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GM CROPS 1996-2012: A REVIEW OF AGRONOMIC, ENVIRONMENTAL AND SOCIO-ECONOMIC IMPACTS

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ABSTRACT

The genetically-modified (GM) varieties of major economic crops, specifically soybean, maize, rape (canola) and cotton, were first grown commercially in 1996. In 2012 they were grown on 170 million hectares, representing a six per cent increase on 2011 (James, 2012) though there was only a small increase in the number of countries involved from 29 to 30. Notably there remains an absence of participants in Europe where proponents continue to voice concerns about possible adverse impacts on human and environmental health as well as the dominance of a few international companies which market the seed. This paper examines the agronomic and environmental impacts of GM crops since 1996 as reported in the published literature. A similar approach is taken to examining the socio-economic impact of GM crops e.g. wealth generation, health aspects and employment. Overall, the impact of GM crops has been positive in both the developed and developing worlds. Agronomically, yields per unit area have increased due to enhanced pest and weed control with added benefits in the case of insect control for non-GM crops grown nearby due to the so-called 'halo, effect. In terms of energy investment, GM crops are 'greener' than non-GM crops because reduced insecticide applications lowers energy input i.e the carbon footprint. Ecologically, non-target and beneficial organisms have benefitted from reduced pesticide use, surface and ground water contamination is less significant and fewer accidents occur to cause health issues in farm workers. The most important adverse characteristic of GM crops is the capacity of insect pests and weeds to develop resistance to GM induced insect resistance in crops or to herbicides used in conjunction with GM induced pesticide resistant crops. Such resistance is not confined to GM crops as resistance in target insects and weeds is evident in non-GM contexts; it does, however, indicate that current GM approaches are relatively transitory in the battle against crop pests and that their viability will depend on good management.

In relation to socio-economic impacts, GM crops have increased income for large- and small-scale commercial and subsistent farmers with associated downstream impacts through investments. Increased gross margins are due to higher revenues and reduced costs in relation to pest management. Issues such as debt problems caused by seed purchase occur but are no more extensive than for conventional crops; the question of crop monopolies by multinational companies remains though it must be acknowledged that such companies have invested cash billions in development and that they have little to gain by pricing farmers out of the market. Health benefits have also been achieved, especially through a reduction in pesticide use. Additional potential benefits of GM crops are discussed including possibilities for the improvement of human health by augmenting specific nutrients i.e biofortification. One example is Golden rice which increases the availability of vitamin A which, through dietary deficiency, causes blindness in millions of people in Asia. In addition, this paper takes an unconventional stance by reviewing the socio-economic impacts of GM varieties in the context of impacts that have arisen from other agricultural technologies. It is proposed that the benefits and problems associated with GM are by no means unique and indeed are similar to those that have long been claimed for other much older technologies. The most significant benefits are increased financial rewards and health benefits. Increased gross margins are due to higher revenues and reduced costs in relation to pest management. A range of problems have been associated with GM crops, including debt and increased dependency on multinationals, but these can also be associated with other agricultural technologies. Overall, GM crops have proved to be a positive addition to the many technologies which comprise modern agriculture.

INTRODUCTION

The discovery of the molecular structure of deoxyribonucleic acid (DNA) by Watson and Crick in the early 1950s (Watson and Crick, 1953) paved the way for modern biotechnology which focuses on gene manipulation to enhance the ability of specific organisms to perform tasks or produce substances for human benefit. Today there are applications in agriculture, horticulture, forestry, environmental remediation, medicine, and forensic science (see reviews in Mannion, 2007, Fukuda-Parr, 2006, Murphy, 2007). The first commercial product of such endeavour was synthetic insulin in 1977 followed in 1988 by rennin, an enzyme used widely in the food industry. However, genetic manipulation has been most widely applied in agriculture and horticulture to produce crops with resistance to herbicides and insects. The first staple crops with engineered traits first became commercially available in 1996; they were: maize (corn), rape (canola), soybean and cotton.

Such crops met with a mixed reception and continue to be controversial today. The technology was embraced in North and South America and China but in Europe GM crops have yet to be adopted due to vociferous anti-GM campaigns. Numerous commentators (e.g. Mannion, 1995a, b and c; Morse, 1995, You *et al*; 1993 and Fox, 1993) in the early1990s drew attention to the potential pros and cons of GM crops. 16 years later it is timely to revisit the controversy. This is especially appropriate in the light of recent (May-July, 2012) protests at Rothamsted Research Station near Harpenden, UK, against the growing of wheat plants engineered to produce a pheromone to repel aphids. This generated several critical articles on GM in the UK press (see for example the article by Joanna Blythman in the *Daily Mail on* 29th May). Several supportive articles also appeared in the scientific media e.g. editorial in *Nature* on May 10th, 2012 which emphasised the necessity of establishing field evidence for GM crop performance and environmental/ecological advantages/disadvantages so as to review the potential of the crop objectively. This plea was reemphasized by Michael Skapinker in the Financial Times on May 31st 2012. The issue was given three columns in the Sunday Times of June 3rd 2012 where Mark Lynas, a former crop vandal, pointed out many of the ambiguous and erroneous beliefs underpinning the supporters of the 'Take the Flour Back' protesters which are often shared by mainstream green movements. Lynas points out that the activities and views of such groups have been more influential than scientific facts in shaping government policy and that this situation is unacceptable.

This discussion paper aims to examine the facts/data surrounding GM crops and to consider whether they have generated agronomic, environmental, economic and social advantages or have resulted in agronomic etc problems. Several reviews have already been published e.g. Ronald (2011) and Barfoot and Brooks (2008) in which the emphasis is generally on socio-economic issues, while that of Lemaux (2008) adopts an environmental approach. This paper adopts an all-encompassing approach in a timely review for the geography and sustainable development literatures due to the spatial variability of GM crops in the developed and developing worlds and subsistent versus commercial agriculture, and in view of the considerable body of data now available which was obtained in the field rather than under experimental field and laboratory conditions. It is also timely in view of the challenge faced by world agriculture, notably a rapidly increasing population in a warming and uncertain world (see Fedoroff, 2010, Fedoroff *et al.,* 2010, Beddington (2010) for the Royal Society (UK), Government Office for Science (UK) (2011) and Godfray *et al* (2010)). Given such pressures some commentators, e.g. Bruce (2012) and Ronald (2011) have already called for (regulated) GM crops to be considered as integral components in strategies for sustainable agriculture. Moreover, can any conclusions be drawn from this and other reviews which might assist policy makers and politicians given that world population is projected to increase from 6.7 billion in 2010 to between 9.1 to 9.3 billion in 2050 (Population Reference Bureau, 2011 and United Nations, 2009) and 15 billion by 2100 (UNFPA, 2011).

