the substitution of GM OSR for other crops.

Yield effects: Yield increases attributed to GM OSR adoption reported in the literature range from 6–11%. Using a Just and Pope (1978) production function, Carew and Smith (2006) estimated that GM OSR varieties had increased yields by 6.8% in the Manitoba region of Canada. Brookes and Barfoot (2012) estimated that in Canada yield increases in the early years of adoption (1996–2002) were nearly 11%. Subsequently, with the development of HT hybrid varieties bred using conventional technologies, the yield advantage of GM OSR varieties was eroded (Brookes and Barfoot, 2012). From 2004 onwards, they estimated that the yield advantage of GM OSR in Canada in relation to conventionally bred varieties ranged from 0% to 4% for glyphosate-tolerant varieties and 10–19% for glufosinate-tolerant varieties. Phillips (2003) notes that in the initial years of adoption, the cleaner crop produced by GM OSR varieties reduced 'dockage' from 6% to 3%, providing an effective yield increase for farmers. However, with GM OSR acquiring a dominant share in OSR production in Canada, the quality premium associated with cleaner crops may not have been available in the later years (Brookes and Barfoot, 2012). The Canola Council of Canada (Zatlyny, 1998) also estimated a yield gain of 0.2 t/ha for GM OSR as it allows farmers to plant their OSR crops earlier, allowing the crop to flower and head in cooler, moister weather.

In the USA, average yield increases of 6% have been reported in the initial years of adoption (Sankula, 2006). In Australia, Brookes and Barfoot (2012) report, based on Monsanto surveys of license holders, that GM HT varieties delivered higher yields in relation to conventional alternatives – by 22.11% in relation to non-GM triazine-tolerant (TT) varieties and by 4.96% in relation to conventionally bred HT varieties – although, as discussed below, the yield gains do not appear to have translated into higher profits for farmers.

Effects on inputs and farm profits: The principal effect on production costs as a result of adoption of GM HT varieties arises on account of reduced crop protection expenditures. GM HT varieties reduce the quantum and frequency of herbicide applications. Prior to the introduction of GM HT varieties, farmers generally used two applications of herbicide – one in the pre-emergence phase and one in the post-emergence phase – and also had to use tillage to remove weeds before planting. GM HT varieties have allowed producers to reduce the application of herbicide to one post-emergence application. The savings in associated labour, fuel and tillage costs also contribute to the overall cost reduction associated with GM HT varieties. In the early years of adoption, a study by the Canola Council of Canada (2001) suggested that input cost savings with GM HT OSR would increase gross margins by as much as 30%. In Canada, cost savings on account of reduced input costs have been estimated at between Can $25/ha and Can $36/ha (Brookes and Barfoot, 2012). In the USA, cost savings due to reduced input use have been estimated at $18–$45/ha for glufosinate-tolerant varieties and $40–$79/ha for glyphosate-tolerant varieties (Brookes and Barfoot, 2012; Sankula, 2006; Sankula and Blumenthal, 2003; Sankula and Blumenthal, 2006). In Australia, input cost savings have been estimated at around Aus $22/ha based on Monsanto’s surveys of licensed farmers (Brookes and Barfoot, 2012).

In order to assess the impact on farm profits from adoption of GM HT varieties (and consequently on the incentives for farmers to adopt the technology), it is necessary to take into consideration the seed price premium and/or the Technology Use (TU) fee that farmers have to pay seed firms in order to access the varieties. The seed price premium and TU fees are levied in different forms and combinations in different countries. The TU agreements entered into by farmers with seed firms to procure seeds of GM varieties generally include conditions such as those that prohibit farmers from using farm-saved seed for subsequent planting. In certain cases, seeds and proprietary herbicides may be offered as ‘bundled packages’ to farmers which incorporate the seed price premium and the technology fees. For the innovating/seed producing firms, the seed price premium and the TU fees constitute a return to the intellectual property rights (IPRs) that the firms have on the GM variety and associated technologies. The level of the seed price premium/TU fees charged by seed companies depends on the market structure, competition from other (conventionally-bred or GM) varieties and the remaining duration of intellectual property protection. In Canada, the cost of technology (seed price premium plus the TU fees) has been estimated at Can $18–$32/ha whilst in the USA it has been estimated at $12–$17/ha for glufosinate-tolerant varieties and $17–$33/ha for glyphosate-tolerant varieties (Brookes and Barfoot, 2012). In

Australia, GM OSR seeds are sold at a premium of Aus $14–15/ha. In addition, a stewardship fee of Aus $1000 per property is levied along with a grain technology toll of Aus $10/t. Depending on the area grown and the yield, the technology costs of using GM OSR ranges from Aus $54–$68/ha (Ministerial Industry GMO Reference Group, 2009). The positive impact of GM OSR adoption on farm profits as a result of input cost savings may be offset (partially or fully) by the costs of technology. This is illustrated in Table 3.1 which shows the impact of GM OSR adoption on farm profits in Canada over the period 1996–2010.

Table 3.1 also shows that in the initial years of adoption of GM OSR in Canada, the cost savings due to reduced input use were more than offset by the costs of technology resulting in a decrease in gross margins of Can $3–$5/ha. It is only after 2004 that the net cost savings have turned positive and have ranged between Can $16–$17/ha in recent years. The estimates of input cost savings in Table 3.1 are broadly consistent with other estimates such as that of Phillips (2003), who estimated input cost savings of Can $27.5/ha (without considering cost of technology). The increase in gross margins of up to Can $71/ha, shown in Table 3.1, are based on an assumed yield increase of 10.7%.

Fulton and Keyowski (1999) have argued that the distribution of yield gains among farmers will not be uniform, because farmers with different locations, weed pressures, agro-climatic conditions, farm structures and management capability will gain differently. They estimate that, owing to variability in farm conditions, GM OSR may, in certain cases, produce a lower return compared to conventionally-bred varieties by up to 7%. In the USA, after taking into account input cost-savings, yield increases and costs of technology, the positive impact on gross margins has been estimated at $22–$90/ha for glufosinate-tolerant varieties and $28–$61/ha for glyphosate-tolerant varieties over the period 1999–2010 (Brookes and Barfoot, 2012; Sankula, 2006; Sankula and Blumenthal, 2003; Sankula and Blumenthal, 2006; Johnson and Strom, 2008). The empirical studies examined above show that the pricing strategies for seed and technology adopted by innovating firms is a key determinant of farm profit impacts of GM OSR adoption. In certain cases, variations in conditions faced by farmers may imply that the positive gains attributed to GM OSR adoption may not be realised by all farmers. The fact that GM OSR saw rapid adoption in spite of modest (or negative) impacts of farm profits in the early years of adoption suggests that non-economic impacts relating to convenience and flexibility in farm management practices, risk management and crop quality and rotations are important drivers of adoption.

Table 3.1. Farm-level impacts of GM OSR adoption in Canada 1996–2010.

Year	Cost savings (Can $/ha)	Cost savings inclusive of cost of technology (Can $/ha)	Net cost saving/increase in gross margins (Can $/ha)
1996	28.59	-4.13	45.11
1997	28.08	-4.05	37.11
1998	26.21	-3.78	36.93
1999	26.32	-3.79	30.63
2000	26.32	-3.79	22.42
2001	25.15	-1.62	23.10
2002	24.84	-3.59	29.63
2003	28.04	-4.05	41.42
2004	21.42	+4.44	19.09
2005	23.11	+4.50	32.90
2006	34.02	+16.93	50.71
2007	35.44	+17.46	66.39
2008	35.53	+17.39	64.76
2009	35.31	+16.82	59.48
2010	33.96	+15.80	71.48

Source: Brookes and Barfoot (2012).

3.2.3. Aggregate welfare impacts

Based on the yield improvements assumed for farm-level impact assessments, it has been estimated that GM OSR adoption provided additional global production of 6.1M t over the period 1996–2010 (0.65M t in 2010) (Brookes and Barfoot, 2012). The same study also estimates that the total farm income gains in Canada from GM OSR adoption increased from Can $6M in 1996 to Can $433M in 2010, providing a cumulative benefit in nominal terms of Can $2.42B. For the USA, the farm income gains were estimated at $31M in 2010 with a cumulative benefit of $225M over the period 1999–2010.

Phillips (2003) examined the economic welfare effects of GM OSR adoption by estimating the aggregate direct impacts of adoption and the distribution of benefits among farmers, seed companies (innovators), processors and consumers. Farmers' net aggregate benefits (after deducting losses on account of lower producer prices due to increased production) were estimated at Can $70 million (Can $27.5/ha). The distribution of the estimated economic surplus generated is shown in Table 3.2.

Table 3.2. Distribution of aggregate economic benefits from GM OSR in Canada.

Year	Producers	Innovators	Processors and Consumers
1997	6%	94%	0%
1998	20%	80%	0%
1999	26%	60%	14%
2000	29%	57%	14%

Source: Phillips (2003).

Over the period 1997–2000, the share of aggregate economic benefits to farmers increased from 6% to 29% while that of seed producers (innovators) decreased from 94% to 57% possibly owing to increased competition from newer (GM and non-GM) varieties and the exhaustion of intellectual property rights on some varieties. Limited gains accruing to consumers may be attributable to a very small decline in prices faced by consumers on account of the market structure of the supply chain and the fact that a very large share (80%) of Canada's production is exported. Studies of the first generation GM crops in the EU (Demont *et al*., 2007) have suggested that GM OSR could provide aggregate benefits of up to £64/ha, 30% of which would accrue to input suppliers and 70% to farmers, with no share of benefits accruing to domestic consumers based on the assumption of no significant change in output price as a result of the adoption of GM OSR in a small, and open, economy.

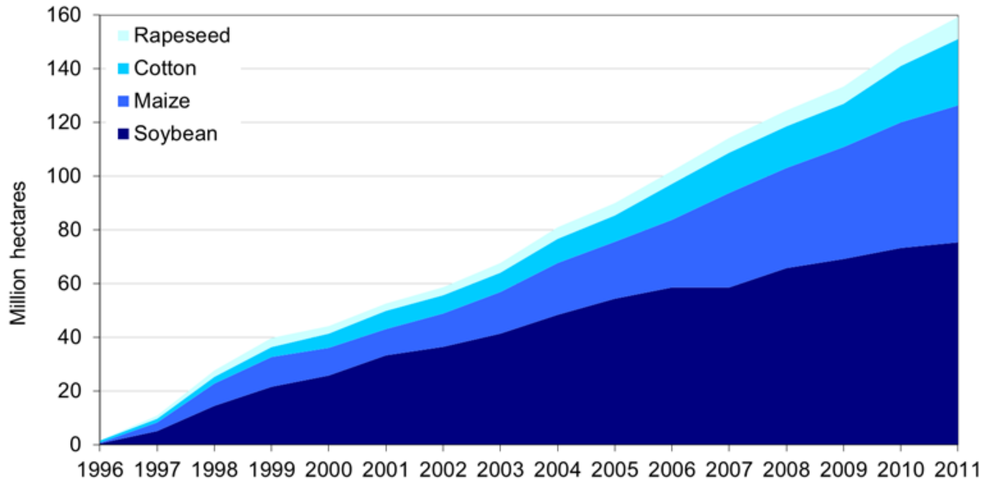
4. Literature review of GM maize

4.1. Status of the maize crop

Maize is the most important cereal grain worldwide in terms of production and the third most important cereal in area terms (FAO, 2013) after wheat and rice. Maize is a source of nutrients, particularly calories and protein, for humans and animals and can be used to produce starch, oil, protein, alcoholic beverages, food sweeteners and fuel (Latham, 1997).

The total worldwide area under maize was estimated at 170M ha in 2011 of which approximately 46.8M ha was estimated to be under GM maize varieties. Maize is mainly grown in the USA, China and Brazil. Maize production, and to a lesser extent consumption, is expected to continue to increase during the next decade with prices expected to be lower than in 2012 as production responds to high prices (OECD-FAO, 2012). In the UK, maize is a minor crop due to the climatic conditions of the country. It is mainly located in the south and west of the country where 194,000 ha were grown in 2013. Although some is grown for the grain, the predominant use of maize in the UK is as forage to complement grass silage (Defra, 2013).

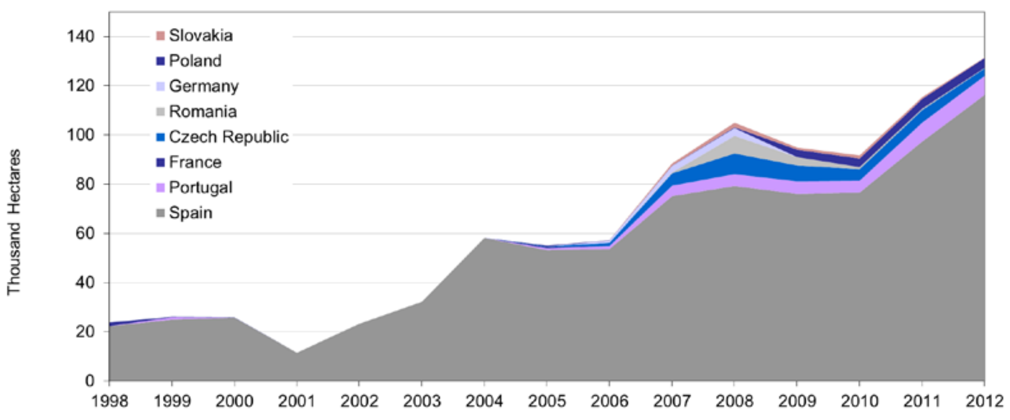
Figure 4.1 shows the area of worldwide adoption of GM crops for four major crops including maize. The rapid adoption of these crops since their commercialisation is the result of a combination of yield protection and lower production costs. Insect resistance (Bt) and herbicide tolerance (HT) are the two main GM maize traits.



Source: James (2011).

Figure 4.1. Area of GM soybean, maize, cotton and rapeseed grown, 1996–2011.

European and Mediterranean corn borers (*Ostrinia nubilalis* and *Sesamia nonagrioides*) are two of the main pests affecting maize production in Europe. The presence of these pests affects yields negatively and, consequently, may have adverse economic effects. Effective chemical control of these species requires that insecticide sprays are applied in the short period which elapses between the eggs hatching and the larvae boring into stems (Farinós *et al*., 2004; Agustí *et al.,* 2005). An alternative control of these pests is the use of insect resistant Bt maize (*Zea mays L. line MON 810*).



Source: USDA (2013b).

Figure 4.2. The area of Bt maize grown in the EU, 1998–2012

GM maize expressing the insecticidal protein Cry1Ab from *Bacillus thuringiensis* (Bt maize) is the only GM maize planted commercially in the EU. GM maize is the second largest in area GM crop cultivated worldwide after HT soybeans (James, 2011). The adoption of Bt maize in Europe started in 1998. Spain is the main Member State in the EU in terms of area of adoption of Bt maize. Figure 4.2 shows the adoption area of Bt maize per EU country.

Table 4.1 shows the number of hectares of Bt maize and conventional maize grown in Spain by region in 2012. The adoption of Bt maize in Spain is concentrated mainly in two regions, Aragon and Catalonia, where the pest pressure is particularly severe.

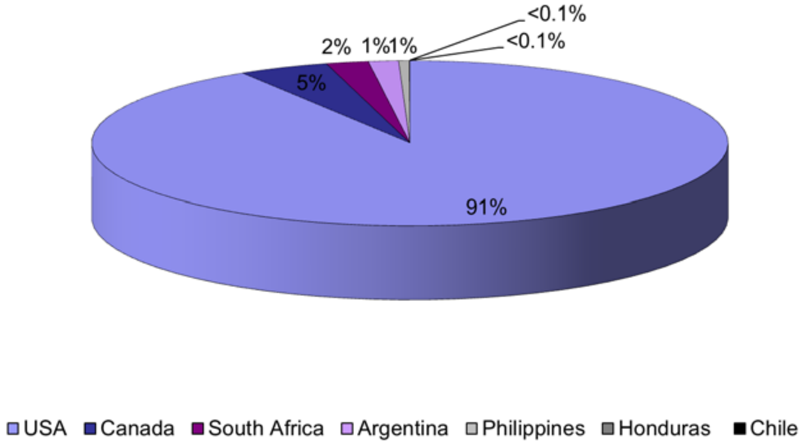
The distribution of the HT maize production area worldwide is shown in Figure 4.3. The USA is by far the largest adopter of HT maize technology in terms of area (91% of the world HT maize cultivated area). GM HT adoption rates have been lower than those for Bt crops. *Ex-ante* estimation of GM HT maize and OSR adoption has been conducted by Areal *et al*. (2012) finding relatively higher rates for GM HT OSR than for GM HT maize. *Ex-ante* adoption rates for GM HT maize were 32, 45 and 45% for Spain, France and Hungary, respectively. Previous research by Demont *et al*. (2008) found slightly higher ex-ante adoption rates (54%) for Hungary.

Table 4.1. The area of Bt maize in Spain by region, 2012.

	Bt maize (ha)	Conventional and Bt maize (ha)	Bt maize as proportion of total maize (%)
Andalusia	10,362	38,991	26.6
Aragon	41,669	61,294	68.0
Asturias	0	333	0.0
Baleares	154	326	47.2
Basque Country	0	313	0.0
Cantabria	0	325	0.0
Canary Islands	0	434	0.0
Castilla-La Mancha	7,883	39,725	19.8
Castilla-León	8	105,061	0.0
Catalonia	33,531	36,245	92.5
Ceuta and Melilla	0	1	0.0
Extremadura	15,952	60,643	26.3
Galicia	0	19,112	0.0
La Rioja	0	668	0.0
Madrid	421	7,331	5.7
Murcia	4	128	3.1
Navarra	5,801	18,715	31.0
Valencia	522	571	91.4
Total Spain	116,307	390,216	29.8

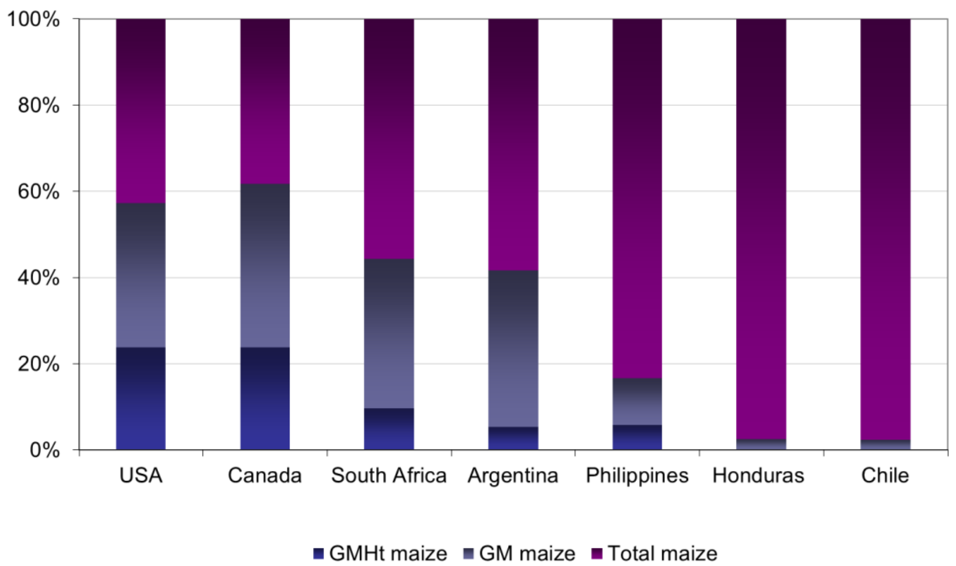
Source: James (2012) and MAGRAMA (2012).

Figure 4.4 shows the adoption rates of GM HT maize, GM maize and conventional maize in 2008 for various countries. HT maize has been commercially used in the USA since 1997. In 2010 almost 86% of the USA's total maize crop was GM, 16% being Bt varieties, 23% HT varieties and 47% stacked varieties.



Source: James (2011).

Figure 4.3. Distribution of HT maize production area worldwide, 2008.



Source: James (2011).

Figure 4.4. Adoption rates of GM HT technology per adopting country, 2008.