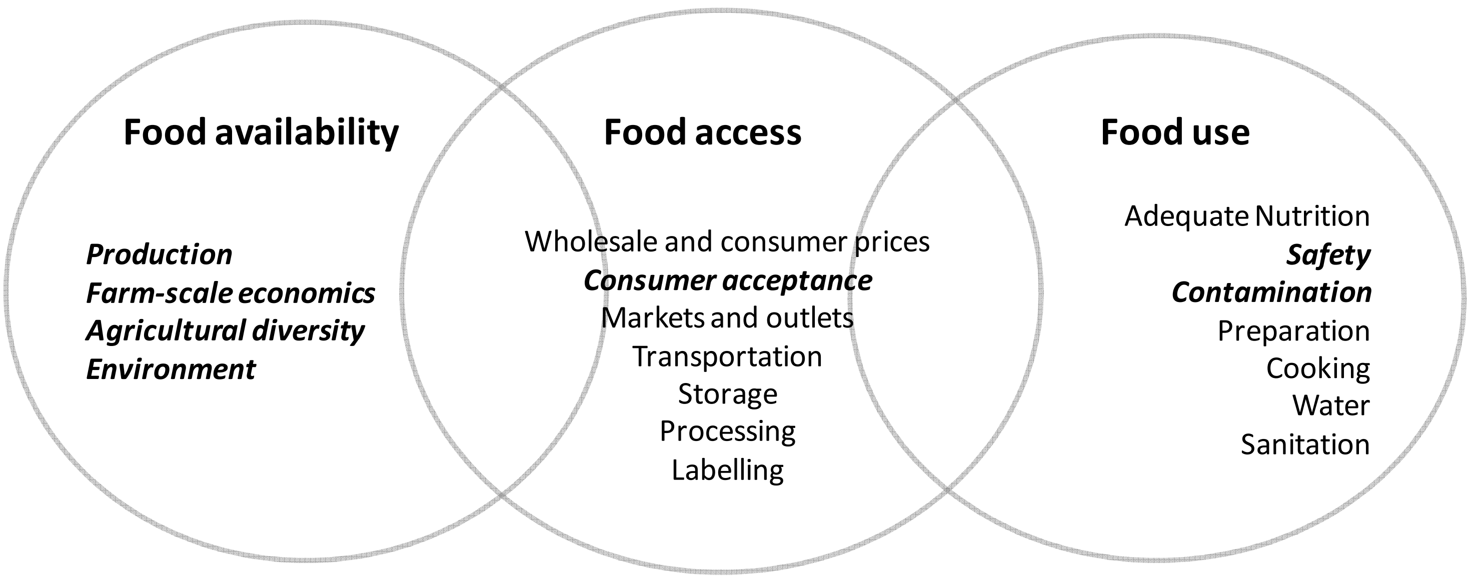
The irony, of course, is that this is an issue that has been recognized for decades and indeed has a history dating back to the 1798-1826 work of Thomas Malthus and his representation of the links between food and population. It is certainly the case that much resource has been dedicated to the science of agricultural production as well as its economics, trade and distribution (Buhler *et al*., 2002). Many countries established a network of publically-funded national agricultural research stations (NARS) and there is a well-established network of international research centres (the CGIAR network; www.cgiar.org). The private sector has also been active and has helped generate new labour-saving and effective machinery as well as inputs such as fertilizers and pesticides. Much effort has gone into the breeding of new varieties of plants and new strains of animals, and this predates by many years the pioneering work of Gregor Mendel (1822-1884) on pea hybridization. Mendel may have discovered the Laws of Inheritance but earlier generations of farmers had been selecting plants with desired characteristics and deriving not only new varieties but also new crop plants. A particularly marked peak in recent times was the 'Green Revolution' programme between the 1940s and late 1970s in Asia and Africa. Many of the new crop varieties of wheat, rice and maize were bred to maximise yield and respond well to fertilizers and irrigation (Lipton and Longhurst, 2011). However since the 1980s it has to be said that the importance of agriculture has diminished in the eyes of many funding agencies largely on the grounds that production was no longer regarded as an issue and the agenda moved towards protecting and enhancing the environment (the Rio Earth Summit took place in 1992), the need for good governance and many other issues they perceived as pressing. Until the late 1990s it was even suggested that agricultural research may have had little positive impact in regions of the developing world, especially Africa (Oehmke and Crawford, 1996). Agriculture, having been in the research doldrums for much of the last three decades, is once again avant-guard as governments' debate and plan their response, even if the agenda has been reformulated as food security rather than agricultural production. The 1996 World Food Summit in Rome defined food security as existing "*when all people at all times have access to sufficient, safe, nutritious food to maintain a healthy and active life*". There are at least three broad elements to this:

1. **Availability of food on a consistent basis. This is related to the production theme noted above. Without adequate and sustainable production food will not be available.**
2. **Access to food. This is a function of factors such as price, distribution and processing, which are in turn related to production but also to more intangible influences such as geopolitics and the complex considerations of world trade.**
3. **Appropriate use. Even if food is accessible it still needs to be consumed in an appropriate manner to reap benefits. This is related to an awareness of adequate nutritional requirements, but is also influenced by access to clean water and sanitation.**

These three pillars, along with some examples of topics within each of them, are shown in Figure 1. 'Access' is taken to be the linchpin spanning the other two pillars, but that is not meant to imply that it is more important; all pillars are equally important and interdependent within the concept of food security. Adequate production is not in itself a guarantee of food security. Underpinning the above list is the provision of enhanced supplies of safe food which is a function of production and distribution. In the 21st century and at a global scale this debate must include GM crops. A further interesting feature of the GM literature has been its tendency to focus on but a few parts of food security, most notably the 'availability' side of Figure 1. In the views of the authors there has been much less research exploring the impacts of GM crops in terms of 'access' (with a notable exception) and 'use' as will be discussed.

Figure 1. GM crops and food security.

The three circles are the pillars of food security and within each of them are some examples of topics that are relevant. The three pillars overlap, although that has been set out here with 'access' as the linchpin. Thus adequate nutrition, a 'use' topic, will depend upon agricultural diversity, an 'availability' topic, but this is mediated via access. The text in bold-italics are the topics that, in the view of the authors, have received most attention in the literature exploring the socio-economic impacts of GM crops. Note how the emphasis is biased towards the left hand side of the diagram with only a few topics receiving much attention under 'access' and 'use'.



Clearly, providing adequate food supplies for an additional c. 37 per cent or c.1.5 billion people is a major challenge. While there are some parallels with the so-called 'Green Revolution' of the 1940s-1970s the world in 2012 is very different and will be vastly different again in 2050. The reasons for such significant change are:

- **Climatic change: the impact of global warming will vary in intensity and spatially but it is likely that all agricultural systems will need to adjust to altered water availability and changes in length of growing season. If global net primary productivity continues to be reduced as droughts increase, as Zhao and Running (2010) report for the period 2000-2009, the enhancement of food supplies will be increasingly difficult.**
- **There will almost certainly be an expansion of agriculture at the expense of remaining natural and semi-natural ecosystems which will decrease global sustainability especially through the loss of carbon storage.**

- **Continued dietary changes in industrialising emergent nations will increase demands for meat and dairy products which are energy and water intensive.**
- **Continued population growth is likely to result in increased poverty and greater divides between rich and poor. This is most likely to occur in Africa as Sánchez (2010) has indicated.**

Other factors which should be considered include the impact of crop production on carbon dynamics; for example Wise *et al* (2009) have shown that increased crop yields per unit area decrease greenhouse gas emissions on a scale similar to that achieved by wind and solar energy. Furthermore Burney *et al* (2010) have shown that greenhouse gas emissions from intensive agriculture are negated by land/ecosystem conservation, i.e. the intact soils of forests, savannas etc act as carbon stores but on ploughing these soils become carbon sources. Moreover, carbon storage is best under no-tillage conditions to which many GM crops are suited. Thus the question arises as to the role of GM crops in future agriculture. Can they contribute to increased productivity or are they too risky? What are their disadvantages and are they outweighed by the advantages. These are the major issues debated in this discussion paper; comments and conclusions are drawn on the basis of evidence from GM-crop production between 1996 and 2012. However, it is important to note that a true and clear examination is constrained by misused and poorly-reported data as highlighted by Morse *et al*. (2012) in relation to economic advantages. Other commentators have also reported on distortions e.g. Waltz (2009) has noted problems of reporting potential adverse impacts of GM crops on organisms; there is also an unwritten belief that it is easier to have work relating to adverse impacts rather than positive outcomes published. By definition, any controversial subject attracts divergent and sometimes confusing opinions as illustrated by Bagla's (2010) paper in the journal *Science* which reports resistance to Bt cotton in pink bollworms as found by Monsanto but which is disputed by other researchers.

It is also timely to note that GM technology is one of many technologies developed since humans began to domesticate the carbon cycle (Mannion, 1995 and 2006) and especially since crop growing began c. 12,000 years ago. Plant breeding is one such technology but soil preparation, water management including irrigation, natural and artificial fertilizer use, and pest management have been developed over the millennia. The introduction of one technology to an agricultural system results in adjustments within the existing components which makes disentangling the impacts and/or reactions of the various components difficult. Nevertheless it is enlightening to consider the socio-economic impacts of GM not just in terms of differences with a notional 'non-GM' place but how they relate to other agricultural technologies. How are the impacts of GM different from what has been seen before? This will also be considered below. These may appear to be simple questions but the answers are far from being simple; indeed the story is still unfolding. Also, of course, any answers can always be dismissed by some as being based upon selective evidence, and it is worth bearing in mind that GM crops are a highly contested technology. Thus it is necessary to state at the outset that this review has not been prompted or funded by any of the protagonists in the GM debate. The intention is to present some of the evidence to the reader, inevitably in a paper this size it is simply not possible to present all of it, and encourage those interested to delve deeper

BACKGROUND

How productive arable agricultural systems are is reliant on the manipulation of crops their environment, i.e the creation of conditions so that crop plants receive good supplies of nutrients, water and light. Traditional plant breeding involving cross breeding between individuals of a species or its close relatives to produce hybrids while soil preparation, weed, insect and disease control and water management are all employed to maximise crop production. Hence a particular genotype (the genes within a plant) will interact with the environment in which the plant is grown. If the combination is just 'right', for example the plant may have genes that allow it to maximise the use of added fertilizer and if that fertilizer is provided, then the yield will be at its maximum. If the same variety is planted without added fertilizer then its yield may be very low; the genes confer no yield advantage whatsoever. This is what plant breeders refer to as the Genotype - Environment interaction, or G X E for short. GM provides an opportunity to address any limitations inherent within crops and to enhance their capacity to overcome environmental limitations by manipulating crop genetic makeup i.e. this is direct manipulation at the molecular level which bypasses time-intensive and expensive conventional breeding. It is also a more targeted approach compared to the production of varieties followed by extensive selection, and it facilitates the inclusion of genetic material from a variety of sources, including non-plant sources, as well as from the same species and its close relatives. The specific techniques that allow scientists to identify desirable genes and to transfer them into a plant need not be covered here. Needless to say that this ability to transfer single genes rather than the many thousands that are transferred during natural processes of sexual reproduction offers a distinct advantage. However, it is important to note that this transfer of a gene into a plant is just part of the story as it has to 'work' (be expressed) within its new home in order for a desired characteristic to be seen. Indeed the irony is that GM crops are no different from their non-GM counterparts in terms of these fundamentals. The G X E consideration remains true for GM crops and there is still a need to make sure that any new genes, from whatever the source, are placed within a genetic 'background' that confers the characteristics that farmers want. Hence the GM technology is not a replacement for many of the tasks that plant breeders have to employ. It helps shortcut some of this, and this shortening of time scale is important, but it does not mean that plant breeders are no longer required.