4.2. Economic impact assessments of GM maize

4.2.1. Introduction

Several studies have investigated the economic impacts of GM crops in different countries with contrasting results. A few studies have analysed the economic performance worldwide (Areal *et al*., 2013; Brookes and Barfoot, 2005; Brookes and Barfoot, 2012; Carpenter, 2010; Qaim, 2009). Generally, results from these studies show that growing GM crops has economic benefits with few exceptions. Economic assessments of GM maize have been few and have particularly focused on Bt maize varieties and less on HT maize. A recent meta-analysis conducted by Areal *et al*. (2013) investigated the economic and agronomic performance of all GM crops worldwide. Areal *et al*. (2013) found that, overall, GM crops perform better than their conventional counterparts in agronomic and economic (gross margin) terms. In particular, Bt crops were found to outpace conventional crops in terms of yields and gross margins, at the expense of higher production costs. The authors pointed out that, although it cannot be discerned whether the advantages of cultivating GM crops were due to the technology itself or to farmers' managerial skills (the so-called GM adopter effect), the GM adopter effect is expected to diminish as the technology advances. Regarding various countries' level of development, GM crops tend to perform better in developing countries than in developed countries, with Bt cotton being the most profitable such crop grown. Areal *et al.* (2013) discussed reasons behind such success in developing countries. The absolute yield difference between developing and developed countries for HT crops may be due to poor management of inputs, such as pesticides, and lack of knowledge about handling them may cause health problems as well as a lack of efficient control of pests in developing countries prior to the adoption of GM crops. Also, the costs of herbicides and pesticides are unaffordable for many farmers in developing countries, preventing conventional crops from reaching their true yield potential.

4.2.2. Farm level impacts studies

Farm-level impacts of GM maize adoption may arise from:

(i) Yield effects: although Bt crops are reported to achieve higher yields, the yields of HT crops are not significantly different from conventional maize.

(ii) Effects on costs of production, particularly because of less spending on sprays. In the case of HT crops the benefits come mainly from the reduction of herbicide sprays used (i.e. lower spray costs and lower labour, machinery and fuel requirements (Bernard *et al*., 2004; Bullock and Nitsi, 2001; Ervin *et al*., 2010; Fernández-Cornejo *et al*., 2002; Phillips, 2003; Qaim, 2009).

(iii) Effects on farm profits resulting from yield and cost effects. Non-pecuniary benefits are also reported as part of the benefits of adopting GM HT crops (Bullock and Nitsi, 2001; Carpenter and Gianessi, 2009; Ervin *et al.,* 2010; Marra and Piggott, 2006). Flexibility and simplicity of use of the technology leads to less time spent on scouting and spraying fields to address weed problems by farmers. Such time-saving may be used on other on-farm and/or off-farm activities that may raise farmers' incomes (Fernández-Cornejo *et al*., 2005; Keelan *et al*., 2009).

Yield effects: Table 4.2 shows a number of scientific studies on Bt maize along with the average yield difference (Bt maize yield – non-Bt maize yield) and standard deviation per study. A total of five out of the six studies which analysed the yield of Bt maize found that it outperformed non-GM maize. The only case in which Bt maize did not outperform non-GM maize was in a trial in South Africa where the average Bt yield was 0.1 t/ha less than non-GM maize (Gouse *et al*., 2009). Average yield differences between Bt maize and non-GM maize have varied from 0.4 t/ha in Canada to 2.1 t/ha in the Czech Republic.

Table 4.2. Studies of the yield of Bt maize compared with non-GM maize.

	Trait	Year	Country	Yield differences[1]	
				Number of trials/studies	Mean (std. dev) (t/ha)
Yorobe and Quicoy (2006)	Bt	2003-2004	Philippines	4(+)/1(-)	0.7 (0.81)
Gouse *et al.* (2009)	Bt	2007	South Africa	1(-)	-0.1 (n.a.)
Fernandez-Cornejo and Li (2005)	Bt	2001	USA	1(+)	0.9 (n.a)
Hategekimana (2002)	Bt	2000-2001	Canada	12(+)/2(-)	0.4 (0.47)
Gómez-Barbero *et al*. (2008)	Bt	2002-2004	Spain	8(+)/1(-)	0.6 (0.52)
Ministry of Agriculture Czech Republic (2009)	Bt	2007	Czech Republic	1(+)	2.1
TOTAL Bt maize				31 [26(+)/5(-)]	

[1] Positive or negative variation GM vs. non-GM.

Source: Areal *et al.* (2013).

Only one scientific reference has been found to report on the yield difference of HT maize (Gouse *et al*., 2009). This found that HT maize yield was 0.5 t/ha higher than the conventional counterpart (Table 4.3).

Table 4.3. A study of the yield of HT maize compared with non-GM maize.

	Trait	Year	Country	Yield differences[1]	
				Number of trials/studies	Mean (std. dev)(t/ha)
Gouse *et al*. (2009)	HT	2007	South Africa	1(+)	0.5

[1] Positive or negative variation GM vs. non-GM.

Source: Areal *et al*. (2013).

Table 4.4 shows the mean of the absolute difference of the yield between Bt maize crops and their conventional counterparts by groups of countries. The average yield difference between Bt maize and conventional maize is 0.55 t/ha with the probability of such an average being above zero (i.e.

Bt maize outperforming conventional maize) of 100% (Areal *et al*., 2013). They also found that the Bt maize yield comparative performance is above other Bt crops analysed such as Bt cotton.

Table 4.4. Mean and standard deviation of absolute difference of the yield between Bt maize crops and conventional maize.

	Mean (t/ha)	s.d.	(Pr Bt maize yield > conventional yield)
All countries: Bt maize vs. conventional	0.35	0.03	100%
Developed countries: Bt maize vs. conventional	0.38	0.06	100%
Developing countries: Bt maize vs. conventional	0.35	0.05	100%
Overall: Bt maize vs. conventional	0.55	0.11	100%

Source: Areal *et al*. (2013).

Effects on inputs and farm profits: The financial benefits of growing GM varieties are usually higher than those achieved by conventional varieties due to the combination of yield protection and the lower production costs associated with a saving in pesticides costs despite the increase in seeds costs. Table 4.5 shows a number of studies of Bt maize along with the average production cost difference (Bt maize production cost – non-GM production cost) and standard deviation. Four out of the seven studies which analysed the production costs of Bt maize in comparison with non-GM maize found Bt maize production costs to be higher than those associated with non-GM maize production. There was only one case in which the average Bt maize production costs were less costly than non-GM maize production. This was a study in South Africa where the average Bt maize production costs were 11€/ha less expensive that than the non-GM maize (Abel, 2006). Average production cost differences between Bt maize and non-GM maize vary from Bt maize production costs being less costly than conventional maize by 11€/ha and Bt maize being more expensive than conventional maize by 87€/ha.

Table 4.5. Studies of production costs of Bt maize compared with conventional maize.

	Trait	Year	Country	Production cost differences[1]	
				Number of trials/studies	Mean (std. dev)(€/ha)
Yorobe and Quicoy (2006)	Bt	2003–2004	Philippines	2(+)/3(-)	87(45.2)
Gouse *et al*. (2009)	Bt	2007	South Africa	1(+)/1(-)	29 (67)
Gouse *et al*. (2005)	Bt	2002	South Africa	4(-)	-11 (5.9)
Gómez-Barbero *et al*. (2008)	Bt	2002–2004	Spain	4(+)/1(-)	11 (11.7)
Abel (2006)	Bt	2006	Czech Republic	1(+)	9.2 (n.a.)
TOTAL Bt maize				[8(+)/9(-)]	

[1] Positive or negative variation GM vs. non-GM.

Source: Areal *et al*. (2013).

Only one study (see Table 4.6) reported on the economic performance of HT maize. This found that the cost difference between HT maize and conventional maize was 106€/ha more for HT maize (Gouse *et al*., 2009).

Table 4.6. Study of production costs of HT maize compared with conventional maize.

	Trait	Year	Country	Production cost differences[1]	
				Number of trials/studies	Mean (std. dev)
Gouse *et a*l. (2009)	HT	2007	South Africa	2(+)	106 (58.4)

[1]Positive or negative variation GM vs. non-GM.

Source: Areal *et al*. (2013).

Table 4.7 shows the mean of absolute difference of the production costs between Bt crops and their conventional counterparts for various countries and Bt maize in particular. The average production costs difference between Bt maize and conventional maize is 14€/ha and the probability of such average being above zero (i.e. Bt maize production costs being higher than conventional maize production costs) is 94% (Areal *et al.,* 2013). Hence, Bt maize production costs are higher on average than non-GM counterpart.

Table 4.7. Mean and standard deviation of absolute difference of the production costs between Bt maize crops and conventional maize.

	Mean (€/ha)	s.d. (€/ha)	(Pr Bt maize > conventional)
All countries: Bt maize vs. conventional	13	8.7	95%
Developed countries: Bt maize vs. conventional	7	12.8	71%
Developing countries: Bt maize vs. conventional	12	9.6	90%
Overall: Bt maize vs. conventional	14	9.2	94%

Source: Areal *et al*. (2013).

Table 4.8 shows a number of studies that have examined Bt maize along with the average net gross margin difference (Bt maize gross margin minus non-GM production cost) and standard deviation for each. A total of seven out of the eight studies which analysed the gross margin of Bt maize in comparison with non-GM maize found Bt maize gross margins to be higher than non-GM maize gross margins. The only case in which Bt maize did not outperform non-GM maize was in a trial in South Africa where the average Bt yield was 0.1 t/ha less than the non-GM maize (Yorobe and Quicoy, 2006). Average yield differences between Bt maize and non-GM maize vary from 0.4 t/ha in Canada and 2.1 t/ha in the Czech Republic.

Table 4.9 shows the mean of the absolute differences of the gross margins between Bt maize crops and their conventional counterparts for various groupings of countries. The average gross margin difference between Bt maize and conventional maize was 52 €/ha (Areal *et al.*, 2013). Hence, Bt maize production costs are higher on average than those for the non-GM counterpart.

Table 4.8. Studies of gross margins of Bt maize compared with conventional maize.

	Trait	Year	Country	Gross margin differences[1]	
				Number of trials/studies	Mean (std. dev) (€/ha)
Yorobe and Quicoy (2006)	Bt	2003–2004	Philippines	3(+)/2(-)	36(112.7)
Gouse *et al*. (2009)	Bt	2007	South Africa	2(-)	-30 (40)
Diaz-Osorio *et al.* (2004)	Bt	2003	Chile	1(+)	51 (n.a.)
Gómez-Barbero *et al*. (2008)	Bt	2002-2004	Spain	3(+)	61 (54.4)
Abel (2006)	Bt	2006	Czech Republic	1(+)	66 (n.a.)
Ministry of Agriculture Czech Republic	Bt	2007	Czech Republic	1(+)	28 (n.a.)
Brookes (2007	Bt	2005–2007	France	2(+)	113 (13.3)
Brookes (2007)	Bt	2006	Portugal	1(+)	115 (n.a.)
TOTAL Bt maize				[12(+)/4(-)]	

[1] Positive or negative variation GM vs. non-GM.

Source: Areal *et al.* (2013).

Table 4.9. Mean and standard deviation of absolute difference of the gross margin between Bt maize crops and conventional maize

	Mean (€/ha)	s.d. (€/ha)	(Pr Bt maize > conventional)
All countries: Bt maize vs. conventional	194	17.5	100%
Developed countries: Bt maize vs. conventional	74	20.8	100%
Developing countries: Bt maize vs. conventional	196	18.7	100%
Overall: Bt maize vs. conventional	52	23.5	99%

Source: Areal *et al*. (2013).

The positive impact of GM maize on farm profits has been estimated by Brookes and Barfoot (2012) for the USA, South Africa and Spain. Table 4.10 summarises the results of farm level impacts of Bt maize adoption in the USA, South Africa and Spain between 1996 and 2010. With regard to the effects associated with the adoption of HT maize, Brookes and Barfoot (2012) highlight that the main benefit has been to reduce costs and improve profitability levels. Brookes and Barfoot (2012) also provide estimates of the national farm income impact of using GM HT maize in the USA and Canada between 1997 and 2010. These estimates are shown in Table 4.11.

Table 4.10. Farm-level impacts of Bt maize adoption in the USA, South Africa and Spain (1996–2010).

Year	Cost savings ($/ha)			Cost savings inclusive of cost of technology ($/ha)			Net increase in gross margins ($/ha)		
	USA	SA	SP	USA	SA	SP	USA	SA	SP
1996	24.71	-	-	-9.21	-	-	45.53	-	-
1997	24.71	-	-	-9.21	-	-	39.38	-	-
1998	20.30	-	37.40	-4.8	-	3.71	35.31	-	95.16
1999	20.30	-	44.81	-4.8	-	12.80	33.05	-	102.20
2000	22.24	13.98	38.81	-6.74	1.87	12.94	32.71	43.77	89.47
2001	22.24	11.27	37.63	-6.74	1.51	21.05	35.68	34.60	95.63
2002	22.24	8.37	39.64	-6.74	0.6	22.18	40.13	113.98	100.65
2003	22.24	12.82	47.50	-6.74	0.4	26.58	41.37	63.72	121.68
2004	22.24	14.73	51.45	-6.36	0.46	28.79	44.90	20.76	111.93
2005	17.30	15.25	52.33	-1.42	0.47	8.72	44.49	48.66	144.74
2006	17.30	14.32	52.70	-1.42	-2.36	8.78	67.13	63.75	204.5
2007	17.30	13.90	57.30	-1.42	0.22	9.55	78.69	182.90	274.59
2008	24.71	11.74	61.49	-8.83	-4.55	10.25	95.00	87.07	225.36
2009	28.21	12.07	58.82	-12.33	-1.99	9.80	84.62	58.38	205.51
2010	32.06	13.23	55.26	-16.18	-2.18	9.21	92.65	66.87	265.96

Source: Brookes and Barfoot (2012).

Table 4.11. National farm income impact of using GM HT maize in the USA and Canada (1997–2010).

Year	National farm income impact (M$) USA	National farm income impact (M$) Canada
1997	3	-
1998	42	-
1999	37	0.8
2000	57	1.8
2001	61	2.5
2002	96	3.6
2003	120	3.4
2004	169	4.9
2005	206	8.7
2006	162	6.7
2007	400	9.8
2008	322	3.7
2009	281	7.7
2010	270	4.2

Source: Brookes and Barfoot (2012).

5. Review of recent work on GM cereals relevant for the UK

5.1. Introduction

The original method for producing the first GM plants (tobacco) in 1983 depended on the use of the natural bacterial vector *Agrobacterium tumefaciens*. It was assumed then that this system could not be applied to cereals so the emphasis for them was focussed on direct gene transfer methods.

However, since then, major improvements have been made to the *Agrobacterium* techniques so that they can be applied to cereals; Dunwell and Wetten (2012) summarise a wide range of GM techniques.

These novel technologies include new methods for the design of constructs (Coussens *et al.*, 2012; Karimi *et al*., 2013), that is the DNA sequences to be introduced and improved methods for DNA delivery. These latter methods include techniques for wheat (Tamás-Nyitrai *et al.,* 2012), barley (Holme *et al.*, 2012) and triticale (Ziemienowicz *et al.,* 2012). There is also an improved understanding of the process of regeneration from plant cells in culture (Delporte *et al.,* 2012), an important aspect of any system for high efficiency transformation.

Temporal and spatial stability of transgene expression, as well as well-defined transgene incorporation are additional features to be considered (Bregitzer and Brown, 2013; Kim and An, 2012). Likewise, it is of practical importance that GM lines can be rapidly identified, both in the laboratory and under field conditions. Another objective in many GM research projects is the development of more efficient methods for the introduction of multiple genes. Additionally, there has been significant progress with efforts to induce site-specific gene integration (Nandy and Srivastava, 2012; Kapusi *et al.*, 2012). Some of these techniques are also associated with the new techniques described below.

Since 1983 the commercial focus became the development of GM maize, as this crop was already hybrid and annual sales of such high-value seed was an established part of the agricultural economy of the USA and elsewhere. In contrast, the other important cereals, wheat and rice, are self-pollinating crops and the value of seed sales is comparatively low and any GM variety could in theory, if not in practice, be saved by the farmer for growth in subsequent years. Thus, there have been attempts to convert inbreeding species into hybrid crops either through the use of chemical hybridizing agents or via GM technology. One GM approach to the production of male sterility, a necessary component of any hybrid system (Feng *et al*., 2013), has recently been exemplified in wheat by expressing a barnase gene (causes male sterility by interfering with RNA production) (Kempe *et al*., 2013).

Below, the specific traits incorporated into GM varieties will be divided into those that provide advantages to the farmer/grower (input traits) and those that modify the characteristics of the harvested product (output traits). As maize has been covered earlier in this review, discussion will predominantly focus on wheat, barley and oats.

5.2. Input trait work

5.2.1. Herbicide tolerance

Following work by Monsanto and AgrEvo in the USA in the late 1990s, most hybrid maize sold there is resistant to one or more herbicides, giving farmers flexible options for weed control. Monsanto also developed a glyphosate-tolerant (Roundup Ready™) version of wheat, and carried out successful field tests in the 1990s. Due to concerns about international trade of GM wheat, this project was suspended in 2005, although recently in April 2013 some HT wheat plants carrying the Monsanto CP4 gene for glyphosate tolerance have been discovered growing on a farm in Oregon; their origin is uncertain (Dunwell, 2014).

5.2.2. Pathogen tolerance

Although there are no commercial GM cereals with pathogen tolerance, there has been a great deal of research on this subject with promising results from both laboratory and field tests, particularly with wheat (http://www.isaaa.org/resources/publications/pocketk/document/Doc-Pocket%20K38.pdf).

Wheat is affected by a number of fungal diseases with *fusarium* having probably the most significant impact on grain quality, causing crown rot and head blight that result in production of small and stunted grains or no grain at all. Some *fusarium* species also produce mycotoxins, compounds which, when ingested by humans or animals, may cause serious illness.

For many years Syngenta worked on the development of a *fusarium*-resistant wheat but this project was suspended in 2007, also after concerns about exports of GM wheat from the USA. Among the genes that have been shown to provide resistance to this fungus are a bovine lactoferrin gene (Han *et al*., 2012), an *Arabidopsis thaliana NPR1* (non-expressor of PR genes) gene (Gao *et al*., 2013), a polygalacturonase-inhibiting protein gene from *Phaseolus vulgaris* (PvPGIP) (Ferrari *et al*., 2012) (see also Janni *et al*., 2013), a lipid transfer gene from wheat (Zhu *et al*., 2012) and the antimicrobial peptides genes *MsrA2* and *10R* (Badea *et al*., 2013). Results from this latter study showed that T3 generation GM plants had a 53% reduction in *fusarium* damaged kernels, and some lines also had a 59% reduction in powdery mildew susceptibility compared with the non-GM control.

Other GM approaches to achieving mildew resistance in wheat include the use of virus-induced gene silencing (VIGS) of *Mlo* genes (Várallyay *et a*l., 2012), alleles of the resistance locus *Pm3* in wheat, conferring race-specific resistance (Brunner *et al*., 2012). Related studies on this latter material showed that the mildew-resistant GM lines harboured bigger aphid populations (*Metopolophium dirhodum* and *Rhopalosiphum padi*) than the non-transgenic lines (von Burg *et al*., 2012). These results suggest that wheat plants that are protected from a particular pest (powdery mildew) may become more favourable for another pest (aphids).

Other recent tests have described resistance to take-all in GM wheat lines expressing an R2R3-MYB gene from *Thinopyrum intermedium* (TiMYB2R-1) *(*Liu *et al*., 2013*)***,** to *Bipolaris sorokinia* by expression of the related gene *TaPIMP1* (Zhang *et al*., 2012), to *Penicillium* seed rot in lines expressing puroindolines (Kim *et al*., 2012), and to rust diseases by endogenous silencing of *Puccinia* pathogenicity genes (Panwar *et al.*, 2013) or expression of the *Lr34* durable resistance gene (Risk *et al*., 2012).

Projects designed to improve virus resistance in cereals include expression of an artificial microRNA to provide resistance to wheat streak mosaic virus (Fahim *et al*., 2012). It has been reported that a wheat line with resistance to yellow mosaic virus (being developed by the Chinese Academy of Agricultural Sciences) is expected to be available in the market by 2015 (http://www.isaaa.org/resources/publications/pocketk/document/Doc-Pocket%20K38.pdf).