So what has caused the fuss with GM crops? It is not the technology per se. After all, GM techniques can be just as readily employed to isolate a particular gene in maize (to confer resistance to pests for example) and to insert it into other maize varieties that lack that gene. Admittedly it is unlikely that a plant scientist would opt to use GM tools as conventional methods of sexual reproduction would be perfectly adequate and a lot cheaper, but the fact remains that GM techniques could be used. If GM technology was limited to such intra-species (within species) transfer of genes then it is unlikely that it would have ever been controversial. Indeed it is unlikely that many people would even have heard about it. Thus it is not the technology *per se* that has prompted the debate but the chosen target. In reality GM techniques have been employed to transfer genes between species rather than within them, and it is the possibility of introducing genes alien to the crop i.e. from bacteria, insects or fish, that is one of the major reasons for controversy. It is the products of using GM that are the issue for many critics and not GM *per se*. However, this might seem odd on first consideration. After all, what is the point of using genes from different species? Could there be enough genetic diversity within a species to allow the conferring of characteristics that are desired? The answer to the latter is firstly that many crops have lost much of their genetic diversity during the long process of domestication by humans. Farmers want certain characteristics and they also want homogeneity. Hence the desired genes may not necessarily be available in the crop germplasm, although there may be closely related plant species, perhaps even the wild ancestors of the crop, where genes for desired characteristics may exist. Secondly it may be the case that genes for the desired traits (characteristics) are known to exist in other plant species or indeed elsewhere such as within micro-organisms. Given that all genes in life on Earth are made from basically the same chemicals then there is no obvious reason why they cannot function when transferred from one species to another. Indeed genes can even be made in the laboratory and in theory it is possible to back-engineer a gene from the desired characteristics. This is what some refer to as 'synthetic biology' (Benner and Sismour, 2005). However, while the science may be 'doable' there is something deeply disturbing for some people about this notion that 'natural' species barriers can be broken. Indeed it is not just a matter of it being disturbing in an ethical sense, as important as that is for some, but also because of the unknowns that may result. After all, ecosystems, even artificial ones, are complex and history is replete with examples of human interventions causing unintended and immense damage. People have suffered as a result of this. Indeed even at the cellular level the knowledge that exists of how genes 'work' (or expressed) is incomplete and many gaps exist. Hence there can be no guarantees from plant breeders that a variety produced by GM methods will have absolutely no negative impacts on human health or the environment. Lawsuits would result if such cast iron guarantees were provided and then subsequently a problem emerged. Hence while a plant breeder may be confident that no problems will emerge from the introduction of a GM variety there is always some uncertainty, and 99.9% confidence is not the same as 100%. This difference can be exploited, of course, by critics as they know that no scientist can give a 100% assurance. Interestingly it is much the same for non-GM varieties. The only difference being in terms of how close to 100% the breeder can achieve. With GM varieties the confidence is not as close to 100% as it is with non-GM varieties. In the early 1990s the potential of GM prompted commentators to refer to the possibilities of creating designer or bespoke crops while others predicted the production of 'frankenfoods'. How far these possibilities have been realised will be considered herein. The traits pinpointed for enhancement are shown in Table 1.

BASIC PRODUCTIVITY i.e. increased production of sugar or starch
RIPENING CONTROL
DISEASE RESISTANCE
INSECT RESISTANCE
HERBICIDE RESISTANCE to facilitate weed control
PLANT ARCHITECTURE
DROUGHT TOLERANCE
FROST TOLERANCE
SALT TOLERANCE
PRODUCTION OF SPECIALITY SUBSTANCES e.g. pharmaceuticals, vitamins

Table 1. Potential targets for the genetic manipulation of crop plants.

The first GM crop was produced by Calgene and approved for marketing by the US Food and Drug Administration (FDA) in 1994. This was the Flavr Savr tomato (see Martineau, 2001 for a history), a tomato genetically modified to alter ripening so that fruits could remain longer on the vine to intensify their flavour prior to harvesting. This is in contrast to their non-GM counterparts which were harvested while green and ripened using ethylene whilst in transit. Production of the the Flavr Savr tomato ceased in 1999 having achieved only limited success, partly because of opposition by anti-GM groups but not because of any adverse environmental impacts or human health impairment.

Rank	Country	Area (10^6ha)	Biotech Crops
1*	USA*	69.5	Soybean, maize, cotton, canola, squash, papaya, alfalfa, sugarbeet
2*	Brazil*	36.6	Soybean, maize, cotton
3*	Argentina*	23.9	Soybean, maize, cotton
4*	Canada*	11.6	Canola, maize, soybean, sugar beet
5*	India*	10.8	Cotton
6*	China*	4.0	Cotton, tomato, poplar, petunia, papaya, sweet pepper
7*	Paraguay*	3.4	Soybean, maize, cotton
8*	South Africa	2.9	Cotton, maize, soybean
9*	Pakistan*	2.8	Cotton
10*	Uruguay*	1.4	Soybean, maize
11*	Bolivia*	1.0	Soybean
12*	Philippines	0.8	Maize
13*	Australia*	0.7	Cotton, canola
14*	Burkino Faso	0.3	Cotton
15	Myanmar	0.3	Cotton
16*	Mexico	0.2	Cotton, soybean
17*	Spain	0.1	Maize
18	Chile	<0.1	Maize, soybean, canola
19	Colombia	<0.1	Cotton
20	Honduras	<0.1	Maize
21	Sudan	<0.1	Cotton
22	Portugal	<0.1	Maize
23	Czech Republic	<0.1	Maize
24	Cuba	<0.1	Maize
25	Egypt	<0.1	Maize
26	Costa Rica	<0.1	Cotton, soybean
27	Romania	<0.1	Maize
28	Slovakia	<0.1	Maize

*regarded as the major producers

Table 2. Global Area of Biotech Crops in 2010: by Country (based on James, 2012).

In the intervening years numerous crop plants have been genetically modified to achieve a range of characteristics as documented in the inventory compiled by Copping (2010). Examples include papaya with resistance to ring spot virus, delayed ripening in cantaloupe melon, bananas with resistance to *Xanthomonas musacearum* or BXW, a wilt-causing bacterium, and enhanced vitamin A production in rice (Golden rice). However, in terms of area and value, GM cereal crops, notably maize, rape (canola), and soybean, plus cotton are the most important. All were first grown commercially in 1995/6; in 2005 c.90 million ha were planted with GM crops and by 2012 the area had increased to 170 million ha in 30 countries (James, 2012). James (2012) states "2012 marked an unprecedented 100-fold increase in biotech crop hectarage from 1.7 million hectares in 1996 to 170 million hectares in 2012 – this makes biotech crops the fastest adopted crop technology in recent history". The most significant producers are given in Table 2 which shows that the USA is the major producer followed by Argentina and Brazil; the latter has increased its GM-growing area by a huge 21 per cent between 2011 and 2012 (James, 2012). The absence of European nations as significant GM crop producers is notable and a reflection of anti-GM sentiment by activists and the influence such groups have had on government policy. As James (2012) states "Five EU countries planted a record 129,071 hectares of biotech Bt maize, up 13% from 2011. Spain led the EU with 116,307 hectares of Bt maize, up 20% from 2011 with a record 30% adoption rate in 2012". In addition, few African nations are listed because of European fears and concern about losing European markets. These and related issues have been examined by Kershen (2010). The most widely adopted crops are those which are herbicide tolerant, especially glyphosate tolerant (see review by Dill *et al*., 2008) as this is a relatively cheap and effective means of weed control. In relation to global crop production, Table 3 shows that GM soybean has been particularly successful and it now occupies c.50 per cent of the total area on which soybean is grown.

GM CROP	AREA PLANTED Million ha	Percentage of Global Area
Soybean	73.3	50
Cotton	21.0	14
Maize	46.8	31
Rape (Canola)	7.0	5

Table 3. The extent of major GM crops in relation to global production in 2010 (based on James, 2010).

The GM traits which are now most widespread are: herbicide tolerance, insect resistance, virus resistance, and delayed ripening. In addition, some crops have been engineered to exhibit more than one trait and are characterised by so-called gene stacking; crops are now available with three engineered traits. One such example is SmartStax maize produced by Monsanto and Dow Agrosciences. This has three GM attributes: protection against above-ground insect pests such as corn earworm, European corn borer, southwestern corn borer, sugar cane borer, fall armyworm, western bean cutworm and black cutworm, protection against below-ground insect pests such as Western, Northern and Mexican corn rootworms, and herbicide tolerance which facilitates broad spectrum weed and grass control (Monsanto, 2009a). This new variety was approved for use in the USA and elsewhere in 2009 and combines traits which were originally engineered individually.

ADVANTAGES AND DISADVANTAGES

As referred to above there are claims and counter claims with regard to the advantages and disadvantages of GM crops and here it is only possible to highlight some of them. Indeed the picture is rapidly changing as practical experiences with the growing GM varieties expands both spatially and temporally. Some claims are based on the actual track record of GM crops, some are based on experimental laboratory and field results, and others are purely speculative. They can be considered in four categories: agronomic issues, environmental issues and economic and social issues though there is some overlap; for example, GM pest resistance confers an economic advantage as production per unit area is increased through a reduction in field losses and there are financial gains as less pesticide is required. The latter also reduces environmental impact and may improve farmer/farm worker health. Another but often overlooked fact is the capacity of GM crops to reduce variability of production and related income year on year, a characteristic which confers stability to farm incomes and facilitates planning. Moreover, additional income can have ramifications in a social context e.g. investment in schooling for children. These are discussed in the sections below.

AGRONOMIC IMPACTS

As stated above, the major objective of GM technology is to improve productivity. However, to date no crops have been engineered to increase productivity and the gains per unit area have largely come from reduced losses as competitors/predators (i.e. weeds, viruses, fungi, insects) have been reduced. Data from many sources indicate that gains have been made in both developing and developed countries and in commercial and subsistent agricultural systems. For example James (2010) cites increases in cotton productivity for resource-poor farmers in India, China and South Africa of 31 per cent, 9.6 per cent and 11 per cent respectively when compared with cotton production by farmers growing non-GM cotton; such gains indicate that in all cases losses through bollworm attack were substantially reduced. Additional gains for GM-cotton farmers in India and China include reduced pesticide use and enhanced income, as shown in Table 4.

COUNTRY	YIELD INCREASE Due to reduced loses	PESTICIDE REDUCTION	FINANCIAL GAIN $/Ha
India	31%	39%	257
China	8%-10%	60%	224

Table 4. Data on resource-poor cotton farms growing Bt cotton in India and China in 2008 (based on PG Economics, 2010).

Morse and Mannion (2009) have identified similar trends in resource-poor cotton farmer communities in South Africa where the benefits have led to the adoption of GM cotton by smallholders in South Africa and elsewhere in Sub-Saharan Africa (Hillocks, 2009). Resource-poor farmers growing Bt maize in South Africa and the Philippines have reaped similar benefits (James, 2010). However, these are snapshots rather than a global view which is much more difficult to achieve, as illustrated by Finger *et al*. (2011) who have reviewed yield benefits of GM crops from a variety of countries. They record a spatial skew in published studies toward some developing countries, notably India, China and

South Africa, which increases their representation within a meta-analysis of GM versus non-GM yield differences compared to the globally more important crop producing countries. Moreover, there are difficulties in making generalisations when primary data sources have been compiled using different methodologies and with different objectives (see Morse *et al.,* 2012 for a discussion). Of especial note is the difficulty of extrapolating long term trends from limited data and there is regularly apparent conflicting 'evidence' reported in the press. For example, some observers, commenting mainly in newspaper articles, have indicated a drop in productivity with some GM crops; such claims have been refuted by Monsanto (2009b), as might be expected. In contrast, peer-reviewed published literature indicates, indeed sometimes concedes, that GM crop output per unit area is generally greater than non GM output across a range of crops with GM varieties (Finger *et al*., 2011). Clearly, this is positive.

CROP	Increased yield 1996-2006 Million tonnes	2006 production increase Million tonnes	Improved yields in 2006
Soybean	55.3	11.6	20%
Maize (corn)	47.1	9.7	7%
Cotton	4.9	1.4	15%
Canola (rape)	3.2	0.2	3%

Table 5. The volumes added to global soybean, maize, cotton and canola crop outputs through the use of GM varieties for the period 1996-2006 and yield improvements for 2006 as compared with yields from non-GM crops (PG Economics, 2009).