5.2.3. Abiotic stress

Following the great commercial success of herbicide tolerant and insect resistant crops, research focus moved to the more difficult subject of tolerance to abiotic stress such as drought, salt tolerance and nitrogen and phosphate deficiency. The first commercial cereal product in this area is the Monsanto GM maize DroughtGard™ variety that expresses *cspB*, an RNA chaperone gene from *Bacillus subtilis* (Castiglioni *et al*., 2008), which increases yield under water-limited conditions. A recent review of drought tolerance in maize has been published by Edmeades (2013).

There is a wide range of other approaches that are being tested at present in order to improve the growth of cereals under conditions of abiotic stress (Saint Pierre *et al*., 2012). For example, wheat over-expressing the 12-oxo-phytodienoic acid gene (*TaOPR1*) significantly enhanced the level of salinity tolerance (Dong *et al*., 2013). Studies on GM rice have also suggested that overexpression of a wheat gene encoding a salt-induced protein (TaSIP) may also be of benefit in enhancing salt tolerance (Du *et al*., 2013). An equivalent investigation demonstrated that GM oats expressing the Arabidopsis *CBF3* gene exhibited improved growth and showed significant maintenance of leaf area, chlorophyll content, photosynthetic and transpiration rates, relative water content, as well as increased levels of proline and soluble sugars under high salt stress (Oraby and Ahmad, 2012). According to a recent report, field trials conducted in Australia in 2009 (Table A.1) showed that wheat lines expressing a salt tolerant gene *(Nax2)* from *Triticum monococcum* produced 25% more yield than the control line in saline conditions http://www.isaaa.org/resources/publications/pocketk/document/Doc-Pocket%20K38.pdf).

In a similar study, two wheat CBF (core binding factor) transcription factors, TaCBF14 and TaCBF15, were transformed into spring barley, and analysis showed that transgenic lines were able to survive freezing temperatures several degrees lower than that which proved lethal for the wild-type spring barley (Soltész *et al*., 2013). Similar results with improved frost tolerance or other abiotic stress were achieved with GM barley expressing the rice transcription factor *Osmyb4* (Soltész *et al.,* 2011) or the wheat *TaDREB3* gene (Hackenberg *et al.,* 2012; Kovalchuk *et al*., 2013). In addition to the problems of reduced growth under conditions of nutrient deficiency, the ions of certain metals inhibit normal development. One example is the inhibitory effect of excess aluminium in acid soils, and this was the subject of a recent genetic study on the root hairs of wheat (Delhaize *et al*., 2012). An alternative approach in this species is represented by a study of the multidrug and toxic compound extrusion gene (*TaMATE1B*) (Tovkach *et al*., 2013). One approach to improving growth in alkaline soils is demonstrated by results from GM rice expressing the barley iron-phytosiderophore transporter (*HvYS1*). This gene enables barley plants to take up iron from alkaline soils.

5.2.4. Yield traits

The obvious aim of all the agronomic traits mentioned to date is to increase or to stabilise yield under field conditions (Shi *et al*., 2013). There are also future new opportunities to improve the underlying physiological performance of the plant itself.

Corresponding transgenic research in wheat has identified the role of TaGW2-A, a functional E3 RING ubiquitin ligase, in regulating grain size (Bednarek *et al.,* 2012). An important quality trait related to yield is the problem of post-harvest sprouting. Among the GM approaches to overcoming this problem is the use of an antisense version of the *trx s* (*thioredoxin s*) gene from *Phalaris coerulescens* to reduce the endogenous *trx h* gene in wheat (Guo *et al*., 2011).

5.3. Output trait work

5.3.1. Modified grain quality

Transgenic technologies provide a large variety of opportunities to modify the nutritional components in cereal crops (Bhullar and Gruissem, 2013; Demont and Stein, 2013; Pérez-Massot *et al.,* 2013). These include modified proteins, carbohydrate, oils and other minor compounds and these will be considered in turn.

Among the first reported GM lines of wheat were ones with modified subunits of the high molecular weight glutenin protein that confers good breadmaking quality. Recent reports in this area include the generation of GM wheat with enhancement in the concentration of high-molecular-weight glutenin subunit 1Dy10 and associated benefit in sponge and dough baking of wheat flour blends

(Graybosch *et al*., 2013). It is also reported that such improved baking quality can be achieved without the need for selectable marker genes (Qin *et al.*, 2013), and that coexpression of high molecular weight glutenin subunit 1Ax1 and puroindoline improves dough mixing properties in durum wheat (*Triticum turgidum* L. ssp. *durum*) (Li *et al*., 2012b). Similarly it is reported that GM methods can be used to reduce the expression of γ-gliadins and thereby potentially improve the dough mixing and bread making properties of wheat flour (Gil-Humanes *et al.,* 2012). As part of related projects it has been shown that the starch characteristics of GM wheat overexpressing the Dx5 high molecular weight glutenin subunit are substantially equivalent to those in non-modified wheat (Beckles *et al*., 2012), and that isolation of enriched gluten fractions from lines modified to overproduce HMW glutenin subunits Dx5 and/or Dy10 may require modified separation technologies (Robertson *et al*., 2013). Studies on the GM modification of such subunits may also lead to the production of novel proteins encoded by altered versions of either the transforming or endogenous genes (Blechl and Vensel, 2013). Another aspect of this type of study that has importance in any future regulatory submission is the determination of potential changes in the allergenicity of the GM material (Lupi *et al*., 2013).

Alongside the many projects that are designed to modify protein quantity and quality in cereals are several that focus on aspects of starch synthesis (Blennow *et a*l., 2013). Many of these projects are designed to produce products with improved health benefits. For example, using a chimeric RNAi hairpin Carciofi *et al*. (2012) simultaneously suppressed all genes coding for starch branching enzymes (SBE I, SBE IIa, SBE IIb) in barley, resulting in production of amylose-only starch granules in the endosperm.

It was observed in a study on GM durum wheat, in which the gene encoding one isoform of SBE was silenced, that various protein differences were present in the endosperm of the transgenics (Sestili *et al*., 2013).

GM triticale lines expressing one or both of the *sucrose-sucrose 1-fructosyltransferase* (*1-SST*) gene from rye and or the *sucrose-fructan 6-fructosyltransferase* (*6-SFT*) gene from wheat accumulated 50% less starch and 10-20 times more fructan, particularly 6-kestose, in the dry seed compared to the untransformed control (Diedhiou *et al*., 2012). This is the first report of GM cereals with production of fructans in seeds.

Suppression of the *CSLF6* gene in wheat has been shown to reduce the level of glucan and provides an opportunity to improve the level of dietary fibre (Nemeth *et al*., 2010).

GM wheat and barley with a range of modified grain traits are among the list of lines that have been tested in the field in Australia (Table 5.1).

Chaudhary and Khurana (2013) produced GM wheat overexpressing the endogenous *HPPD* gene and observed a 2.4 fold increase in the level of tocochromomanol, one of an important group of plastidic lipophilic antioxidants, which may have significant benefits in the human diet.

Table 5.1. Field trials of GM wheat and barley in Australia: applications and licences for Dealings involving Intentional Release (DIR) into the environment.

Number	Organisation	Description	Crop(s)	Trait	Date
DIR117	CSIRO	grain composition, nutrient utilisation	wheat, barley	nutrition, yield	Mar 2013
DIR112	CSIRO	grain composition, nutrient utilisation	wheat, barley	nutrition, yield	Mar 2012
DIR111	CSIRO	grain composition, nutrient utilisation	wheat, barley	yield, disease, stress	Feb 2012
DIR102	Uni. Adelaide	abiotic stress	wheat, barley	yield, stress	Jun 2010
DIR100	CSIRO	drought, heat	wheat	yield, stress	Jun 2010
DIR099	CSIRO	grain composition, nutrient utilisation	wheat, barley	nutrition, yield	Mar 2013
DIR094	CSIRO	nutrient utilisation	wheat, barley	yield	Jul 2009
DIR093	CSIRO	grain starch	wheat, barley	nutrition	Jun 2009
DIR092	CSIRO	grain composition	wheat	nutrition, processing	May 2009
DIR080	Vict. Dept. Prim. Indust.	drought	wheat	abiotic stress	Jun 2008
DIR077	Uni. Adelaide	stress, glucan	wheat, barley	stress, nutrition	Jun 2008
DIR071	Vict. Dept. Prim. Indust.	drought	wheat	abiotic stress	Jun 2007
DIR061	Grain Biotech	salt tolerance	wheat	stress tolerance	Withdrawn
DIR054	CSIRO	grain starch	wheat	nutrition	Apr 2005
DIR054	Grain Biotech	salt tolerance	wheat	stress tolerance	Apr 2005

Summary of data from the Office of the Gene Regulator. Available at: http://www.ogtr.gov.au/internet/ogtr/publishing.nsf/Content/ir-1

Results relating to iron and zinc accumulation in GM wheat expressing a ferritin gene have been discussed recently by Neal *et al*. (2013). In addition to increases in the levels of vitamins and minerals, GM techniques have also been used recently to improve the content of beneficial compounds such as flavonoids (Ogo *et al*., 2013) and sakuranetin, a flavonoid phytoalexin (Shimizu *et al*., 2012a) in rice. Related research demonstrating the effects of purple, anthocyanin-containing, wheat on extending the lifespan of nematodes (Chen *et al*., 2013b) may be developed through GM technology.

5.3.2. Enzymes, diagnostics and vaccines

Dunwell (2014) reviews work on GM products that can be loosely described as the above heading. However, all of this work, some of which has been commercialised already, concerns largely maize with some on rice. At present this has limited benefits for the UK, thus, it will not further be discussed here.

5.4. The pipeline of future products

5.4.1. Field trials work on GM cereals

One simple method to assess the direction of future research on GM cereals in both commercial and non-commercial programmes is to examine the various public databases that summarise the applications for field testing. Such information is available from the regulatory authorities in the various jurisdictions around the world. Data for the USA are available at http://www.isb.vt.edu/search-release-data.aspx and can be summarised as follows:

Maize: A total of 8294 applications for maize have been submitted in the period from 1996 to date (latest 14th June 2013). Many of these are from commercial companies and understandably have limited details of the genes being tested because of Confidential Business Information (CBI) restrictions. However, among the most recent applications from a non-commercial institution is one from the Cold Spring Harbor Laboratory that lists a total of 78 genes to be tested.

Wheat: A total of 510 applications for wheat have been submitted in the period from 1996 to date (latest 22nd April 2013). The traits for trial in the 13 applications for 2013 include: nitrogen use efficiency (Arcadia); *fusarium* resistance (Uni. Minnesota); nitrogen metabolism, drought/heat tolerance, water use efficiency, yield increase, modified flowering time, altered oil content, fungal tolerance, insect resistance, herbicide tolerance (Monsanto); increased carbohydrate, improved grain processing (Uni. Nebraska); herbicide tolerance (and other CBI traits) (Pioneer); CBI traits (Biogemma); and breadmaking quality (USDA).

Barley: a total of 109 applications were submitted in the period from 1994 to 2013 (latest 15th May 2013). The traits for trial in the 6 applications for 2012 include: starch quality (USDA); nitrogen utilisation efficiency (Arcadia); *fusarium* resistance (USDA); and Rhizoctonia resistance (Washington State University).

Data for the EU are available at http://gmoinfo.jrc.ec.europa.eu/gmp_browse.aspx and are summarised in Table 5.2. This list is relatively short and does not include many of the commercial trials of maize. Interesting trials include testing wheat designed to have reduced levels of epitopes linked to celiac disease, and that designed to deter aphids by expression of an alarm pheromone (Yu *et al*., 2012).

Table 5.2. Summary of selected field trials of GM cereals in the EU.

Number	State	Date	Institution	Subject
B/ES/13/19	Spain	May 2013	INIA	Bt maize
B/ES/13/20	Spain	May 2013	CSIC	Wheat with low content of celiac-toxic epitopes
B/ES/13/15	Spain	March 2013	Limagrain	Bt, HT maize
B/ES/13/16	Spain	March 2013	Uni. Lleida	High vitamin maize
B/DK/12/01	Denmark	April 2012	Univ. Aarhus	Cisgenic barley with improved phytase activity
B/ES/12/484	Sweden	Feb 2012	Swedish Univ. Agric. Sci.	Barley with improved nitrogen use efficiency
B/GB/11/R8/01	UK	Oct 2011	Rothamsted	Wheat producing aphid alarm
B/PL/11/02-10	Poland	Sept 2011	Plant Breed. Acclim. Instit.	Transgenic Triticale
B/CZ/11/2	Czech Republic	Mar 2011	Instit. Exper. Botony	Barley with phytase
B/IS/09/01	Iceland	Apr 2009	ORF Genetics	Transgenic barley, comparison of processing quality

Available from JRC database (http://gmoinfo.jrc.europa.eu/gmp_browse.aspx)

Data from Australia are available at http://www.ogtr.gov.au/internet/ogtr/publishing.nsf/Content/ir-1

A summary is given in Table 5.1 which identifies trials of wheat and barley with modified grain traits and with various genes providing tolerance to abiotic stress. More complete detail may be obtained from the application dossiers published by the various regulatory authorities.

5.4.2. Patents

In any consideration of future trends it is of great value to assess the patent literature, as this provides a summary of those novel technologies that are the subject of research activity, particularly in commercial companies who will publish information in patent applications prior to it emerging in the conventional scientific literature. The most recent overall review of this area is that of Dunwell (2010) who includes a discussion of IPR relevant to the research scientist and to those interested in international development, globalisation, and sociological and ethical aspects of the public- and private-sector relationships. Data on patent application and granted patents are available in many publically accessible databases with the most complete being that at http://www.patentlens.net/. The extent of patent activity in the area of GM cereals is exemplified by the selection of recent US patents (Table 5.3) and patent applications (Table 5.4). The subject matter of these patents, taken from a short period of time, covers all the major themes discussed in this review. It is always necessary to point out the commercial reality that few, if any, of the patents and applications in these lists will ever produce a financial profit. The most common reasons for this lack of success are unexpected additional costs of development or failure of the underlying science during the transfer from laboratory to field scale.

Table 5.3. Summary of selected granted patents relating to GM cereals. Data are from the USPTO (http://www.uspto.gov/patents/process/search/index.jsp).

Number	Date	Inventor	Subject
8,440,886	14 May 2013	Lundquist *et al*.	Transgenic maize
8,440,881	14 May 2013	Park *et al*.	Genes for yield
8,431,775	30 April 2013	Hegstad *et al*.	*knotted 1* gene
8,431,402	30 April 2013	Vasudevan *et al*.	Sorghum regeneration
8,426,704	23 April 2013	Hirel *et al*.	Glutamine synthetase
8,426,677	23 April 2013	Yu *et al*.	GA20 oxidase
8,426,676	23 April 2013	Oswald *et al.*	Pyruvate kinases
8,420,893	16 April 2013	Gordon-Kamm *et al*.	AP2 domain transcript. factor
8,415,526	9 April 2013	McGonigle	Artificial microRNAs
8,404,933	26 March 2013	Chen *et al*.	Herbicide resistance gene
8,404,930	26 March 2013	Wu *et al*.	Monocot transformation
8,404,929	26 March 2013	Gruis *et al*.	Reducing gene expression

Table 5.4. Summary of selected patent applications relating to GM cereals. Data are from the USPTO (http://www.uspto.gov/patents/process/search/index.jsp).

Number	Date	Inventor	Subject
20130133111	23 May 2013	Lyznik *et al.*	MAPKKK genes to improve yield
20130133101	23 May 2013	Rodiuc *et al*.	Phytosulfokines and pathogen resistance
20130125266	16 May 2013	Hiei *et al*.	Agrobacterium, barley transformation
20130125264	16 May 2013	Frankard *et al*.	Genes for yield
20130125258	16 May 2013	Emmanuel *et al.*	Genes for yield
20130117894	9 May 2013	Frohberg *et al.*	Starch synthase
20130117888	9 May 2013	Sanz Molinero *et al*.	Genes for yield
20130116124	9 May 2013	Fernandez *et al.*	Bacterial volatiles and starch
20130111634	2 May 2013	Champion *et al.*	Jasmonic acid
20130111620	2 May 2013	D'Halluin *et al.*	Meganucleases
20130111618	2 May 2013	Mankin *et al.*	Herbicide tolerance

6. The scenarios used for the modelling

6.1. Why a scenario-based approach was adopted

Within the scope of a small project such as this, it would not be possible to explore the full implications of adoption of GM cereal and oilseed crops for UK agriculture, as the range of possibilities is potentially limitless. Although there are only a relatively small number of GM traits currently available for crops of relevance for UK agriculture, this number will, as the literature review chapters above have indicated, increase substantially in future years. To limit the scope of the work undertaken in this project, a scenario-based approach has been adopted where a small number of case studies, i.e. crop-trait combinations, have been selected for more in depth analysis. These case studies are used to illustrate the type of impacts that the introduction of GM crop production might have on agriculture in the UK more broadly. This chapter outlines the process by which these scenarios were selected, including the choice of parameters by which the scenarios were defined and identified a subset of scenarios i.e. crop-trait combinations, for in-depth modelling.

6.2. Defining the scenarios

The scenarios were defined on the basis of the following three parameters: crop type; GM trait type; and time scale to commercial availability. The reason for defining the scenarios on the basis of these particular parameters will become apparent in the following explanation.

6.2.1. Crop type

Scenarios have been defined for each of three crop types: cereals, oilseeds and maize, on the grounds that these crops are of interest to the sponsor of the project, HGCA. While maize is not important in terms of arable area, it has been included for three reasons. First, with climate change maize might become more important as an arable crop. Second, there are already commercially available traits for maize. Third, maize is an important crop in the feed supply chain.

6.2.2. GM trait

The choice of GM traits was made on the basis of a number of criteria:

- the trait had to be appropriate for one or more of the crops identified above;
- the trait had to be demonstrably useful to UK agriculture, or address some problem that UK currently faces, or might face in the future;
- there should be some data available, in the academic or grey literature, based on field trials or modelling, indicating the agronomic and/or economic impacts of the traits;
- field trials and modelling data available in the academic or grey literature had to be relatively recent; and
- data available in the academic or grey literature should be based on agronomic conditions close enough to UK conditions to permit transfer to the UK setting.

6.2.3. Time scale

While relatively few commercialised GM traits are currently available for GM crops suitable for cultivation in the UK, research and development is gathering pace and there are a large number of relevant traits in the development pipeline (see Chapter 5). This means that any impacts experienced by UK agriculture resulting from the introduction of GM cultivation today would be quite different from the impacts experienced, say, five or ten years from now, due to the different GM traits likely to be available in the future.

Obviously, traits that are still in the early stages of development cannot be analysed quantitatively in this analysis due to lack of agronomic and economic data. However, if this analysis were limited only to traits for which extensive field trials or commercial data were available, then a forward looking view of the potential impacts of GM crop cultivation in the UK would not emerge. To overcome this limitation, it was decided to include in the scenario design a time dimension. The scenarios would therefore have two time steps: 5–10 years and 10–20 years ahead. Traits would be considered for the 5–10 year time step where reliable data were available from commercial settings (i.e. full commercial production had begun), or from field trials. For the 10–20 year time step, traits would be considered that were still at the very early stages of development, but where some aspects of the technologies had been demonstrated through academic studies, or applications for technology patents. Figure 6.1 shows the type of traits identified from the literature review and stakeholder consultation, as either currently available, or likely to be available over different time-steps for the crops oilseed rape and maize.

For the 5–10 year time step, because of the relative richness of the data available, a detailed quantitative analysis has been undertaken, while for the 10–20 year time step, the analysis has been rather more qualitative. As no commercial or field trials data were available in the literature for cereals, the 5–10 year scenarios were based on traits for oilseeds and maize. However, cereals were included in the scenarios for the 10–20 year time step.

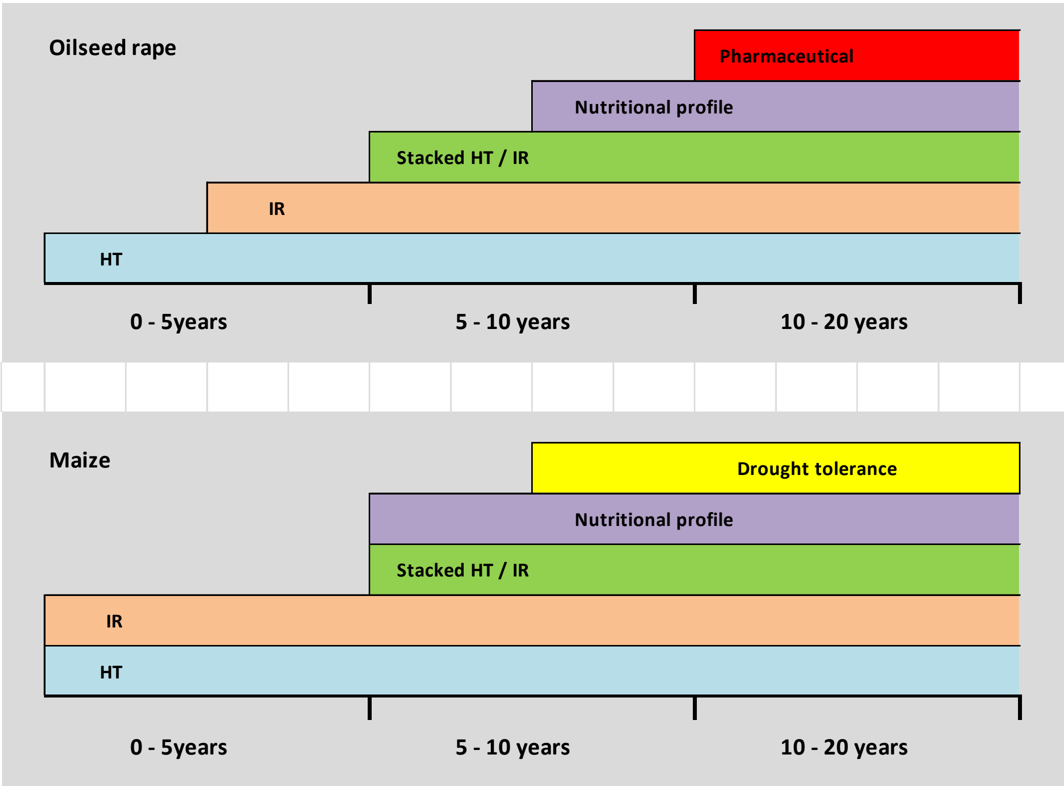


Figure 6.1. Trait types identified for OSR and maize for the three time periods under consideration.

6.3. The scenario development process

Scenario development was an ongoing process that took place over the whole course of the project, involving a number of distinct stages of development, as shown in Figure 6.2.

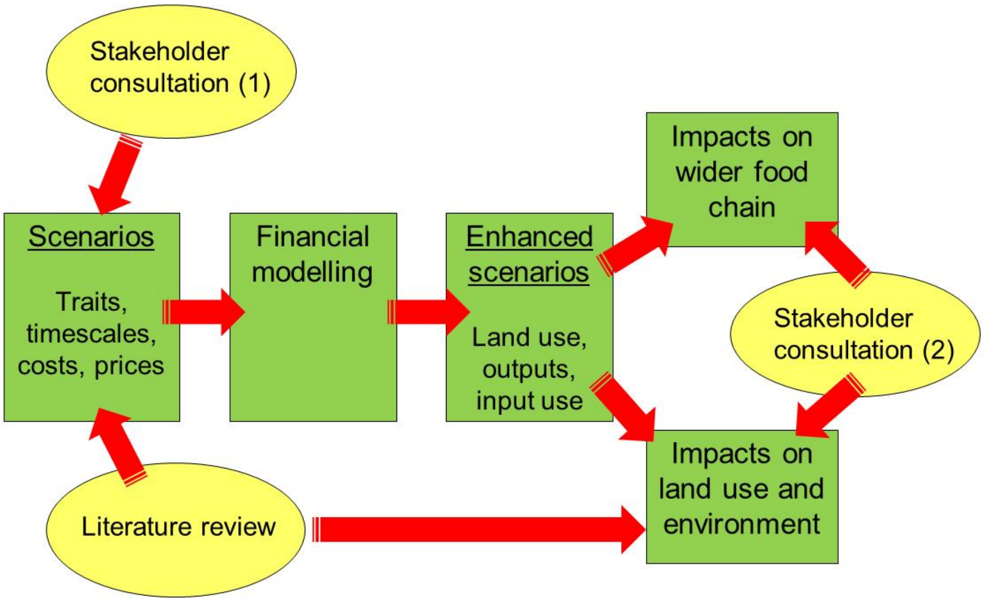


Figure 6.2. A schematic showing the development of the scenarios through input of data from various sources at different stages of the project.

A first round of scenario development took place at an early stage in the project, based on the parameter decisions outlined above. The scenarios resulting from this stage of development fed into the farm-level financial modelling (reported in Chapter 7). The outputs of the farm-level financial modelling were used to enrich the scenarios, which were then used as a basis for assessing the wider food and feed-chain, as well as environmental impacts of GM crop production. The scenarios therefore evolved over the course of the project, becoming more complete and detailed, rather in the way that the Special Report on Emissions Scenarios (IPCC, 2000) was developed, from their first beginnings as a basic and broad-brush view of the possible future social, economic and political future landscapes.

The first phase of scenario development involved a number of discrete steps:

- agreement on the set of scenario parameters used to define the scenarios with HGCA;
- the establishment of the number of scenarios to be analysed and population of the scenarios with data, based on the availability of data in the literature review;
- review of the scenario data and accompanying assumptions by a group of independent expert stakeholders; and
- revision of the scenarios by the project team in light of stakeholder input.

In stage two of the scenario development, the results of the farm-level financial modelling were incorporated into the scenarios, together with data from the literature review and input from expert stakeholder groups, to generate enriched scenarios showing the impacts of GM crop uptake on the wider food and feed chain. Stage three involved further expert stakeholder input to explore the potential environmental impacts of uptake of GM technologies in the UK.

6.4. The pre-farm-level financial modelling scenarios

One of the stated objectives of the project was to: 'propose traits that could have a positive impact on production economics and the environment and where these traits may benefit the consumer'. This objective was met, in part, in the identification of a list of crop traits which are potentially suitable for the UK setting, that are either already commercialised (in other parts of the world), undergoing trials prior to commercial release, or still in the research pipeline, i.e. will potentially become available in the different scenario time-steps. A list of these high potential traits was drawn up for each of the study crops, using data derived from the literature review, consultation with stakeholders and a thorough search of the US/EU/AUS datasets of patent and release to environment applications. Tables 6.1 to 6.3 below list these traits and provide summary information on the nature of their potential usefulness to UK agriculture, as well as indicating a likely time-line for their commercialisation.

As not all of the traits presented in Tables 6.1 to 6.3 above can be subject to in-depth modelling, a smaller sub-set of traits for each crop was identified and taken forward to the modelling stage. Table 6.4 below lists this sub-set of traits. This sub-set of traits has been selected on the grounds that, for maize and OSR at least, they have the best agronomic data available in the literature, as they are already widely commercialised and studied in other regions of the world.

Table 6.1. Traits for maize identified as being potentially suitable for UK agriculture with a guide to their timeline for future availability.

Trait		Who would benefit?			Nature of benefits	Likely scale of economic benefit (High, Moderate, Low, None)	Time to availability (years from present)
Input side	Output side	Farmer	Consumer	Environment			
Pest resistance (Bt) Conveys resistance to the pest *Baccillus Thuringiensis* (Bt), also known as European Corn Borer. While this is not a problem in the UK currently, some believe that it will become a major problem in the near future.		✓		✓	• Reduced use of insecticides • Lower labour, machinery and fuel requirements • Reduced yield suppression under increasing pest pressure	Moderate	Zero
Herbicide tolerance (Glyphosphate & Gluphosinate)		✓		✓	• Reduced yield suppression under increasing weed pressure • Lower labour, machinery and fuel requirements • Easier and more flexible weed management (incl. less tillage) • Lower volumes of herbicide used • More use of broader spectrum/ less toxic herbicides • Lower environmental load	Moderate	Zero
Stacked traits (Bt-HT)		✓		✓	See above	Moderate	Zero
Insect resistance		✓			• Reduced yield suppression under increasing lepidopterans	?	5–10
Crop composition			✓		• Amylase content	?	5–10
Drought tolerance		✓			• Drought tolerance	?	10–20
Crop composition			✓		• High levels of the amino acid lysine (nutritional fortification)	?	10–20

Table 6.2. Traits for OSR identified as being potentially suitable for UK agriculture with a guide to their timeline for future availability.

Trait		Who would benefit?			Nature of benefits	Likely scale of economic benefit (High, Moderate, Low, None)	Time to availability (years from present)
Input side	Output side	Farmer	Consumer	Environment			
Herbicide tolerance (Glyphosphate)		✓		✓	• Lower labour and fuel costs • Easier and more flexible weed management (incl. less tillage) • Reduced yield suppression under increasing weed pressure • Lower volumes of herbicide use • More use of broader spectrum/ less toxic herbicides • Lower environmental load	Moderate	3–4[#]
Herbicide tolerance (Gluphosinate)		✓		✓			3–4[#]
Herbicide tolerance (Bromoxynil / Ioxynil)		✓		✓			3–4[#]
Herbicide tolerance to newer herbicides (Dicamba)		✓		✓	As above	Moderate	3–4
Stacked traits (IR-HT) Resistance to OSR diseases such as: blackleg, sclerotina, phoma stem canker • Insect resistance – flea beetle, pollen beetle		✓		✓	• As above for weed management • Lower labour and fuel costs for reduced insecticide/pesticide application • Reduced yield suppression under increased pathogen pressure. • Lower environmental load.	Moderate-high	5–10
Heat tolerant- high yield OSR		✓			• Yield protection under high moisture stress/drought conditions	Moderate	5 –10
	Genetically modified OSR for: food (e.g. lower saturated fat content)	✓	✓		• Higher prices for farmers and nutritional benefits for consumers.	High	5
	Industrial (e.g. improved detergents)	✓	✓		• Higher prices for farmers and economic benefits to industry and consumers.	High	5–10
	Pharma. (e.g. anticoagulants, anti-HIV drugs)	✓	✓		• Higher prices for farmers and consumer benefits through healthcare benefits.	High	10–15
	Oilseed producing Omega-3 oils as a human dietary supplement	✓	✓		• Higher prices for farmers and nutritional benefits for consumers.	High	5–10

[#] Whilst HT OSR is already extensively grown worldwide, these are spring-sown varieties. As agronomic conditions in the UK make autumn-sown varieties more economically viable, it would be necessary to develop HT traits for autumn-sown varieties for the crop to be of use for UK arable farmers.

Table 6.3. Traits for cereals identified as being potentially suitable for UK agriculture with a guide to their timeline for future availability.

Trait		Who would benefit?			Nature of benefits	Likely scale of economic benefit (High, Moderate, Low, None)	Time to availability (years from present)
Input side	Output side	Farmer	Consumer	Environment			
Disease resistance (Yellow Mosaic Virus)		✓		✓	• Lower fungicide application rates	?	?
	Post-harvest grain sprouting	✓	✓		• Reduced losses in storage & transport leading to higher output and more revenue for farmers and processors • Lower consumer prices	?	?
	Protein quality: high molecular weight glutenin protein		✓		• Increases proportion of bread wheat harvest suitable for high quality bread	?	?
	Altered grain composition for nutrient utilisation efficiency	✓	✓		• Improved nutrient quality	?	?
Insect resistance (e.g. aphids)		✓		✓	• Lower insecticide applications • Lower environmental load • Lower input costs • Lower labour and fuel costs • Reduced yield suppression under high pest pressure	?	?
	Low content of coeliac-toxic isotopes	✓	✓		• New niche product suitable for coeliac disease sufferers • Price premia for farmers producing for the niche market	?	?
Fusarium tolerance		✓		✓	• Lower fungicide application rates • Reduced output value losses • Reduced costs to feed manufacturers	Moderate	5–10
Nitrogen use efficiency		✓		✓	• Lower N application rates • Lower costs of production • Lower environmental burden	Moderate	5–10
Take-all resistance		✓		✓	• Lower herbicide application rates • Lower costs of production • Lower environmental burden	Moderate	5–10

Table 6.4. The initial modelling scenarios

	Time from the present (years)	
	5–10	10–20
	Trait	Trait
Maize	Insect resistance	
OSR	Herbicide tolerance	
Cereals	Herbicide tolerance	Drought tolerance

The following list represents the complete set of data requirements for the modelling:

- crop (either: wheat, barley, oats, maize, OSR);
- type of trait (must be suitable for UK setting and where reliable agronomic/financial data available);
- time step (5–10 years; 10–20 years);
- yield response (under different levels of biotic and abiotic stress – see Chapter 7);
- impacts of trait on production costs;
- impacts of trait on market prices; and
- coexistence measures (and costs) necessary at the farm level.

Tables 6.5 and 6.6 show the scenarios listed in Table 6.4 above populated with data drawn from the literature review and the stakeholder consultation.

6.5. Coexistence measures at the farm level

As part of the scenario parameters, it was considered necessary to account for a range of coexistence measures that farmers would have to adopt in order to be able to grow GM crops in the UK, as these would have direct financial costs. EU regulation requires member states (MS) to adopt measures to ensure coexistence between GM and non-GM crops at the farm level. Most EU countries have already developed these, but the UK has yet to do so, as commercial GM crop production is not permitted here. No draft set of measures is available either. As a result, to derive a suitable set of coexistence measures and costs for this study, reference was made to the outputs of the EU PRICE project, recently undertaken by some of the current project team (Jones and Tranter, 2014). In that project, a set of 5 coexistence measures was identified as likely in the UK setting (see Table 6.7), based on common practice in other member states.

Table 6.5. Scenario data (for use in the farm-level financial modelling) for maize and OSR.

Future situation	OSR (5–10 years)	Maize (5–10 years)
Traits available	Herbicide tolerance - both glyphosate and glufosinate tolerant varieties	Bt
Conditions resulting in yield change	Prevalence of high weed pressure	Prevalence of European Corn Borer
Change in market price[1]	1–2% decline[2]	No change
Effect on farm management and cultivation practices	(i) Less herbicide applied (1 application) (ii) Lower labour and fuel costs (iii) Crop quality improvement (iv) More convenient/flexible for the farmer (v) Cleaner crop produced	(i) Less time spent viewing crop for signs of pest (ii) Less pesticide applied (iii) Lower labour and fuel costs
Yield change - good growing conditions	Zero	Zero
Yield change - environmental stress	6% yield increase at 41–50% of max severity of environmental stress 11% yield increase at 81–100% of max severity of environmental stress	10% increase per hectare
Change in production costs	1% decrease	5% decrease
Effect on Gross Margin	4–5% increase per hectare	15% increase per hectare

[1] Market prices may change for a number of reasons, including: lower production costs or availability of a price premium for value added to the product.
[2] A small decline in farm gate prices is assumed to result from a combination of increased supply of oilseed crops (from higher yields) and lower production costs.

Table 6.6. Scenario data (for use in the farm level financial modelling) for cereals.

Future situation	Cereals (5–10 years)	Cereals (10–20 years)
Traits available	Herbicide tolerance	Drought tolerance
Conditions resulting in yield change	Prevalence of high weed pressure	Droughty conditions
Change in market price	No change	2–3% increase
Effect on farm management and cultivation practices	(i) Less herbicide applied (1 application) (ii) Lower labour and fuel costs (iii) Crop quality improvement (iv) More convenient / flexible for the farmer (v) Cleaner crop produced	
Yield change - good growing conditions	None	
Yield change - environmental stress	5% increase	5% increase
Change in production costs	10% saving	10% saving
Effect on Gross Margin	10% increase	10% increase

Table 6.7. Likely coexistence measures for the UK if GM crops allowed.

Coexistence measure	Extent of burden to farmer
5 year record keeping of seed purchases and product sales	
Asking your neighbours about their plans to cultivate their equivalent conventional crop	Lowest
Cleaning the drill after sowing GM seeds	
Planting a 12 row buffer zone	Highest
Planning the sowing of your GM crop in such a way that it does not coincide with your neighbour's planting (4 weeks difference in April and 2 weeks in May)	

As part of the PRICE project, UK farmers were surveyed to elicit their attitudes to these measures, along with estimates of the degree of difficulty involved in complying with them and their cost. It was found that the most burdensome in terms of time and cost was the measure requiring farmers to plant a 12 row buffer zone between GM and any contiguous non-GM crop of the same species (Jones and Tranter, 2014). It was decided that this measure should therefore be reflected in the financial model (and is reported there). The other measures are either of very low significance or are impractical to include in the model we used.

7. Modelling the potential yield and gross margin of Bt maize or HT OSR grown as single crops and HT OSR in a rotation scenario with wheat and barley

7.1. Introduction

A dynamic economic model, developed previously to predict the potential yield and gross margin of a set of crops grown in a selection of typical rotation scenarios, was amended and used to model the performance of two GM crops as they could be expected to perform in the south of the UK, if cultivation is permitted. The model was designed to simulate varying levels of pest, weed and drought pressures, with associated management strategies regarding pesticide and herbicide application which affect the crop itself, and also persistence effects influencing following crops. The model makes provision for the costs of complying with postulated regulations concerning coexistence with neighbouring non-GM crops.

This chapter describes the use of the model to predict yield and gross margin of:

- transgenic insect-resistant *Bacillus thuringiensis* (Bt) maize, as a single crop;
- transgenic HT OSR, as a single crop; and
- HT OSR in a four crop rotation: wheat, second wheat, OSR, barley, wheat.

As mentioned earlier in Chapter 4, Bt maize is currently extensively grown in Spain, particularly in parts of Spain affected by pest pressures as well as in Portugal. HT OSR is not yet available for cultivation in the EU, but a spring variety has been profitably grown in Canada (as HT 'Canola') since 1998 (see Chapter 3); no equivalent HT winter rape is currently available.

Conclusions are drawn about conditions in which adoption of these transgenic crops would be profitable in the UK, having regard to farmers' attitude to risk.

Many previous studies have been published concerning the economic impact of transgenic crops, and some of these economic studies have been based on the formal representation of economic models. In the research project "Sustainable Introduction of GMOs into European Agriculture" (SIGMEA) funded by the Sixth Framework Research Programme of the EC, Gómez-Barbero and Rodríguez-Cerezo (2006) estimated the global economic welfare generated by adoption of four dominant transgenic crops. They concluded that (at that time) on-farm benefits were derived from the reduction in associated production costs. Spatial effects of the introduction of transgenic crops were modelled by Munro (2008), who noted that coexistence with conventional crops is associated with strong regulation on planting patterns. Bohanec *et al*. (2008) reported on use of a qualitative multi-attribute model within the ECOGEN (EC Framework 5) and SIGMEA projects. The model was considered useful for what-if analysis of realistic cropping systems. Van Ittersum *et al.* (2012) reviewed ways to estimate the yield potential of maize in various scenarios worldwide.

The effect of weed pressure on yield has been studied by Van Acker *et al*. (1997), and Froud-Williams (2007) recommended various strategies for weed management. The model described here calculates potential yield variation in response to the various weed pressures using coefficients obtained from published data (Fulton and Keyowski, 1999; Brookes, 2003; Gómez-Barbero *et al.,* 2008; and Otiman, 2008).

7.2. Description of the model

7.2.1. Time period

Crop rotations typically extend over two to seven years; the model accommodates scenarios of crop sequences adopted over any period within this range. This enables the effects of crop and crop management choices on subsequent crops to be modelled.

7.2.2. Time step

As the model is an economic model, as opposed to a model of crop development, we considered that one month time steps are sufficient to model the management decisions that may be made during a crop cycle.

7.2.3. Area to be modelled

Coexistence costs are largely set by the need to provide separation from conventional crops on adjacent land, and so the cost will vary with the area occupied by a transgenic crop. The model allows for simulations with a range of field sizes. For instance, the user can specify average field sizes between 5 and 80 ha.

7.2.4. Choice of sets of crops

The model allows the selection of conventional crops and crop sequences which are common in a given biogeographic region. Where theoretically appropriate, the genetically modified (GM) alternative can be selected.

7.2.5. Physical and economic parameters

A table of typical yield per hectare of the selected crops, together with seed costs and ex-farm value per tonne at harvest was compiled using published data from Lang (2011) and Nix (2013).

7.3. Model assumptions

No allowance is made in the economic model for any price premium obtainable for non-GM maize or for non-GM OSR. It is known that the insistence of some supermarkets that poultry be reared with feed that does not include GM soya has had the effect of creating a price premium of up to 20% for imported non-GM soya (Defra, 2009). A workshop convened in 2012 by the European Commission's JRC concluded that there was 'a lack of sound information about the specific situation of the markets for non-GM IP crops which precludes the development of appropriate economic models to predict the evolution of markets and price premiums' (JRC, 2012). The yield of each crop in a sequence is initially assumed to be as in published data for that crop for typical farms in that region. Then the potential yield is recalculated as an empirical function of:

- pest pressure, taking account of past management policy and prior conditions;
- weed pressure, taking account of tillage and weed management policy, and prior conditions; and
- GM traits.