Moreover, increased productivity has been identified by PG Economics Ltd (2009) for GM crops for the period 1996-2006 and for 2006, as shown in Table 5. For example in 2006 comparisons between GM and non-GM varieties of soybean, cotton and maize indicate that increases in productivity of 20 per cent, 15 per cent and 7 per cent respectively. Such results are encouraging given PG Economics statement that "the evidence presented derives from peer reviewed scientific journal articles and is representative of real impacts at the commercial and subsistence farm level". The increased productivity for soybean and cotton are especially encouraging. Most increases are the result of pest reduction which curtails field losses and a further advantage has emerged in soybean production areas in Argentina and Paraguay where it has been possible to adopt 'no-tillage' cultivation i.e. direct seed drilling combined with fertilizer application instead of ploughing. This is advantageous because soil erosion is curtailed, water and energy are conserved and carbon storage in the soil is maintained. Such practice has reduced the overall production cycle for soybean to such an extent that land used for wheat production can now be double cropped with soybean.

Hutchison *et al.* (2010) have examined production and economic data for commercial maize production in the corn (maize) belt of the USA where the predominant pest is the European corn borer (*Ostrinia nubilalis*; Lepidoptera). Five states achieved economic gains of $6.8 billion of which $2.5 billion derives from Bt maize (i.e. maize engineered with genes from the bacterium *Bacillus thuringiensis*) and $4.3 billion to non-Bt maize. The substantial increase in the latter is attributed to the so-called 'halo effect' of the Bt crops (for further discussion see Tabashnik, 2010); this means that the insect control extends beyond the Bt crop itself into neighbouring fields of non-Bt crops because of reduced pest populations. Other factors which contribute to the success or otherwise of Bt crops involves management, especially the value of refugia i.e. islands/patches of non Bt crop within the Bt crop, and the cheaper price of non Bt maize at c.30 per cent less than the modified variety.

GM crop varieties with modifications to cope with environmental stress e.g. drought, salty soils are only now close to being released commercially so it is not possible to judge their potential commercial success. As Cominelli and Tonelli (2010) have highlighted, the genetic mechanisms of plants which deal with abiotic stresses are complex; traits for drought tolerance, drought avoidance and salt tolerance are being researched. Monsanto, for example, has produced a drought-resistant maize which is engineered with a gene from the bacterium *Bacillus subtilis.* Experiments indicate a yield increase of between six and ten per cent and the variety is expected to be available commercially in 2012 (for further discussion Service, 2009 and Gilbert, 2010). Research on the development of GM salt-tolerant crops is also underway as Li *et al.* (2010) have reported in relation to maize. Experimental plots of the GM variety showed improved yields in comparison with conventional varieties and would allow cropping on land with soils salinized through poorly managed irrigation. However, the drawback of both drought- and salt-tolerant crops is their potential to encourage the expansion of cropping into areas of remaining natural ecosystems.

ENVIRONMENTAL AND ECOLOGICAL IMPACTS

Although the most significant advantage of GM crops so far grown commercially is increased yield per unit area due to reduced losses there are other advantages in relation to the environment. There are also real and potential disadvantages. Reduced pesticide use in the case of insect resistant crops is a major gain. This and direct drilling affect the carbon footprints of cropping systems. In addition there are issues relating to the development of resistance by weeds and insects to engineered herbicide and insecticide traits in crop plants, as might occur in relation to chemical herbicides and insecticides, the potential for modified genes to spread into wild relatives which then become pests, and detrimental impacts on beneficial organisms especially insects. As pointed out in the section above, the development of crops with resistance to environmental stresses may lead to encroachment on existing natural ecosystems which are currently considered marginal for arable agriculture.

In relation to pesticide use, Barfoot and Brooks (2008) have shown that major gains have been made in terms of quantity used, environmental benefits and cost savings. Their data, for 1996-2006, are given in Table 6. This shows that pesticide use for all major GM crops has declined substantially with a parallel decline in the Environmental Impact Quotient (EIQ). The EIQ is a model which reduces data on environmental impact to a single value; it combines information on the three main components in agricultural systems: farm worker, consumer, ecological impact. As Table 6 shows the greatest gains were for herbicide tolerant soybeans. Barfoot and Brooks state that this was particularly important in the USA and Argentina and for GM herbicide tolerant canola (rape) in Canada. Such data are important for the protagonists of GM herbicide tolerance because scenarios of increased herbicide use have been presented as a deterrent and this has clearly not occurred. Notwithstanding it is true to say that the herbicide, predominantly glyphosate, is marketed by only one company (Monsanto) which also produces the GM seed and there are concerns about the operation of a monopoly in such an important area of food production. Substantial reductions in pesticide use have also been reported for GM insect resistant maize, notably in Canada, South Africa and Spain, as well as insect resistant cotton, notably in China, Australia and the USA.

TRAIT	Change in volume of active ingredient used (million kg)	Change in field EIQ impact (in terms of million field EIQ/ha units)
HT soybeans	-62.4	-5536
HT maize (corn)	-46.7	-1172
HT cotton	-32.1	-616
HT canola	-7.9	-372
IR maize (corn)	-8.2	-452
IR cotton	-128.4	-5628
TOTALS	-285.7	-13776

HT: Herbicide tolerance IR: Insect resistance EIQ: Environmental Impact Quotient

Table 6. Data on pesticide reduction in GM crops 1996-2006 (based on data in Barfoot and Brooks, 2008).

Barfoot and Brooks (2008) also looked at the EIQs and found that the difference between developed and developing countries was quite small i.e -6610 and -7166 respectively. An additional beneficial affect has been a shift to the herbicide glyphosate which is more environmentally benign than the alternatives atrazine andr metolachlor. The latter are environmentally mobile and contaminate groundwater, and may have adverse toxicological effects on aquatic organisms. The shift has been especially noteworthy in the USA (Rivard, 2003). In addition, Livermore and Turner (2009) report that in the USA there has been an annual reduction of some 27,000 tonnes of active pesticide ingredient between 1996 and 2006.

If pesticide use is reduced there is a reduced input of fossil fuels and so the carbon footprint declines. The adoption of no-tillage methods also save energy as the use of farm machinery diminishes and it encourages carbon sequestration in soils. Barfoot and Brooks (2008) note that in 2006 fuel reduction due to GM crop cultivation resulted in saving carbon dioxide emissions of 1215 x 10^6 Kg; this is approximately equivalent to taking 540,000 cars off the roads while they estimate that a further 13.5 x 10^9 Kg of carbon dioxide was saved through sequestration in the soil which is equivalent to removing six million cars from the roads.