In each month, simulated pest and weed pressures are updated. At levels pre-set to represent the levels at which management would intervene with pesticide or herbicide application to limit yield loss, the appropriate application is implemented and costed, and the associated pressure reduced accordingly. Thus, the sensitivity of the model to management attitudes to risk can be represented by changes to the critical level of potential loss at which management actions are triggered.

Sensitivity to assumptions about the value per tonne of crop harvested, and to the technology premium charged by the seed supplier, can readily be tested by changing the values in the table of input parameters.

If crops are grown in rotation, it is assumed that pest pressure is reduced with change of host crop. If the crop is IR, it is assumed that the pest population is greatly reduced by the toxin exuded by that crop. It is assumed that weed pressure is greatly reduced by post-emergence application of glyphosate or glufosinate on a GM herbicide tolerant crop, and that this removal of weeds also has a beneficial effect on the subsequent crop.

The economic benefit of having the option to adopt no-till or low-till preparation has not been included in the examples below, but may be significant, and coupled with the non-pecuniary benefit of simplified crop management, tends to increase the overall incentive for GM crop adoption.

7.4. Results

The model outcomes are summarised below in the form of charts and tabulated data. The simulations generate monthly data for current pressures (on arbitrary scales), treatments applied, and predicted crop yield, so each simulation can be examined subsequently with selectable amount of detail.

7.4.1. Continuous maize

The yield of Bt maize in comparison with equivalent conventional maize under increasing pest pressure is shown in Figure 7.1. The Bt maize offers no advantage unless pest pressure is encountered; the figure represents the case where loss in yield under increasing pest pressure is counteracted by sufficient application of pesticide to maintain yield of the conventional crop at an acceptable level.

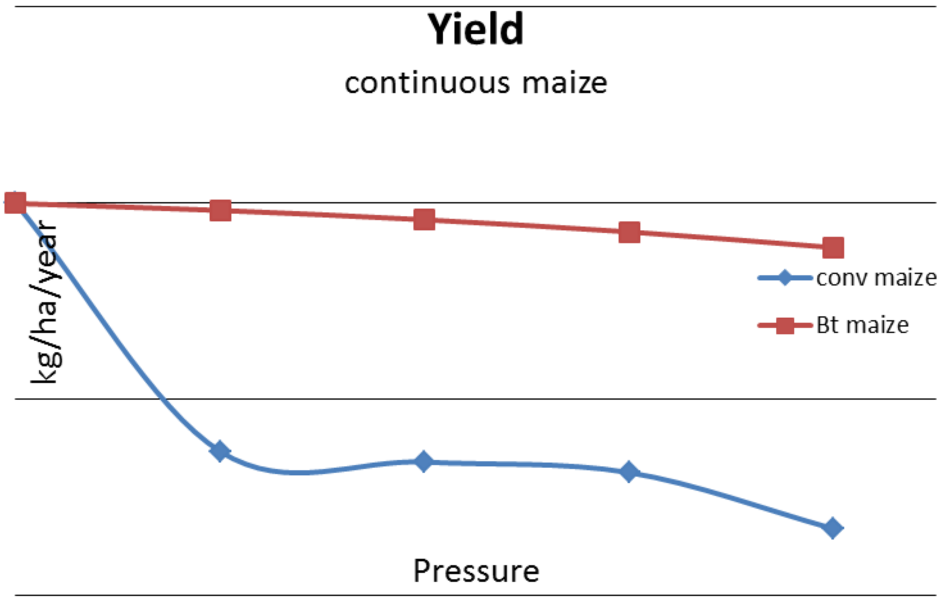


Figure 7.1. Yield of conventional versus Bt maize.

Table 7.1 shows the predicted gross margins for a single maize crop, the scenario shown in Figure 7.1. The output was obtained by running the model for the months from soil preparation to harvest at five levels of threat of pest damage. When there is no pest pressure, the gross margin is depressed by:

- the technology premium; and
- the cost of providing a buffer zone to comply with likely coexistence regulations.

When the size of the buffer zone is small relative to the field size, for example a 40 ha field, the adoption of the Bt variety is predicted to be profitable even with relatively light pest pressure.

Table 7.1. Adoption of Bt maize, gross margins.

Pest Pressure	Conventional maize	Bt maize	Change: GM/Con.
	Gross margin, £/ha	Gross margin, £/ha	%
(None)	914	898	-1.8
Mild	836	889	6.3
Moderate	776	880	13.4
Severe	760	869	14.3
Very severe	744	857	15.2

Source: Based on Gomez-Barbero *et al*. (2008).

7.4.2. Continuous OSR

The yield of HT OSR is, similarly, no better than equivalent OSR in the absence of weed pressure (Figure 7.2). In this example, the simulation is again run in monthly steps from soil preparation to harvest, in this case at five levels of weed prevalence, but even at the most severe prevalence the weed pressure is insufficient to trigger an application of herbicide for the conventional crop.

The gross margin predictions corresponding to the scenario of Figure 7.2 are shown in Table 7.2. Here again, the technology premium and the likely coexistence cost reduce the gross margin in the absence of weed pressure. At any field size, the HT OSR is protected by the removal of weeds with post-emergence application of glyphosate or glufosinate. The value of this, as before, is only fully realised if the coexistence cost penalty is limited by making the buffer zone small relative to the total crop area. There is very little quantitative information available on the yield of HT OSR in the presence of weeds, partly because arable soils become almost free of weeds after adoption of HT crops in a rotation (Beckie *et al.,* 2006).

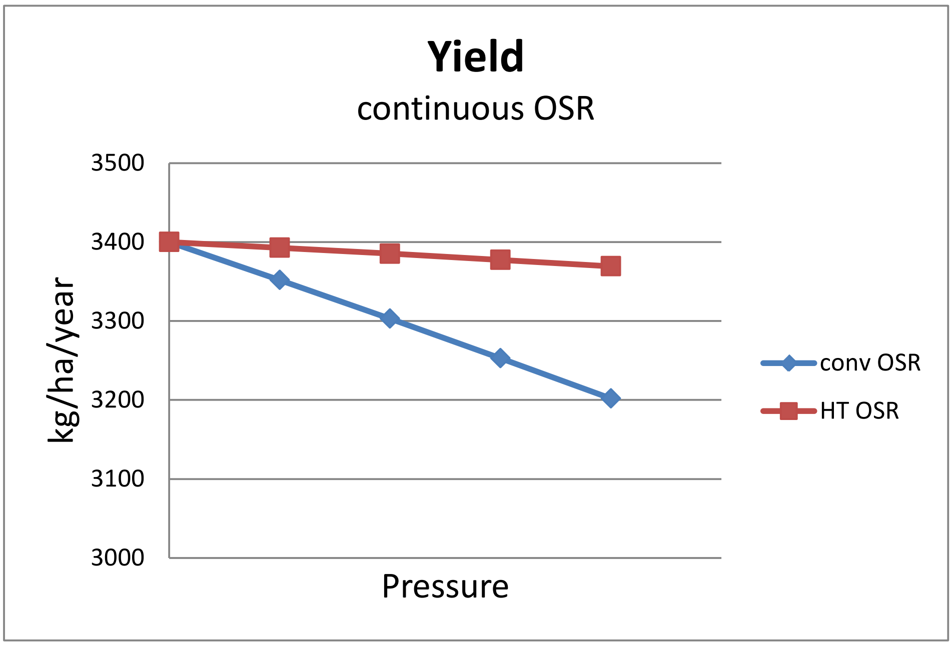


Figure 7.2. Yield of HT OSR versus conventional equivalent.

Table 7.2. Adoption of HT OSR, gross margins.

Weed pressure	Conventional OSR	HT OSR	Change: GM/Con.
	Gross margin, £/ha	Gross margin, £/ha	%
(None)	759	725	-4.5
Mild	740	724	-2.1
Moderate	719	723	0.6
Severe	675	722	6.9
Very severe	618	721	16.6

Source: Based on Fulton and Keyowski (1999).

7.4.3. Crop rotation: wheat, second wheat, OSR, barley, wheat

Figure 7.3 shows the simulation of yield of OSR and HT OSR within a four crop rotation scenario, alongside the yield of a crop of conventional barley following either of the OSR crops. This simulation was extended to the weed pressure at which the conventional OSR crop required additional herbicide to maintain yield. As before, the HT OSR yield benefits from the removal of weed pressure with post-emergence application of glyphosate or glufosinate and, in this scenario, the yield of the following crop of conventional barley is also protected.

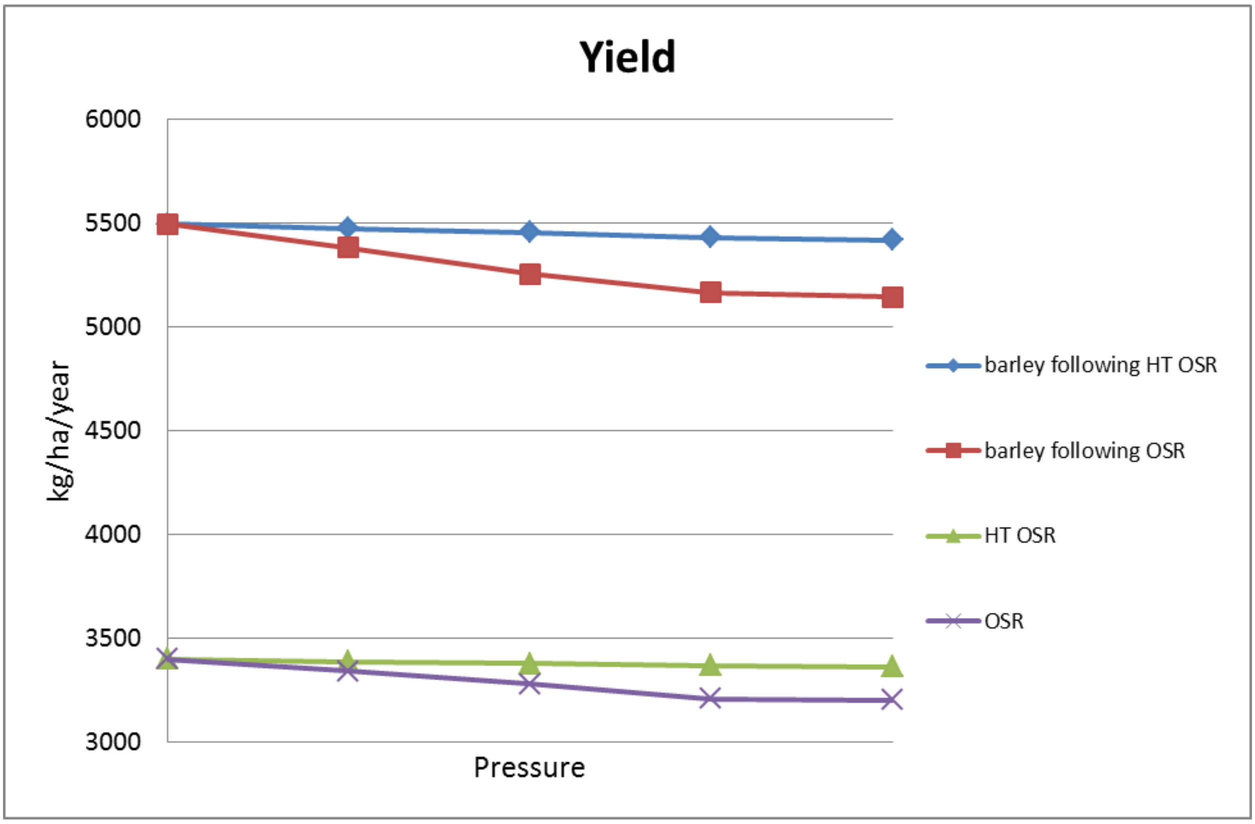


Figure 7.3. Yield of OSR or HT OSR followed by barley in a four crop rotation.

Table 7.3 shows the average gross margin over all crops in the rotation under varying weed pressure. The weed pressure and the need to make additional applications of herbicide throughout the rotation, which includes conventional OSR, depress the average gross margin for the whole cycle. Substitution of the HT OSR for conventional OSR helps to maintain the overall gross margin at an acceptable level. In this example, the coexistence cost is relatively less important for a smaller field size, because the buffer zone would only be required for one year in five.

Table 7.3. Overall gross margins following adoption of HT OSR in a four crop rotation.

Weed pressure	2 wheats-OSR-barley-(wheat…	2 wheats-HT OSR-barley-(wheat…	Change: GM/Con.
	average margin, £/ha	average margin, £/ha	%
(None)	713	706	-1.0
Mild	694	697	0.5
Moderate	672	688	2.3
Severe	632	677	7.1
Very severe	595	655	10.2

7.5. Discussion

A common feature of all the above model results is that the direct cost of compliance with coexistence regulations is reduced for farms that grow the crops on large contiguous areas or in a regional consortium, compared with the likely coexistence costs for those that have near neighbours who grow conventional crops. This is because the cost of maintaining a buffer zone falls on the farm growing the transgenic crop. In instances where neighbouring farms agree that they will all adopt a transgenic crop, the cost of coexistence can be vanishingly small (Skevas *et al.*, 2010).

These simulation outcomes are consistent with the comments made by stakeholders on these and similar scenarios, in several respects:

- *Bt maize*. In corroboration of the published evidence from Spain (Gómez-Barbero *et al.*, 2008), stakeholders tend to agree that Bt maize enables yield to be maintained in the presence of pest pressure, with a useful contribution to gross margin.
- *OSR*. Although the strong performance of HT OSR in Canada (as 'HT Canola', Fulton and Keyowski, 1999) is not directly relevant to the UK scenario, most stakeholders concur that yield losses of conventional OSR attributable to weed pressure can be avoided by adopting HT OSR with a net positive contribution to gross margin.
- *Advantage of post-emergence herbicide*. Stakeholders confirm that there may be quantifiable benefits from the convenience and flexibility for crop management.
- *HT crop in a rotation*. The HT crop has added value in being cleaner than a conventional crop, and also leaves the soil in cleaner condition, reducing preparation costs for the following crop, and also enabling yield potential of the following crop to be maintained.

It should be pointed out that there is uncertainty about several aspects of the simulation outcomes. In particular:

- *Value of the crop*. The market value of a crop depends on unpredictable market prices at the time of harvest.
- *Costs of technology*. Seed suppliers commonly vary the technology premium they charge for IR and HT crops, depending on the pressures anticipated for a particular crop.

- *Growing conditions*. All crops are affected by weather variations.
- *Management attitudes to risk*. A side effect of adoption of IR and HT technology is that the management of a crop with respect to pest and weed pressures is, to some extent, predetermined, and so the gross margin is less affected by timing of decisions about application of treatments.

The model can be used to test the sensitivity of the predictions made to variation in these and other parameters. However, so far, there is insufficient experience of the above scenarios in UK farming to provide data to be used for meaningful assessment of these sensitivities. The speed of take-up of new technology is linked to the extent of benefit that is offered, and this has been the experience with GM crops elsewhere in the world (James, 2012).

8. Environmental impacts of GM crop adoption – the international outlook

8.1. Introduction

The environmental effects of GM crops are still under scrutiny and scientific debate. Since the commercialisation of GM crops, there have been a number of studies that have analysed the environmental impact of GM maize (Brookes and Barfoot, 2012; Henry *et al*., 2003; Kendall *et al.,* 1997; Morse *et al*., 2006; Park *et al.*, 2011; Wesseler *et al*., 2011). The focus has been mainly on the potential damage associated with the adoption of GM crops where environmental impacts of GM crops are compared with environmental impacts of non-GM crops. However, potential benefits of GM crops have been the focus of some literature too (National Research Council, 2010). Environmental concerns have mainly focused on impacts associated with pesticide and fertiliser use and emissions of GHG.

In examining the environmental impacts of GM crops, it is useful to distinguish between direct impacts (e.g. impacts on local fauna) and indirect impacts (arising as a consequence of changes in agronomic practices associated with GM crops) and also between immediate, delayed and cumulative changes (Smythe *et al.*, 2011). Agronomic practice changes giving rise to environmental effects include the timing, mode and frequency of herbicide application, the combinations of pesticides used, tillage practices and crop rotations. A comparison of active ingredient use in GM and non-GM crops provides a more robust indicator of the differences in the environmental impacts of the associated pesticide regimes. A more comprehensive indicator of environmental impacts is the Environmental Impact Quotient (EIQ), a measure developed by Kovach *et al.* (1992). Where there appear to have been a number of EIQ applications in assessing the impact of Integrated Pest Management (IPM) or evaluating pest management strategies in both developed and developing countries (see, for example, FAO, 2008), their use as a decision control tool appears to be limited. This measure, which is periodically updated, takes into account the toxicity and other environmental characteristics of individual products and the effects on farmers, consumers and the ecology to provide a single field value per ha. . For any herbicide regime, the EIQ value can be multiplied by the active ingredient used per ha to provide a measure of the environmental impact at the field level. EIQ has been extensively used in empirical studies measuring the environmental impact of pesticide and herbicide use including in GM OSR (Brimner *et al*., 2004).

Environmental impacts of growing GM crops have been examined using a number of methodologies such as: life cycle analysis (LCA) (Bennett *et al*., 2004; Strange *et al*., 2008); descriptive statistics after compiling information on insecticide and herbicide use, and GHG emissions (Brookes and Barfoot, 2012); and statistical tests using data from monitoring fields (Morse *et al.,* 2006), and wider trials such as the UK Farm Scale Evaluation (Henry *et al.,* 2003). Such impacts have been measured using an array of indicators such as number of species, number of individuals, number of sprays (mg/m^2), kg of active ingredient, kg of pesticide per ha and litres per ha. Indicators have been constructed in order to account for several of these aspects. For example, the impact of Bt maize on soil microbes has been analysed finding no evidence of a negative effect on them (Al-Deeb *et al.,* 2003; Motavalli *et al*., 2004; Saxena and Stotzky, 2001). The biocide index and the field use rating of the EIQ are usually used to measure and compare the relative environmental impacts of GM crops (Brookes and Barfoot, 2012; Morse *et al.,* 2006). The assessment of the environmental impacts of GM OSR can be complex as these impacts occur along several dimensions and across varying time scales, involving numerous impact mechanisms. The principal environmental effects examined in the empirical literature on GM OSR impacts have been: (i) the reduction in the use of herbicides; (ii) carbon sequestration/reduction in carbon emissions associated with reduced fuel use and zero-tillage practices; (iii) the risks posed by the development of resistant weeds (on or off site), and (iv) the persistence of volunteer HT OSR in subsequent rotations and outcrossing of GM HT OSR with wild relatives.

8.2. Herbicide use

The adoption of GM HT varieties is generally not associated with a reduction in the volume of herbicides used in most cases (Qaim, 2009), but does lead to the substitution of selective herbicides which are more toxic to the environment by less toxic broad spectrum herbicides (Giesy *et al*., 2000; Williams *et al*., 2000). Effective weed control using GM OSR can have spill-over benefits across the whole crop rotation (inclusive of non-GM crops). Gusta *et al*. (2011) have examined the multiyear benefits in weed control from the adoption of GM HT OSR in Canada. In a survey of over 600 farmers in Western Canada, they found that 54% of the respondents reported a second year benefit from the technology and 63% of those reporting assigned an economic value to this benefit of Can $15.05/acre. The spill-over benefit varies by the HT system adopted (i.e.

Roundup Ready, Liberty Link or Clearfield) with the Roundup Ready system producing higher spill-over benefits.

GM HT varieties are expected to provide better control of weeds in OSR. However, the feasibility of OSR expansion would be constrained by the prevalence and severity of other pests/pathogens and plant diseases. The lower toxicity of glyphosate compared to the selective herbicides that it replaces provides the main rationale for the development of GM HT varieties tolerant to such herbicides. A comparison of only the volume of herbicide used in GM HT and conventional OSR is not very informative about relative environmental effects because it does not take into account the differences in the products and application regimes used for GM and non-GM crops and the differences in the environmental characteristics of the products (in terms of toxicity, mobility and persistence).

Brookes and Barfoot (2012) report that in Canada herbicide active ingredient use on GM glyphosate-resistant OSR (0.65 kg/ha) and GM glufosinate-resistant OSR (0.39 kg/ha) has been considerably lower than in conventional OSR (1.13 kg/ha). The average EIQ load for GM HT OSR has also been lower than that for conventional OSR (10/ha for GM glyphosate-resistant OSR, 7.9/ha for GM glufosinate-tolerant OSR versus 26.2/ha for conventional OSR).

Other studies have reported higher levels of reduction in herbicide active ingredient use from the adoption of GM OSR in Canada. Smythe *et al.* (2011) estimated an annual reduction in herbicide use of nearly 1.3M kg for Western Canada alone. Empirical evidence from the USA (Brookes and Barfoot, 2012; Sankula and Blumenthal, 2003; Sankula and Blumenthal, 2006; Johnson and Strom, 2008) also suggests significant reduction in herbicide use in OSR following the adoption of GM HT varieties. The saving in herbicide active ingredient usage for GM HT OSR varieties has been estimated at between 0.5–0.75 kg/ha over conventional varieties (Sankula and Blumenthal, 2003; Sankula and Blumenthal, 2006; Johnson and Strom, 2008), although the active ingredient use advantage of GM glyphosate-tolerant OSR has been eroded in recent years as a result of the introduction of Clearfield varieties.

Clearfield OSR (which is non-GM but dominates conventional plantings in Canada) has altered the comparison of active ingredient use in GM and conventional OSR as GM glyphosate-resistant OSR uses marginally more active ingredient (+0.13 kg/ha) but, GM OSR on average, still has a lower environmental footprint (EIQ load factor) than Clearfield OSR. Brookes and Barfoot (2012) estimate that in 2010, based on comparisons with Clearfield OSR, the reduction in herbicide use in Canada was 0.22M kg with a reduction in EIQ load factor of 21.2%. Cumulatively, between 1996 and 2010, it is estimated that herbicide active ingredient use for OSR fell by 18% (11.9M kg) while the EIQ load factor fell by 28%. Cumulatively, since 1999, the amount of active ingredient use for

OSR in the USA is estimated to have fallen by 37% with a reduction in EIQ load of 47% (Brookes and Barfoot, 2012).

Using data from a number of empirical studies, Brookes and Barfoot (2012) estimated that in the three countries where GM OSR has been adopted – Canada, USA and Australia – there has been a significant decrease in the volume of herbicide applied to OSR and the associated environmental impact. They estimate that in 2010, herbicide active ingredient use was 6.2% lower (a reduction of 0.4M kg) compared to the level of use if the entire crop had been planted to conventional varieties, with the EIQ load factor being lower by 18.7%. They estimated that cumulatively between 1996 and 2010, the adoption of GM OSR had resulted in reduction of herbicide active ingredient use by 18.2% (a saving of 14.4M kg) compared to the counterfactual of conventional planting, with the cumulative EIQ load being lower by 27.7%.

The work on socio-economic and environmental impacts of GM crops by Brookes and Barfoot (2012) also provides estimates for herbicide usage for maize for a number of countries. Overall, they found that both average herbicide active ingredient (ai) use and the average field EIQ/ha on the maize crop (both GM and conventional) has been decreasing since 1996.

8.3. Weed control risks

There have been concerns raised that extensive use of HT crops will lead to problems with the development of herbicide resistant weeds. The reason for this, it is argued, is that use of HT crops leads to changes to the type of herbicides used, with both broader spectrum herbicides predominating and, importantly, fewer active ingredients in the herbicide. To illustrate, Smythe *et al*. (2011), cite Young (2006), who reports a decline in the average number of active ingredients applied to HT cotton and soya bean of around 50% between 1994 and 2001. To rehearse the argument, repeated use of the same few active ingredients (typically just one or two), such as glyphosphate (HT crops are largely tolerant to glyphosphate), leads to demographic changes in weed populations with herbicide resistant weeds (which already exist in small numbers in wild populations) surviving preferentially and coming to dominate those populations. It is reported in the literature (see, for example, Brookes and Barfoot, 2013) that weed resistance to glyphosphate has become a problem in some countries, such as the USA. For example, there are 13 weeds recorded as having glyphosphate resistance in the USA.

In a survey of over 600 farmers in Western Canada, Smythe *et al*. (2010) reported that “more than 94% of the respondents reported that weed control was the same or had improved following the commercialisation of GM OSR, less than one quarter expressed any concern about herbicide resistance in weed populations, 62% reported no difference in controlling for volunteer GM OSR than for regular OSR and only 8% indicated that they viewed volunteer GM OSR to be one of the top five weeds they need to control". Strategies for weed resistance management in HT OSR crops are similar to those for non-HT OSR crops – measures include restricting rotations, use of multiple herbicides and/or mechanised control measures (Canola Council, 2005).

In the early years of adoption of GM HT OSR, a major environmental concern was that HT traits would outcross with weedy relatives and that GM HT OSR could become a pervasive and uncontrollable volunteer in non-OSR crops which could significantly reduce or offset the gains to farmers from GM HT OSR adoption. Mayer and Furtan (1999) suggested that volunteer OSR in subsequent crops was likely to be a larger problem than gene transfer to weedy relatives. They estimated that any infestation of HT wild mustard above 4 plants/m^2 was likely to reduce producer benefit from GM HT OSR to zero. More recent studies appear to have mitigated some of these concerns, which is also reflected in the near universal adoption of GM HT OSR in Canada and the rapid growth in area in the USA.

8.4. Insecticide use

The work on socio-economic and environmental impacts of GM crops by Brookes and Barfoot (2012) provides estimates for both average volume of insecticide and average field EIQ value since 1996, the year in which Bt maize was commercialised in the USA. Table 8.1 shows the comparison of the average US maize insecticide use and its environmental load between conventional and Bt maize for 1996–2010. Reductions in average insecticide use and environmental load have been found also in other countries where insecticides have been used traditionally on maize (Brookes and Barfoot, 2012).

The environmental benefits derived from reduced pesticide use in the USA have been somewhat wider due to the widespread adoption of GM IR maize technology which has resulted in 'area-wide' suppression of target pests such as the European corn borer in maize crops with the consequent reduction of pesticide use in conventional maize fields (Hutchinson *et al*., 2010). An association was found between area wide suppression of the primary pest the European corn borer and Bt maize use, which resulted in estimates for cumulative benefits over 14 years of $6B with $4.3B of this total accruing to non Bt maize growers (Hutchinson *et al*,. 2010).

Table 8.1. Average insecticide use (active ingredient) and its environmental load for conventional and Bt maize in the USA.

Year	Average ai/ha (kg): conventional maize	Average ai/ha (kg): Bt maize	Average field EIQ: conventional maize	Average field EIQ: Bt maize
1996	0.66	0.61	19.3	18.1
1997	0.65	0.59	19.0	17.7
1998	0.71	0.63	20.3	18.4
1999	0.63	0.61	18.4	18.3
2000	0.62	0.54	18.2	16.4
2001	0.51	0.49	15.5	14.4
2002	0.48	0.30	15.0	10.5
2003	0.55	0.41	16.0	12.5
2004	0.57	0.30	16.7	10.3
2005	0.43	0.33	12.8	11.2
2006	0.53	0.34	15.4	10.5
2007	0.39	0.24	11.9	7.9
2008	0.31	0.27	9.6	8.3
2009	0.26	0.21	8.7	7.0
2010	0.51	0.4	17.1	14.0

Source: Brookes and Barfoot (2012) derived these estimates from GfK Kynetec database.

8.5. Gene flow issues

Another environmental concern related to growing GM crops is the possible gene flow (cross-pollination) from GM crops to non-GM crops and wild relatives, which may have implications for plant diversity and ecological systems (Dunwell and Ford, 2005). GM OSR has the potential to hybridize with wild relatives, as do other crops yet to see GM varieties in the market-place, such as wheat, barley and oats, either through pollen transfer or escape of seeds during harvest, transport and processing (Dunwell and Ford, 2005). This has implications for plant diversity and ecological systems.

As a result, EU policy recognises that “European farmers should have a sustainable possibility to choose between conventional, organic and GMO production”, underlining that economic damage or losses derived from the introduction of GMO have to be avoided (European Council, 2006). The EU legislation establishes a threshold of 0.9%, above which the marketed products containing GMO authorised to be used have to be labelled as a GM product.

In order to avoid cross-pollination, the EU policy established recommendations for isolation distances that aim at reducing the risk of cross-pollination. Such distances have varied over time and vary between countries. It is worth noting that implementation of isolation distance may slow down adoption particularly in the early phases of adoption (Areal *et al*., 2012) and, therefore, it is important to have information on the relationship between separation distance between a GM crop and its conventional counterpart and the probability of gene flow. For GM maize, the distances suggested to ensure a 95% level of confidence to meet the 0.9% threshold established by the EU, are 12 m of border rows (or buffer strips) plus 12 m of fallow isolation (Marceau *et al*., 2013). It is worth noting that gene flow may also occur during the harvest, transportation and processing stages (Dunwell and Ford, 2005).

8.6. Carbon sequestration

Studies have found significant correlations between adoption of HT OSR and farmer use of minimum or zero tillage practices (Smythe *et al*., 2011; Young, 2006). In agronomic terms, low and zero till agriculture improves soil structure and increases, or rather slows the rate of loss of soil organic matter that occurs through oxidation, resulting in improved nutrient and water retention (greater drought tolerance) and lower fertilizer application requirements. In economic terms, low and zero tillage means less use of powered agricultural machinery in seed bed preparation, leading to lower fuel use and reduced labour costs. Environmentally, low and zero tillage results in lower carbon (equivalent) emissions from reduced fuel use and greater carbon sequestration in soils, through maintenance of higher organic matter content.

Although the shift to reduced tillage practices in Canada and the USA have been driven by a number of factors – and cannot be attributed to the adoption of HT varieties alone – the high degree of weed control facilitated by the adoption of GM HT OSR has been a contributory factor in the increased use of no-tillage production of the crop.

While conservation tillage practices offer a number of agronomic benefits – such as better moisture retention and reduced soil erosion – an important environmental effect is carbon sequestration (as a result of reduced soil disturbance and consequent retention of carbon in the soil). Brookes and Barfoot (2012) estimate that whilst no-till / reduced till cultivation sequesters carbon at the rate of 55 kg/ha/year, conventional tillage releases carbon at the rate of 10 kg/ha/year. Using carbon sequestration co-efficients estimated by McConkey *et al.* (2007), Smythe *et al*. (2011) estimate that in Western Canada reduced tillage associated with GM HT OSR has led to 1M t of carbon being sequestered or not released annually compared to 1995. Brookes and Barfoot (2012) also estimate that the cumulative, permanent reduction in tillage fuel use in GM HT OSR in Canada over the period 1996–2010 was 301.7M litres, equivalent to a reduction in carbon dioxide emissions of 806M kg. This reflects a 37% reduction in fuel usage from 49.01 litres per ha in conventional tillage to 30.62 litres per ha in no-till/reduced till cultivation.

8.7. Summary

Scientific evidence so far seems to indicate that there is no environmental damage associated with the growing of GM crops (Dunwell and Ford, 2005) and they may possibly even be beneficial to the environment (Brookes and Barfoot, 2012; Park *et al.,* 2011; Wesseler *et al*., 2011). GM crops can reduce the pressure on natural habitats from agricultural land use through their higher yields. This is particularly the case for Bt traits, as no significant differences in yield are usually found between HT traits and conventional counterparts (Areal *et al*., 2013). It has also been found that growing GM varieties results in fewer pesticide applications than their conventional counterparts thus reducing the amount of chemicals in the environment, lowering the risk of pesticide residues in food and feed crops and potentially increasing on-farm diversity of insects and other pollinators (Nickson, 2005; Sanvido *et al.,* 2007; Wesseler *et al.,* 2011; Wu, 2006). This has led to some authors claiming that environmental concerns about GM crops have been politically driven whilst also pointing out that a number of environmental effects have not yet been quantified (Wesseler *et al*., 2011).

9. Land use and environmental impacts of possible GM production in the UK

9.1. Context

The nature of the land use and environmental impacts that will result from the uptake of GM crops by UK farmers will depend on the state of a number of parameters, including:
at the farm level:

- the crop-trait combinations adopted, and,

at the regional and national level:

- the time span for GM uptake (onset and rate of uptake), and,
- the final scale of GM crop production.

The nature of the environmental impact of GM crops is determined by the type of trait adopted, while the extent of these impacts is determined by rate and area of uptake. The nature of the impact arises from the GM crops acting on the environment both directly and indirectly. Direct impacts occur by a number of means, for example through possible gene-flows from the GM crop to the environment, the effect of plant-produced pesticides on insect populations, or perhaps even through unintended impacts of output traits, such as nutraceutical residues. Indirect environmental impacts occur when farmers adapt their management practices in response to the use of GM technologies. These impacts can be either positive or negative on the environment, for example reducing tillage and thereby lowering CO2 emissions, or reducing the number of crop types in rotations because growing GM IR crops lower pest pressures in following crops.

Because the nature of the environmental impacts depends primarily on the type of traits adopted, careful choices have to be made in the selection of traits for use in this analysis. Chapter 6 outlines a range of different trait types that might be available to UK agriculture over the next few decades.

However, it would be impractical to try to analyse here the potential environmental impacts of all of these trait types for two reasons. First, because little or no existing environmental impacts data exist for some of these trait types, so any conclusions drawn are likely to be speculative at best, and second, trying to capture all possible trait types would make such an analysis cumbersome. For these reasons, it makes sense to limit the analysis undertaken here to those traits that have been used in the financial modelling i.e. the input side traits, IR and HT, as these are currently being commercially exploited in other countries, have been subject to most experimental research and, therefore, have the best available data on environmental impacts for consideration here.

While limiting the analysis to currently available input side traits would seem to run the risk of yielding a rather short-term land use and environmental assessment, this isn't necessarily the case. While GM technology companies may develop a whole range of new trait types in the future, for example affecting crop nutritional profile, these are unlikely to be marketed separately from input side traits (such as IR and HT) that are already being exploited i.e. novel output side traits are likely to be stacked on existing IR and HT traits (or novel input side traits), so that the benefits of these existing traits will not be lost. Indeed, the stakeholder consultation exercise conducted as part of this analysis has suggested that farmers in the USA have already indicated that they would not buy GM soya varieties with altered nutritional profiles unless the existing HT trait is also retained. As these novel output-side traits will have far less significant environmental impacts than existing input-side traits, it makes sense to make these input-side traits the focus of this analysis, as they will likely to be in use for some considerable time to come.

9.2. Methodology

The analysis presented here is based on a synthesis of data derived from a number of sources i.e. the global literature review of environmental impacts presented in Chapter 8, the economic modelling of Chapter 7 and the scenarios constructed for the modelling reported in Chapter 6, and, finally, a stakeholder consultation exercise.

The stakeholder consultation was carried out by means of a questionnaire administered by email. The stakeholders were drawn from a number of groups, including UK farmers (one of whom had past experience of GM crop trials), farming groups (e.g. HGCA, Agricultural Industries Confederation and the NFU), Defra and Government agencies, seed and agricultural technology companies, academics and industry consultants. The stakeholder consultation had two purposes. First, to supplement the data collected via the literature review i.e. plugging gaps in coverage and to capture more recent data and experience, especially from the agricultural and biotech industries that had yet to reach academic publications. Second, to localise the global data on environmental impacts available in the literature i.e. evaluate the relevance of overseas experience and modify values and conclusions in light of the UK farming context.

While the primary focus of the environmental analysis is the traits used in the economic modelling, some exploration of other trait types is undertaken, albeit in a more qualitative and discursive manner. The analysis is largely qualitative to facilitate the synthesis of data from multiple sources, including stakeholder input, much of which is also qualitative in nature. However, where quantitative data are available from empirical studies, these are reported, although they may be presented as data ranges to reflect the presence of multiple data sources offering different individual data values.

The analysis and reporting is undertaken in a structured way, dealing with key issues related to this debate individually, with a more over-arching assessment in the conclusion section which draws the threads together. While the farm financial analysis has been undertaken on the basis of unique combinations of traits and crops, the environmental analysis will focus on specific traits, generalising over different crop types as a way of isolating trait effects and also limiting the scale of the analysis that has to be undertaken.

9.3. Land use impacts at the UK level

9.3.1. Introduction

For the purposes of this analysis, the land use impacts are limited to the following issues: (i) date of first uptake of GM crops; (ii) rate of adoption by farmers; (iii) land area planted at the time that the market has reached maturity; and (iv) geographical distribution of production. The issue of management practice (and changes to this) will be dealt with in sections 9.4.1 and 9.4.2. While indicator (iii) seems somewhat vague, it is perhaps more meaningful in practice than some alternatives measures that might be used, such as area planted after a fixed interval of time, or the maximum achievable proportion of GM crop.

Such measures would seem to offer more precision, but when dealing with such a speculative question any additional accuracy that they seem to offer would be more perceived than real. In this sense, the market maturity measure lies somewhere between the two suggested alternative measures and implies the proportion of the national crop sown to GM in the medium term. At this notional point in market development, additional areas of GM production might ultimately be planted, but the period of rapid increase in planted area has ended. This indicator is therefore based on the assumption of the traditional ‘S’ shaped adoption curve, as illustrated in Figure 9.1, with tails of indeterminate length (see Rogers, 1983).

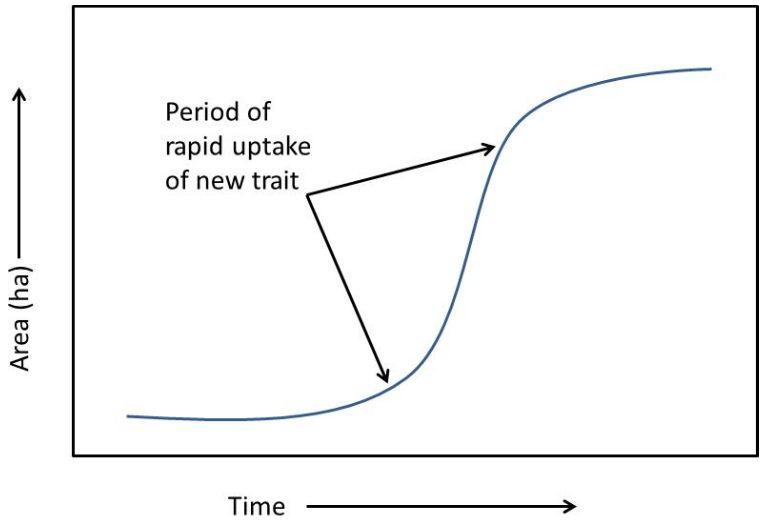


Figure 9.1. Classical ‘S’ shaped curve of rate of technology uptake

9.3.2. Date of first uptake

The dates of first uptake for the different crop-trait combinations are subject to great uncertainty, primarily because such decisions are tied to changes in EU or UK Government policy, rather than evolving market or technology conditions. What it is safe to say, however, is that by the time any political decision has been taken to allow commercial production of GM crops in the UK, and the supply chain has taken all necessary steps to accommodate them, such as complying with regulation on coexistence with conventional crops, there will likely be rather more GM traits available from which farmers can choose than there are at present. In this situation, uptake of multiple crop-trait combinations is likely to begin simultaneously, unless staggered by a staged licensing process.

9.3.3. Rate of uptake

Data are available from other countries that might be used to suggest a possible rate of uptake of GM crop production in the UK. However, there are complications in the UK context that first have to be acknowledged. UK farmers are, as a class, as well-capitalised, educated and technologically developed as any farmers in the world. Thus, there is every reason to suppose that once licensing is achieved, uptake of GM crops would be as rapid in the UK as in any other country so far recorded. In the UK, however, the particular role of consumer opinion and supermarket power must be factored in. If significant numbers of consumers refuse to accept food products containing GM ingredients and supermarkets react to this by retaining existing moratoria on GM products, this would act to significantly delay the rate of uptake of GM crops by UK farmers, regardless of their personal attitudes towards the technology and the benefits that might accrue to them from adopting it. However, if the simplifying assumption is made that official licensing of commercial GM crop production takes place at a time when consumer opposition to GM food ingredients has largely disappeared, the rate of uptake of GM crops could follow the pattern seen, for instance, in countries such as Canada. There is certainly evidence from studies that shows that consumers are much more willing to purchase GM products than their sceptical attitudes would suggest (see, for example, Lusser *et al*., 2012). For example, commercial production of GM HT OSR in Canada began in 1997 and by 2012 (15 years later) accounted for 97.5% of the OSR planted area (Smyth *et al.,* 2011; James, 2012). What might complicate this picture is the possibility of a staged licensing process as suggested above. For example, GM crops for industrial uses might be licensed for production in the UK, but not GM crops for human or animal consumption. Such a scenario would act to slow the rate of GM uptake. However, as there is no way, from this vantage point, to know if such a scenario is possible, it is safest to assume that there will be no staging of introductions of GM technology beyond that which occurs in the normal bureaucratic round.