These are undoubtedly positive impacts of GM crops (see also Knox *et al.*2012). However, the longer term prospects may not be as positive due mainly to the potential for the development of resistance to herbicides, especially glyphosate, and insecticides in weed and insect pests respectively. Such resistance to conventional pesticides has already been documented. For example, there is evidence for resistance in diamondback moth *(Plutella xylostella),* a major pest of cruciferous vegetables (cabbage, broccoli, cauliflower etc.), to conventional Bt pesticides (Tabashnik *et al.* 2000 and 2003). Owen (2009) states that globally 13 weed species are known to be glyphosate resistant; nine of these occur in the USA and include two species of *Conyza*, compositae, and two species of *Lolium* which are grasses (Powles, 2008a and b). If resistance develops, the gains due to the cropping of GM varieties will be relatively short lived. This means that there will be limited returns for the considerable investment made for GM crop development and the issue of adequate food production will require further solutions none of which will be quick or easy. Consequently, crop management to limit the spread of resistance is a major concern of farmers especially in North America (Harrington *et al.* 2009) and much hinges on the use of refugia (see below). On a positive note the 'halo' effect of planting insect-resistant GM crops is heartening. For example, Wu *et al.* (2009) report advantageous repercussions of the planting of Bt cotton on 3 million hectares of cotton amidst 22 million hectares of maize, peanuts, soybeans and vegetables in China which has reduced bollworm (*Helicoverpa armigera*) populations on other host crops, a factor which will affect, and reduce, subsequent insecticide applications.

Good management is an essential means of limiting the development of resistance in insects to insect resistant Bt crops, notably through the incorporation of refugia within the GM-cropped area. Refugia comprise areas planted with conventional non-GM crops, the objective being that populations on insects with no or very little resistance to Btinsect-resistant crop genes will survive and reproduce to produce offspring which will dilute the potential for resistance of the insect population by interbreeding with those surviving within the GM crop (see reviews by Raymond and Wright, 2009, and Tabashnik and Carrière, 2009). Each GM crop should have its own refuge strategy in terms of size and distribution and will vary between crops with single modified or stacked multiple modified genes. Despite prescribed management techniques, which often comprise c.20 per cent of the cropped area, the first case of insect resistance was reported in 2008 (Tabashnik *et al.,* 2008) from the US states of Mississippi and Arkansas where the bollworm *Helicoverpa zea* is a major pest. This is a concern and the use of refugia is, in general, a cause for concern. It may be straightforward to implement in large commercial agribusinesses in the developed world but where farming is small-scale and/or subsistence it requires outreach education programmes which are not always available or effective.

Herbicide tolerance also requires management as discussed by Owen (2009). As stated above GM herbicide tolerance has been engineered mainly in relation to glyphosate; indeed c.90 per cent of Ht crops have modified genes conferring resistance to glyphosate and they include some of the world's major crops i.e. soybean, cotton, maize and canola (rape) which, as Table 2 shows, are grown on millions of hectares in the USA, Canada, Argentina and Brazil. If resistance occurs and becomes widespread the ramifications for financial losses and global food supplies are considerable. Such large scale reliance for food on a small range of crop varieties is worrying and there are parallels with reliance on phosphates which are essential imports in many regions but which have limited sources. There is evidence that rates of resistance are increasing as Owen (2009) notes that between 2004 and 2008 six new species of weeds with glyphosate-resistant genes were recorded in the USA. In view of the vast increase in glyphosate use in the last two decades this development is unsurprising and more might have been expected given the intense selection pressure. Moreover, how the resistance developed needs to be addressed. Did a significant proportion of a weed's population with natural resistance survive to confer advantage on their progeny? Did cross breeding between GM crops and their wild relatives occur? Or have transfers occurs between related weed populations?

All populations are characterised by variations in the degree of tolerance/resistance to particular herbicides so any weed population will have individual plants with herbicide tolerance. Over generations natural selection will favour such plants due to 'survival of the fittest' so that the population of plants with resistance to the regularly-used herbicide will increase. This may be accelerated if management is lax. For example, if less than recommended quantities are applied the outcome will not achieve any saving as it will generate an increased population of resistant weeds; or if farmers apply higher than recommended doses resistant mutants will be favoured and they, in turn, will be best suited to passing on those genes. Herbicide-tolerant GM crops will be no less susceptible to this process as non-GM crops (see Powles, 2008a and b). It is highly likely that the increasing use of glyphosate and glyphosate-resistant crops will accelerate the development and spread of resistance. In Europe the situation can best be described as precarious as EU regulations about pesticides, including herbicides, have been tightened. This makes the discovery and registration of new pesticides very difficult so glyphosate is likely to remain a major herbicide and thus increase the pressure for the development of resistance in weed populations even if GM herbicide-tolerant varieties continue to be ostracised. This issue has been discussed by Dewar (2010) in relation to glyphosate-resistant maize.

The possible development of ‘superweeds’ i.e. weeds with herbicide resistance, and so-called to generate anti-GM sentiment, has also been examined by Owen (2009) and Owen *et al.* (2011). This hinges on gene transfer between crops and their wild relatives and is especially important in agriculture since many staple crops are grasses as are many weed species. There is established evidence for gene flow between cultivated plants and their wild relatives (see Ellstand, 2003, for comments). Gene transfers between the chief glyphosate-resistant GM crops (Owen, 2008; Mallory-Smith and Zapiola, 2008) and weedy relatives have occurred in some GM crops e.g. canola (oilseed rape) and maize (corn). This makes weed management more difficult and increases the expense of crop production. A further aspect of gene transfer is the likelihood of exchanges between GM crops and their traditionally-bred counterparts. Actual examples have been cited by Legere (2005) who refers to the discovery of genes for both glyphosate and glufosinate herbicide resistance in non-GM canola (rape seed). This has implications for the juxtaposition of GM crop and non-GM crop cultivation and is especially significant in relation to organic farming which excludes the cultivation of GM varieties and the use of pesticides. To ensure that no contamination occurs between the two necessitates the presence of an intervening buffer zone and its management which, in turn, requires co-operation between farmers. Additional precautions include the staggering of planting dates, and the use of crop varieties with differently-timed life cycles, notably different maturity dates, as discussed by Dlugosch and Whitten (2008). However, there is an irony associated with the exclusion of GM crop varieties from organic farming systems in that some, notably insect-resistant crop varieties, eliminate pesticide use and so could contribute substantially to yield increases (see discussion in Ronald and Adamchak, 2008).