9.3.4. GM share of total crop plantings

Based on experience elsewhere, it might be supposed, with some confidence, that assuming no obstacles on the demand side, plantings of GM oilseed crops offering input side advantages would account for 90% or more of total production of GM crops in the UK within 15 years of onset of commercial GM production. Indeed, with the likelihood that the global market for GM crops will be further developed by the time UK commercial production of GM crops begins, the rate of uptake of these crops could be accelerated beyond what has been seen in other countries in the last decade. With total available croppable area (including temporary leys) in the UK in 2012 standing at 6.3 M ha, full transition of OSR (756k ha) and maize (158k ha) to GM would put GM crop production on around 15% of croppable land in the UK (Defra, 2013). However, the most significant environmental impacts of GM crop adoption would occur if GM cereals varieties were available such as HT wheat or, as a number of stakeholders have suggested, varieties with GM traits offering protection from fungal infestations, particularly *Fusarium*.

9.3.5. Geographical distribution of production

In terms of the geographical distribution of GM production, the type of input-side traits currently available would be suitable for all of the UK's production regions and so it would not be expected that there would be significant regional variation in rates of GM uptake. Some traits currently under development might offer region-specific benefits, for example drought tolerance in wheat. Drought tolerance might be of interest, as a form of yield insurance, to cereals farmers in the east of England, particularly when farming on light or clay soils, where drought is more frequently a problem, especially if the yield losses incurred in years of normal rainfall were not too prohibitive. The issue of the desirability of this trait, in the UK context, is revisited below.

9.4. Potential environmental impacts of GM crop production in the UK

9.4.1. Impacts of HT traits

There is a view in the international literature that HT traits do not, in general, reduce the physical volumes of herbicides used, but do lead to the substitution of selective herbicides with less toxic broad spectrum herbicides such as glyphosphate and gluphosinate (Qaim, 2009). For this reason HT crops would offer environmental benefits in the UK context in terms of reductions in the amount of herbicide active ingredients used in crop production.

Experiences with HT OSR production in countries such as Canada, the USA and Australia can be used to illustrate the scale of herbicide active ingredient savings that would be possible in the UK. Brookes and Barfoot (2013) estimate active ingredient savings arising from HT OSR cultivation, averaged for Canada, USA and Australia of 17.3% for the period 1996–2011, although this figure had fallen to 6.4% in 2011. This latter figure is based on current practice and is much lower than has been observed in the past, largely due to the introduction of Clearfield OSR, which has lowered non-GM crop herbicide requirements. Stakeholders have suggested that the active ingredient savings of future HT wheat traits would be greater than those observed for oilseeds, perhaps as much as 18% in spring wheat and up to 50% in winter wheat. However, as there is a Clearfield equivalent of wheat available in the UK (from BASF), these savings should be thought of as possible maxima.

9.4.2. Impacts of IR traits

Currently available IR traits provide environmental benefits by reducing the use of insecticides applied to crops, such as maize and cotton, to combat some of their major insect pests. Of these two IR crops widely commercially exploited to date, only Bt maize has any relevance to the UK. Bt traits produce natural toxins (Cry proteins) which combat stem and stalk boring insects, earworms, cut worms and rootworm. Reviews by Brookes and Barfoot (2013) and others show that there is considerable variation between countries in the insecticide active ingredient savings delivered by use of Bt maize, ranging from a saving of 34% (2011) in Spain to 93.8% in Canada. A number of reasons are posited to account for these differences, including that: insect pest types and pest pressures vary between regions; and farmer response to pests varies between regions depending on the susceptibility of pests to insecticides. So, for example, farmers in regions where stem boring pests are prevalent may not be inclined to try to combat these pests as they are hidden away inside stems and so are largely protected from external spraying.

While there are a number of maize insect pests in Europe that Bt traits can usefully combat, stakeholder perception is that the primary usefulness of Bt in the EU lies in combatting the European corn borer. At the present time, this pest is not a problem in the UK. However, this analogue is still useful as the range of the European corn borer is seen to be moving northwards and the pest may well become problematic in the UK at some point in the near future. Additionally, IR traits will likely be developed in the future for other crops of relevance to the UK e.g. wheat. This would be a very significant development as the UK now has a large number of insect pests.

Brookes and Barfoot (2012) have shown that while there has been considerable year to year fluctuation in rates of insecticide active ingredient (ai) application per ha in countries growing maize in the last two decades, rates of ai application have been generally falling in both the non-GM and GM contexts. However, ai savings by IR maize relative to non-GM have been maintained. Some studies (e.g. Hutchinson *et al*., 2010) suggest that observed ai savings in the major maize-producing countries might be conservative estimates, due to the effect of extensive IR maize production in suppressing insect pest numbers in non-GM maize crops in the same region.

At the present time, there would perhaps be little demand for IR maize in the UK. However, if the European corn borer were to become a problem in the future, IR maize would become relevant. The wide variation in insecticide savings reported above makes it difficult to provide estimates of likely savings in the UK context, but taking the most conservative figure for ai savings found in the literature, it is possible that adoption of IR maize would result in savings in rates of insecticide ai applications perhaps in excess of 35%. Should IR traits become available in other crops, especially cereals, even greater savings in aggregate insecticide use would be available. For IR maize, percentage EIQ reductions are not seen to be systematically greater than ai reductions, but rather are broadly similar in scale (Brookes and Barfoot, 2012). This is largely due to the fact that pest pressure in maize is lower in the UK than in many other crops, leading to lower insecticide applications per ha in non-GM production and also due to the limited effectiveness of insecticides against some pests, leading farmers to neglect attempts to control them by this means.

9.4.3. Other trait types

While output-side traits may have beneficial financial impacts on UK agriculture in the future, they are unlikely to have significant impacts on the environment, either directly through pest resistance, or indirectly through crop management change. Of course, a few exceptions to this rule can be envisioned. For example, crops possessing traits that produce pharmaceutical or industrial compounds might have direct impact on fauna, but these are likely to be minority crops in terms of the eventual area of production. Drought resistance traits are likely to be available for wheat in the near future and these obviously have some potential to impact the environment globally, for example by changing land use through allowing wheat to be grown in areas formerly too arid for crop survival. However, in the absence of significant climate change in the near future, developments of this kind are unlikely in the UK, where drought resistant varieties are likely to be grown only as a form of yield insurance in areas where wheat is already widely grown, and where low rainfall depresses yield in some years (such as in the far eastern counties of England). In the UK, climatic limitations to cereals production are not due to “droughtiness”, but rather are due to high rainfall in westerly and northerly regions, where there are also lower average temperatures, especially due to cloud cover and sometimes altitude. These environmental challenges would suggest that GM traits (for cereals) conferring tolerance to water inundation and low soil temperatures in the spring (thus affecting spring germinating crops) would be more useful for UK agriculture.

9.5. Carbon savings

Low tillage, or zero tillage, agriculture (sometimes called conservation tillage) is being increasingly adopted in UK agriculture as it offers a number of agronomic, economic and environmental benefits. However, it has been pointed out that increased use of low/no-till cultivation in the UK, with its short interval between harvest and sowing, might increase risk of fungal diseases such as fusarium, requiring elevated fungicide application.

There is no reason to suppose that use of HT crops would not increase use of low till seed bed preparation in the UK, resulting in direct drilling of seeds into the stubble of preceding HT crops. Lal (2004) estimates carbon emissions reductions for low till verses full till at between 30–35 kg C/ha/year depending on the technique used. UK cropped soils typically hold between 10–150 tonnes of soil organic carbon per ha (Lal, 2004), but these values have been in decline.

McConkey *et al*. (2007) estimate that between 0.1 and 0.16t/ha/year of additional carbon is sequestered under zero till. Taking the more conservative of these low till estimates for use in the UK context, it can be estimated that if half of the UK OSR area (756/2 = 376kha) were low till, an additional 15,000t of carbon would be sequestered annually. If zero till were used on the same area, then using the most conservative estimate, an additional 37,600t of carbon would be sequestered annually compared to full till on the same area. In 2013, total UK emissions of the basket of six greenhouse gases covered by the Kyoto Protocol were provisionally estimated to be 569.9 M t carbon dioxide equivalent (MtCO2e) (DECC, 2014).

Increasing use of low and zero tillage practices would also result in carbon savings through lower fuel use. Brookes and Barfoot (2012) estimate fuel savings from Canada in 2010 of 6.4 l/ha/year resulting from a move from conventional tillage to zero till in OSR production. Using these coefficients it can be estimated that fuel savings of 2.4 M l per year would be achievable in the UK for zero till compared to full till on half of the 2012 OSR area (756,000 ha).

There are no official farm practices data published in the UK relating to the area of low and zero tillage. To get some idea of current levels of min till practice, the University of Reading’s Agriculture and Food Investigation Team were commissioned to carry out a short telephone survey of arable farmers in the south central, south and south east of England. Of 84 farmers surveyed, 45% carried out min till practices on at least some of their land. Accounting for indications given of min till area, it can be estimated that a possible maximum of 25% of arable land is now cultivated in this way. Anecdotal evidence from the survey also suggests that this area has seen rapid expansion in the last 5 years, but that this has mostly taken place on larger holdings and that further expansion is being held back by the cost of the necessary equipment and concerns about weed management. With 75% of arable land still cultivated using more traditional tillage methods, and perhaps 567 ha of OSR area, projected increases in OSR conservation tillage of the order of 376 ha (as suggested above), largely driven by the introduction of HT crops, are entirely feasible. Such an increase would generate the kind of carbon savings from sequestration and reduced fuels use also postulated above. While some authors have raised the caveat that adoption of HT crops is not the sole driver of uptake of low and zero till seed bed preparation, experience in other countries, such as Canada and the USA, strongly suggests that it is one of the more significant drivers of this trend.

9.6. Environmental risks

9.6.1. Development of herbicide resistant weeds

It is undoubtedly the case that, should HT crops be grown on a wide scale in the UK, problems with herbicide resistant weeds (especially glyphosphate resistance) will be experienced. However, UK farmers are already experiencing the issue of herbicide resistance, in the absence of HT crops. Experience elsewhere suggests that the methods used to deal with herbicide resistance in non-GM cropping systems work equally well with GM systems. These methods include: introducing full tillage for a time (perhaps one season) to eliminate weeds from the seed bed, and use of different and complementary herbicides, either alongside those that are experiencing resistance, or in place of them. It has been observed in the literature (Smyth *et al*., 2011), that the number of active ingredients applied to HT crops, as well as the volume of active ingredients, has been increasing in recent years to deal with the problem of herbicide resistant weeds. This has had the effect of reducing the environmental advantage that HT has over conventional crops, but it does not entirely eliminate it.

9.6.2. HT volunteers in following crops

Stakeholders voiced strong opinions that the experience with HT OSR in North America would be replicated in the UK; the consensus being that the problem of HT volunteers (of any HT crops) in following crops, would be no greater than for conventional crops and that there are suitable, traditional methods (i.e. tillage) to deal with any problems that did occur.

9.6.3. Impacts on fauna

Because IR crops are engineered to produce insecticidal proteins, there is the possibility that they will impact non-target organisms resident in the crops, particularly beneficial arthropods important for pollination, decomposition and biological control (including predators for crop pests). Numerous laboratory and field-scale experiments have been carried out to test for the impacts of IR crops on non-target insects. However, a number of large-scale meta-analyses of these studies have been carried out, for example, Marvier *et al*. (2007), Wolfenberger *et al*. (2008) and, most recently, Naranjo (2009). Naranjo (2009) found that while there was some evidence of limited loss of condition and reproductive fitness of non-target organisms exposed to Bt proteins, these effects were largely limited to organisms that preyed on the Bt targets or used them as hosts. However, the main observation was that 'insecticides have a much more dramatic negative effect on non-target organisms than do Bt crops'. The environmental benefits observed in other countries through use of IR maize, in terms of reduced losses of non-target organisms, is greatly to be desired, especially in view of the much reported losses of desirable insects, through insecticide use, such as honey bees and other pollinators, in this country (Potts *et al.,* 2010).

There is evidence that target insect populations can, through demographic change, quickly spread resistance to Bt proteins in exactly the same way that resistance to artificial insecticides can occur (Tabashnik and Gould, 2012). The introduction of IR crops, such as Bt maize, into the UK would obviously bring with it the risk that this problem will develop. However, stakeholders argue that the risks of Bt resistance occurring are no greater than the risk of resistance to some commercial insecticides and because farmers and scientists are already familiar with the issue, mitigation measures are available and indeed already practiced here in the UK that could be deployed to counter such problems (for example crop rotations and judicious use of insecticide sprays). Measures to delay the onset of population resistance to Bt proteins have also been suggested and tested, including the establishment on farms of 'refuges' of crops that do not produce Bt proteins, near to Bt crops, to allow the susceptible pests to survive (Carriére *et al.*, 2004).

9.6.4. Gene flow issues

Out crossing with wild relatives

The likelihood of GM crops outcrossing with wild relatives in the UK is difficult to predict as outcrossing potential is affected by a number of factors, including: the management practices of individual farmers, local topographic and climatic conditions, the inherent outcrossing potential of the plant itself and the presence of wild relatives in the local environment. While the first of these risk sources are location specific, some very general conclusions can at least be drawn about the last two. Inherent outcrossing potential varies from species to species depending on the extent to which they self-pollinate. Species that predominantly self-pollinate have the lowest outcrossing potential. While maize has an inherently high out crossing potential, in the UK setting this is largely offset by the fact that there are no wild relatives of maize with which domesticated maize could hybridise. Oilseeds, such as OSR, are largely but not entirely self-pollinating, but as there are wild relatives available for hybridisation in the UK, oilseeds have a moderate outcrossing potential (Glover, 2002). Cereals are very largely self-pollinating and are considered to have low outcrossing potential (ibid).

While work on containment strategies is on-going, for example through the use of 'terminator' technology, no GM-based containment technologies are currently available for use in commercial farming. UK agriculture would therefore face the same risks of outcrossing that are currently faced by countries that have already adopted large-scale GM cropping. Of the GM crops currently available for cultivation in the UK, perhaps most concern attaches to HT OSR, which some believe might confer herbicide tolerance to weedy relatives. However, it is considered unlikely (ibid) that HT genes would be stable in weed populations that were not subject to herbicide treatments. In addition, experience of HT OSR cultivation in Canada and the USA has shown that outcrossing rates of HT genes from OSR to wild relatives is low and that HT weeds can be controlled in conventional ways by use of more specific herbicides.

Gene flows to cultivated non-GM crops

All GM crops, both those currently commercially grown and at the development stage, have the potential to cross pollinate non-GM equivalents and wild relatives (Dunwell and Ford, 2005). A number of so-called 'coexistence' measures have been recommended by the EU and these have been taken up in nationally tailored packages by some Member States, though not in the UK as yet. Prominent among these containment measures is the requirement to maintain separation distances between standing GM and non-GM equivalent crops through the use of fallow zones, or buffer strips containing non-GM equivalent crops that are sold as GM. However, Areal *et al*. (2012) have shown that this might slow down adoption. Field studies have demonstrated that such measures are effective in maintaining non-GM equivalent crops at below the statutory 0.9% threshold for adventitious presence at the 95% confidence level (see, for example, Marceau *et al.,* 2013 for trials with maize). There is every reason to suppose that, if the UK adopts packages of coexistence (containment) measures similar to those currently operating in, for example, Spain and Portugal, then legally and environmentally adequate containment of gene flows between GM and proximate non-GM equivalent crops can be achieved.

10. The impacts of the supply of UK-produced GM crops on the wider supply chain

10.1. Introduction

At an early stage in the project, discussions took place between the research team and HGCA on how best to deliver the analysis of the impacts of UK GM crop production on the supply chain. It was agreed that the complexity of the wider supply chain, especially the food chain, would make any assessment of the impact of GM crop production extremely challenging, with widely variable outcomes dependent on the sub-sector concerned. As a means to simplifying the analysis and adding coherence, it was agreed that the analysis should be confined solely to the feed supply chain, as this is much simpler in structure than the food chain, with fewer agents involved and far fewer product lines.

For a number of reasons, the analysis of the impact of UK GM crop production on the feed supply chain had to be more qualitative than the analysis of farm-level impacts, including that:

(i) there is considerable heterogeneity in the nature of feed supply chain businesses;
(ii) it would be difficult to obtain baseline economic data for these businesses;
(iii) there are few studies on the impacts of GM adoption on feed chain businesses; and consequently,
(iv) there is uncertainty over likely business responses to the presence of market demand for, and domestic supply of, GM products. To illustrate, the big UK retailers formerly had a requirement that non-GM feeds must be used by all livestock producers in their UK supplier base, but subsequently most of these retailers dropped this requirement when it became difficult to source non-GM feeds on the international market.

In this study, three sources of data were used to inform the feed supply chain analysis:

(i) a review of the literature;
(ii) the outputs of the financial modelling of crop production (including GM trait, supply and price effects); and
(iii) the opinions of feed chain stakeholders.

The primary source of data for the analysis was the consultation with feed supply chain stakeholders. The consultation was undertaken in a semi-structured way through the use of a questionnaire containing 13 questions requiring free-form answers. The questions were grouped under four themes, covering the issues of:

- the potential economic impacts of GM crops to the feed chain;
- the nature of possible segregation of GM products in the feed chain (coexistence);
- the potential cost of coexistence; and

- potential structural impacts on the feed supply chain resulting from coexistence.

The content of the questionnaire was informed by the literature review and discussions with stakeholders at a workshop held at the University of Reading in October 2013. Before full deployment, the questionnaire was piloted with a feed chain stakeholder and adjustments made to the design in light of comments received. Consultations were carried out with representatives from the sectors of feed mills and manufacturers, livestock feed nutritionists, feed suppliers and farming groups.

10.2. Potential economic impacts of UK-grown GM crops in the feed chain

10.2.1. What kind of traits would provide benefits to the feed supply chain?

The UK feed sector is already using imported GM products in the manufacture of livestock feeds. Indeed, feed chain stakeholders suggest that most compound feed supplied in this country already contains at least one GM ingredient. These products include GM soya meal and soya hulls, as well as maize co-products like US maize gluten feed and US corn-based distillers dried grains. These are labelled as potentially being from GM sources, according to EU feed labelling legislation.

Of the GM crop-trait combinations currently available, two have been identified in this study as being both suitable for UK agronomic conditions and offering potential benefits i.e. HT OSR and IR maize. These GM crops have been shown to offer potential cost savings to UK farmers, with HT OSR gross margins shown in the modelling exercise to be 2.3% higher than conventional OSR when grown in typical rotations with moderate weed pressure. Both of these crops, or products derived from them, are currently used extensively in livestock feed manufacture in the UK.

As the current GM traits in these crops do not alter their nutritional profiles, the UK feeds sector would only develop a preferential interest in them if they were available at lower cost than the non-GM equivalent. This might be the case based on lower costs of production. Additional indirect benefits might also be available, due to the potential of the GM traits to uphold crop yield and quality in years of heavy weed pressure, which would lead to reduced variability in domestic supply and price.

An agronomic trait that would be of more benefit to the feed sector would be resistance to mycotoxin-producing fungi, such as *fusarium*. In wetter parts of the country, cereals can be impacted by mycotoxins which, when used untreated in livestock feeds, can have a negative impact on livestock health and growth rates. For example, *fusarium* can elevate rates of infertility in pigs, and is often countered by the use of a mycotoxin binder in feed rations. Boring insects can cause increases in mycotoxin levels in maize, suggesting that IR maize offers potential benefits. However, maize does not suffer significantly from such pests in the UK at present.

Of more direct interest to the feeds sector would be GM traits that enhance the nutritional profile of crops, although these traits are currently some distance away from market readiness. The most significant nutritional challenge faced by the livestock feeds sector is securing sufficient high quality crop-based protein, at a reasonable price. In recent decades, imported soya bean meal has been the protein source of choice. GM traits that raised the crude protein content, or protein quality, of high volume carbohydrate crops such as cereals, or oilseeds (fed as oilseed meals after crushing to remove the oil), would be of great interest to the feeds sector. Other nutritional traits that would be of interest to the feeds sector include:

- for ruminants, higher content of digestible protein (e.g. in oilseed meals) that are not degraded in the rumen (rumen by-pass proteins);
- better amino acid profiles of protein-rich crops, such as peas and beans, as well as lower fibre content;
- omega 3-enriched oilseeds;
- reduced presence of anti-nutritional factors in crops such as pulses; and
- higher gross yields in protein-rich crops such as peas, beans and lupins.

Improved nutritional profiles mean that balanced, optimal, feed rations can be produced at lower cost i.e. using cheaper and potentially more locally available feedstocks, which require less use of expensive remedial treatments, for example, heat and enzyme treatments to reduce anti-nutritional factors, or use of crystalline amino acids to improve amino acid balance. For the livestock producer, cheaper feeds would mean lower costs of production and higher margins, while optimised rations would mean faster growth rates.

10.2.2. What sector within the feed supply chain is likely to be the key player in deciding whether UK-produced GM crops are used?

As considerable volumes of imported GM crop products are already used in the UK feed supply chain, this question is primarily of relevance to UK-grown GM crop-trait combinations that are not currently found in the UK feed chain.

The sector(s) likely to push for uptake of UK production of GM crops and their use in the feed chain will vary according to trait type and its beneficiaries. Agronomic traits, which lower production costs, reduce yield losses and generally contribute to easier production practices, or higher producer gross margins, would be championed by the producer community and their representative organisations, because at least some of the benefits of these types of trait would accrue to them. Dealers and feed manufacturers may also support the use of traits conferring resistance to fungal infestations, as these would offer potential benefits to them in the form of improved feed quality, reduced manufacturing costs and reduced storage losses.

Feed manufacturers would likely encourage the uptake of crop-trait combinations that improved nutritional profile where these had been proven, in trials, to provide benefits to them in terms of lower raw ingredient costs (for example, through lower requirements for soya inclusion, or reduced use of crystalline amino acids), lower manufacturing costs (for example, through less batch testing, or reduced enzyme or heat treatment), or increased feed quality, for example, the production of more protein dense, or energy rich feeds. Feed manufacturers might also be interested in crop traits that resulted in feeds that reduced methane production. This might be useful to supply a market niche where livestock producers have an interest in reducing the carbon footprint of their product, perhaps to comply with future regulation, or retailer or assurance scheme certification.

It has been long thought that retailers, especially supermarkets, acting as agents for the consumer, would act as a brake on uptake of UK GM crop production, due to their sensitivity to residual public concerns about the use of GM ingredients, including in the feeding of livestock. However, based on current evidence, such as the use of GM soya in most concentrated livestock feeds, this now seems unlikely. Indeed, some feed-sector stakeholders consulted for this study were of the view that consumer opposition to inclusion of GM ingredients in foods and livestock feeds was already a non-issue. In support of this they point out that over the last few years there has been increasing presence on supermarket shelves of products with GM ingredients, and livestock products derived from GM feeds, with no adverse consumer reaction. One consultant commented:

> 'The fact that consumers willingly and maybe knowingly buy GM tortilla crisps and rib eye GM corn fed steaks from the USA is proof that this is a media and political campaign not a consumer driven one. We already eat imported chicken fed on GM soya and import GM soya to feed our chicken – this transition happened over the last two years and no one noticed or complained.'

It is possible that supermarkets might even welcome the uptake, by UK agriculture, of GM traits that conveyed particular nutritional improvements that might be of benefit to their customers i.e. which can be marketed with a price premium, or traits which reduced product prices.

10.3. Segregation of GM products in the feed chain

10.3.1. How feasible would it be to ensure segregation throughout the feed chain?

The difficulties associated with segregation and identity preservation (IP) in the feed chain would vary according to the severity of the thresholds for adventitious presence that had to be enforced. An IP system designed to ensure a 0.1% upper maximum GM inclusion rate, would require a complete system (sometimes called 'hard identity preservation') involving a paper trail allowing traceability and recording, independent verification and testing right throughout the chain, starting with the seed used by farmers, then on-farm, post-harvest (for example during on-farm storage) during transport, and at arrival for storage or processing at manufacturers. There is currently no legal requirement for IP at this level in the UK so, unless supermarkets or other agents demand it, the current threshold for adventitious presence of 0.9% will continue. This requires a far less stringent segregation/IP regime (sometimes called ‘soft identity preservation’) perhaps only involving a paper trail covering verification and testing of seed and the crop on arrival at the end user, for example on placement in storage bins at the compounder. Loads tested on arrival for storage and found to breach the 0.9% maximum threshold would be rejected and remain the property of the producer, who would presumably transfer them to other outlets that did not have a non-GM requirement. It is also possible that other voluntary, practical steps, might be taken by feed manufacturers, such as placing contracts with certified non-GM farms and managing their own supplier base. The ‘soft identity preservation’ system already exists in the UK feeds sector.

It is also worth noting that IP might not only be necessary to protect non-GM lines, but also to protect GM lines where nutritional traits are involved. If nutritional traits confer a price premium, there will always be a need to monitor for possible fraud.

On the issue of the feasibility of introducing segregation and IP, one stakeholder commented:

> ‘Non-GM feeds to [the 0.9%] limit have been produced in the UK for many years now, so there’s no reason why that cannot be achieved in the future i.e. the segregation techniques are already well known in the international and UK supply trade. Maybe there will be education required on farms and UK grain stores but the knowledge is already well advanced and well tested’.

10.3.2. What coexistence measures are likely to be needed?

Inadvertent cross-contamination is the greatest risk to exceeding GM thresholds. This can occur in fields, during transport, in stores, during initial processing (oil crushing, flour milling, etc.), during feed manufacture and on the farm through mixing of feeds. To ensure standards are met, the following actions would likely be necessary, most of which are already being observed:

- separate storage facilities at all points (bays, bins, etc);
- cleaning of common delivery systems (stores, conveyors, loading equipment, lorries, etc.);
- testing to ensure the ingredients and derived products are as advertised;
- a paper trail (audit and verification); and
- labelling.

10.3.3. Will segregation always be required, or is it likely that the non-GM supply chain, for some products, will disappear after a time?

Auditing of some kind will always be necessary. However, it is possible that segregation of GM and non-GM crops could be rendered irrelevant if both the demand for non-GM versions of particular crops and the domestic and international supply of the non-GM versions become severely restricted. Experience with GM OSR in Canada suggests that, if the agronomic advantages of a crop are large enough, non-GM production might all but disappear in the UK quite quickly. If this is accompanied by a loss of public interest in the distinction between GM and non-GM crops, then regulation might be adjusted to reflect this new reality. Even under these conditions, however, segregation and testing might need to be retained where GM traits for altered nutritional profile yield a premium large enough to be a temptation to commit fraud.

Some feed chain stakeholders consulted for this project argued that segregation in the UK feed chain has already all but disappeared and that many bulk handlers of feeds, such as elevators and exporters, are now refusing to segregate due to the extra costs involved, which would put them at a disadvantage compared to overseas competitors. Many suppliers are consequently now giving notice that their supplies are classed as GM and they are offering no alternative. One consultant commented:

> 'Most major elevators and exporters now refuse to guarantee segregated material - non GM is too small a market and it is too much hassle to segregate in a busy high throughput silo.'

10.4. The cost of coexistence

10.4.1. What specific coexistence measures would be most significant in terms of costs?

Testing and audit are already commonplace in the feeds sector, including that related to GM IP, as a consequence of the importation of GM soya and GM maize products for use in feed manufacture. Obviously, an expansion of handling of GM product lines arising from UK production of other crops, such as oilseeds, will mean that additional segregation/IP measures will be needed if segregation in the supply chain is practised. In these circumstances, those measures likely to be most significant in terms of costs would be (i) the requirement for extra storage (for example, most animal feed mills have restricted storage capacity), to allow for physical separation of GM and non-GM products lines at various points in the supply chain; and (ii) additional testing, although the final significance of this will depend on the frequency of testing that has to be undertaken. This will be decided by a combination of legal requirements and market demands. The installation of additional storage facilities would require significant capital expenditure which will add to depreciation costs over the life of business assets. However, of more significance would be the costs of additional testing. With each test costing in the low hundreds of pounds, costs at this level will be particularly disadvantageous to smaller-scale businesses who deal in smaller product batch sizes.

10.4.2. Who would likely bear any additional costs associated with coexistence?

Under circumstances where segregation is required in the feed chain, all agents involved in the chain would probably end up carrying some of the additional costs. The agent with the least power i.e. the agent who cannot easily pass on additional costs, would probably be the livestock producer, who is selling to the strongest agent, the retailer. There are some differences of opinion on the effect of segregation on costs on the feeds chain. Some stakeholders suggest that, given the volatility in prices of both feed and meat, the actual costs of segregation will be very small in relation to net market variation. However, other stakeholders suggest that these costs would not be inconsiderable and because of this feed chain agents would resist them. This resistance would express itself in widespread abandonment of segregation, with non-GM certification only being offered in a few specialist cases and where a price premium is paid.

10.5. Structural impacts of coexistence

Stakeholders were of the opinion that there is a low likelihood that uptake of GM crops production in the UK, and associated coexistence measures, would drive associated structural change in the feed supply chain, for example, by contraction or expansion, or business mergers etc. In their view, the industry was much more likely to be impacted by drivers such as ‘political’ intervention and the ongoing general over-capacity in the UK feed industry.

In terms of the power relationships between agents in the feeds supply chain, or between the supply chain and farmers, the supply of UK-produced GM crops and associated coexistence measures would only lead to changes if the balance of supply and demand were affected. This might occur, for example, if there were strong demand for a particular nutritional trait, and little supply. In this situation, producers would have much greater market power and their product would command a price premium. However, such a scenario would likely be short-lived as other producers would quickly be attracted by the higher margins available and enter production themselves. Changes to power relationships in the feed chain might therefore occur for a time in specific sectors, but permanent changes are unlikely.

When asked whether the supply of GM crops from UK agriculture would result in any changes to the balance of supply (by trading volume or value) through different parts of the feed supply chain, stakeholders expressed uncertainty. It was generally accepted that no permanent sector-wide changes would result, but some specific, time-limited instances could be envisioned. For example, if new nutritional traits became available that would make some feed stocks more attractive, perhaps by providing higher protein content, or better amino acid balance, these products might displace products currently being used. However, this would likely only result in GM lines of a crop replacing non-GM lines of the same crop.

11. Summary, discussion and conclusions

11.1. Method

This desk-based study reviewed the potential economic and environmental impact that uptake of GM crops could have on UK agriculture, with a particular focus on cereals and oilseed crops. The research was carried out by an inter-disciplinary team of seven highly experienced scientists and economists from the University of Reading's School of Agriculture, Policy and Development. The approach was to address the key research questions using, as a framework, a set of scenarios for the potential uptake of GM crop technologies in the UK. This was followed by the use of both qualitative and quantitative research methods which included a literature review, stakeholder consultation and financial modelling, to further define the scenarios and to provide, where possible, outcomes data, covering such issues as the land use and environmental impacts of adoption of GM crops, as well as their impact on the feed chain.

11.2. The extent of GM crops

The worldwide area of so-called canola, edible OSR low in both erucic acid content in the oil and glucosinolates in the meal, was 34M ha in 2012, of which 27% was under GM herbicide tolerant varieties. This proportion has grown rapidly since 2000. Only four countries currently grow GM OSR. Canada is the leading producer but it is also grown in the USA, Australia and Chile. In Canada, almost 100% of the total OSR area is now GM. Farm level economic effects of adopting GM OSR have been found to include: increased yields, largely from better weed control; lower production costs from reduced crop protection expenditure; higher profits despite the seed price premium; and more convenient and less pressured farm management practice.

After wheat and rice, maize is the most important cereal grain grown worldwide. Some 170M ha of maize was grown globally in 2012 of which 28% was GM. The main producer countries are the USA, China and Brazil. In the UK, maize is a relatively minor crop with most of the production being used for silage. Insect resistance (IR), namely Bt, and herbicide tolerance (HT) traits are available. Spain has the largest area of GM maize in Europe, all of it Bt to counteract the European and Mediterranean corn borer pests. Benefits at the farm level of adopting GM maize were found to be: slightly increased yields; lower costs of production, largely from reduced expenditure on pesticides; and higher profits resulting from reduced production and management costs.

11.3. Review of development work on GM cereals relevant for the UK

A review of recent development work on GM cereals (wheat, barley and oats) traits that might be relevant for UK agronomic conditions was carried out. These were divided into those that might provide advantages to the farmer (input traits) and those that change or modify the nature of the harvested product (output traits). It was found that there had been some input trait work on: herbicide tolerance; pathogen tolerance especially against fungal diseases; abiotic stress such as drought, salt tolerance and nitrogen and phosphate deficiency; and yield traits stabilised under field conditions. As for output traits, work has been done on modifying the nutritional profile of crops and also for the production of medicinal products including enzymes, diagnostics and vaccines.

In order to try to make an assessment of the future direction of research on GM cereals in both commercial and non-commercial settings, an examination of public regulatory databases of applications for field testing of GM cereals was carried out. This found that there have been almost 9000 applications in the USA since 1996 for maize and 510 for wheat, 15 in Australia for wheat and barley since 2005 and only 10 in the EU for all crops since 2009. There have also been a number of patent applications and granted patents related to GM cereals in the USA for both input and output traits.

11.4. Scenario building

Within a relatively small project such as this, it was not possible to explore the entire range of implications of adoption of GM cereal and oilseed crops for UK agriculture as the potential range is limitless. Thus, a scenario-based approach was adopted where a few case studies, or crop-trait combinations were selected for analysis. These were then used in the farm-level financial modelling.

The scenarios were defined on the basis of the following three parameters: crop type; GM trait type; and the time scale of likely commercial availability for farmers. Scenarios were defined for the three crop types of interest to UK farmers: cereals; OSR; and maize. The choice of GM trait was based on four criteria: whether it was appropriate for the crop types above; whether it would be useful to UK agriculture; data availability in the literature on the agronomic/economic impacts of the traits; and whether or not there were field trials and/or modelling data in the recent literature relevant to the UK's agronomic conditions. Because few commercial trials were available for GM crops suitable for the UK, a time dimension was incorporated into the scenario design: a 5–10 year time step, capturing traits already explored in field trials or where relatively reliable real-world data were available; and a 10–20 year time step where traits were to be considered which were at the very early stages of development.

The scenario development process took place over the life of the project and involved a literature review, stakeholder consultation and financial modelling. The initial modelling scenarios were for 5–10 years ahead capturing: IR maize; HT OSR; and HT cereals. For 10–20 years ahead, available traits were assumed for drought tolerance in cereals. As it was assumed that UK farmers would have to carry out a range of coexistence measures if they grew GM crops, and as the UK has not yet proposed such a set of measures, reference was made to a current EU project that the researchers were involved with to define these. These were taken forward to the modelling phase.

11.5. Financial modelling at the farm level

A dynamic financial model, developed previously to predict the yield and gross margin of various crops grown in a selection of typical rotation scenarios, was adjusted and used to model the performance of Bt maize and HT OSR as they could be expected to perform in the south of the UK, if cultivation is permitted in the future. The model simulates different levels of pest and weed pressure, with associated management strategies including different rates of pesticide and herbicide applications. The model also enables consideration of the cost of complying with possible regulations concerning coexistence with neighbouring non-GM crops.

For this project, the model was used to predict the yield and gross margin of: Bt maize as a single crop; HT OSR as a single crop; and HT OSR in a four crop rotation (wheat, second wheat, OSR, barley). The model operates in monthly time steps over a time period of seven years for a full range of conventional crops and GM equivalents where appropriate. It allows for the simulation of a range of field sizes and the physical and financial parameters are based on officially-funded survey data.

It was found that for continuous production of Bt maize, no advantage was offered in terms of either yields or gross margins unless pest pressure was encountered. In the absence of pest pressure gross margins would be reduced by the seed premia and likely coexistence costs. However, gross margins for GM maize would be higher (6.3%) than for the conventional crop if mild pest pressure was present rising to 15.2% for very severe such problems.

For HT OSR, the technology premium and likely coexistence costs reduce the gross margin in the absence of weed pressure. The level of weed pressure needs to be severe before the GM crops perform significantly better in gross margin terms (+6.9%) than the conventional equivalent.

When the model considered HT OSR in a four crop rotation, compared with conventional OSR, the proportionate rise in gross margin of the former compared with the latter was visible at mild levels of weed pressure; at very severe levels of weed pressure the benefit was 10.2%.

For each of the above model results, the direct costs of compliance with coexistence regulations is reduced for those growing the crops on large continuous areas, compared with the likely costs for those having near neighbours who grow conventional crops.

11.6. Environmental impacts of growing GM crops

Clearly, environmental impacts data does not yet exist for GM crop traits yet to be adopted widely across the world. As a result, the analysis undertaken in this project concentrated on the input side traits used in the financial modelling, IR and HT, as these are being grown in various countries on a substantial scale, providing some data on their environmental impact in the literature. This was enhanced by stakeholder consultation.

GM OSR adoption has been found to result in a 30% reduction in use of herbicide active ingredients. Studies have shown a high correlation between adoption of HT OSR and farmer use of minimum or zero-tillage practices. Such practices lead to better moisture retention and less soil erosion as well as increased carbon sequestration and reduced fuel use. Around 15 years ago some were worried about the weed control risks of growing GM OSR. However, since then weed management problems have not been observed to increase markedly.

A wide range of studies on the environmental impacts of growing Bt maize have observed reduced pesticide use than conventional counterparts, lowering the risk of their residues in food and feed, and potentially increasing the number and diversity of insects and other pollinators. In the EU, where some Bt maize is grown, it has been found that coexistence measures have been successful in preventing gene flow problems.

The evidence from other countries shows that uptake of GM OSR was rapid. Thus, there is no reason to suppose that this pattern would not be repeated here, as arable farmers tend to be as wealthy, educated and technologically advanced as their counterparts elsewhere in the world. However, all of the HT crops currently available are short season varieties, which would not be as suitable for the UK as winter-sown crops. Adoption of Bt maize in the UK might not happen as quickly as, so far, maize has not been subjected to pest pressure.

11.7. The effect of GM crop adoption on the UK feed supply chain

A largely qualitative analysis, using the reviewed literature and stakeholder consultation, considered the likely impacts on the wider UK supply chain of the adoption of GM crops. To reduce this task to manageable proportions, the analysis was carried out on the feed supply chain only and solely considered the two likely near-term GM crop trait combinations of HT OSR and Bt IR maize.

It was concluded that the feed supply chain actors would not be unduly impacted by these two GM crops becoming grown widely in the UK as both are already being imported for livestock feed without farmers and consumers being concerned at all. Furthermore, it could be argued that widespread adoption of such crops could well lower the price of livestock feed with market-based benefits to all.

In the future, it is possible that there will be a wide range of GM traits that could enhance the nutritional profile of crops, and these could be very valuable to the various actors in the feed chain. As things develop, segregation of GM products in the feed chain could become an important, and costly, issue. However, it was found that most of those consulted thought that this potential problem would reduce over time and would not result in any long-term structural changes in the feed supply sector in the UK.

11.8. Conclusion

To conclude, in brief, the authors feel that the adoption of currently available and appropriate GM crops in the UK in the next five or so years could provide benefits to both farmers, consumers and feed chain actors without causing environmental change beyond that associated with conventional cropping systems. It is likely that over the next decade more GM traits will become available, some of which might benefit consumers directly through improved nutritional profiles. Furthermore, the possibility cannot be ignored that unless British farmers are allowed to grow GM crops in the future, the competitiveness of farming in the UK may decline relative to overseas competitors. This will be particularly true if new global GM releases help meet specific agronomic challenges that are faced by UK farmers growing mainstream crops. These conclusions echo those of the European Academies Science Advisory Council (2013) which have recently been endorsed by Owen Patterson, PC, MP, Secretary of State for the Environment, Food and Rural Affairs in his speech in January 2014 to the Oxford Farming Conference.

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