There is also the possibility that GM crop species could themselves become weeds, as Gilbert (2010) has reported based on information presented at a conference of the Ecological Society of America in August 2010. An examination of traits from canola obtained from 288 sites in North Dakota, USA, by researchers from the University of Kansas, revealed that c.80 per cent had one GM trait Approximately 50 per cent were resistant to Monsanto’s herbicide *Roundup* (glyphosate) and the other 50 per cent were resistant to Liberty (the herbicide glyphosinate) a Bayer product. In addition, two individual plants were found to have resistance to both which represents a new, un-engineered trait that developed in the field. The high incidence of ‘feral species’ at widely disparate locations often at considerable distance from fields of GM crops, as well as the new stacked trait, not only reflects inadequate management but also highlights the potential for the spread of modified genes and the relatively rapid development of resistance. However, generalisations are not acceptable as

Warwick *et al.* (2009) have concluded based on their investigation of gene transfer through pollen and seed between crops and their wild relatives; the urge investigations which inform regulatory bodies need to be conducted on a case by case basis. In addition, precautions are necessary during post-harvest activities of transport and processing to ensure that GM and non GM crops are not mixed and thus enable accurate food labelling.

In principle, increased yields from croplands could result in shrinkage of the area of land being used and thus leave land for 'nature' (see comments by Matson and Vitousek, 2006). Although yields have indeed increased (see agronomic gains above) there is no evidence for land being returned to 'nature'. Although no evidence is available for GM crops in particular, Ewers *et al.* (2009) show that where yields of staple crops have increased the land released is put to other economic uses. In many developing countries the released land has been used to grow other crops and in many developed countries little change occurred, possibly because of subsidies. However, some positive trends were noted: where yield increases per unit area were high, forest loss, i.e. loss of remaining natural ecosystems, was reduced. In creased yields due to GM crops might follow a similar pattern.

Concerns have also been expressed about the possible adverse impacts of GM crops on beneficial organisms. This is particularly relevant to GM Bt crops. However, there is little evidence to support this possibility as reflected in, for example, the work of Duan *et al.* (2008) who have re-examined 25 laboratory based studies on honey-bee mortality in Bt crops. Indeed there is some evidence that GM crops might have a beneficial effect on non-target organisms as Marvier *et al* (2007) suggest based on their examination of the results of 42 field experiments; they state that "non-target invertebrates are generally more abundant in Bt cotton and Bt maize fields than in non-transgenic fields managed with insecticides". This was not the case in all the GM fields examined. Another study by Lu *et al.* (2010) involved monitoring the impact of Bt cotton crops for a 10-year period in six provinces of northern China and found that populations of mirid bugs (Heteroptera Miridae) increased in sufficient numbers so as to be considered a serious pest in other regional crops, including vegetables, cereals and fruit, grown by more than 10 million small-scale farmers. Nevertheless China has not banned GM crops. However, in Germany a policy change was brought about when work on laboratory force-feeding trials of ladybirds and daphnia with GM corn variety MON810, designed to combat some lepidopteran pests such as *Ostrinia nubalis* (European corn borer), by Schmidt *et al* (2009) and Bohn *et al* (2008) respectively showed elevated mortality rates for both of these beneficial organisms. This work was a major factor leading to a ban imposed in 2009 on the cultivation of GM corn variety MON810 by the German Federal Office of Consumer Protection and Food Safety. This work has been heavily criticised by Ricroch *et al.* (2010) who conclude that numerous flaws in experimental design undermine substantially the findings of Schmidt *et al* (2009) and Bohn *et al* (2008); Ricroch *et al.* also report that their review of some 41 related studies published in 2008 and 2009 show no or very limited impact of GM corn MON810 on non-target organisms. They urge caution in relation to the emphasis of such selective, and possibly flawed, evidence for policy making and argue that the broad spectrum of research should be considered when government bodies review GM crops for cultivation. The breadth of such research should also be brought to the attention of the media to encourage responsible reporting and to keep the general public well informed.

The studies referred to above are concerned with above ground plant/animal communities and little work on below-ground impacts has been reported, including impacts on fungi and bacteria, or on processes. One exception is that of Powell *et al.* (2009) who undertook a series of field and laboratory-based studies in conventional and glyphosate –tolerant maize and soybean crops in

Ontario, Canada, to examine the biodiversity of soil organisms and on litter decomposition. Their results show that there was an initial but minor alteration in soil biota but that it was short lived. This suggests resilience within the soil system, though long-term monitoring is necessary to test this resilience further. No discernible trends were found in terms of litter decomposition; some reduced decomposition with increased soil organic matter was noted in some plots but not all. Another study by Kapur *et al.* (2010) in India on culturable and non-culturable microbial diversities in soils supporting Bt cotton and non-Bt cotton crops shows that Bt cotton had no discernible adverse impact on soil microbial communities.

ECONOMIC IMPACTS

The economic impacts of GM crops have been addressed recently by a several authors including Qaim (2009), Carpenter (2010) and Finger *et al.* (2011). These reviews conclude that overall that there have been economic advantages for growing GM crops although there is between-country and even within-country variation and problems with the reporting of economic data and the analysis of statistics which makes comparisons difficult (Smale, *et al.*, 2006; Morse *et al.*, in press). Barfoot and Brooks (2008) have detailed socio-economic gains from GM crop use. In overall financial terms GM crops have increased farm incomes by some $33.8 billion for the period 1996-2006, with $6.9 billion being added in 2006. Barfoot and Brooks (2008) estimate that on a per crop basis the increase in producer income up to 2006 varied from 0.13% (herbicide tolerant cotton) to 13.15% for insect resistant cotton. This is not the same as benefits to consumers, of course. The greatest gains in income have been with GM soybean since this has experienced the greatest expansion in terms of acreage and hence economic value. While Barfoot and Brooks (2008) analysis is global they have claimed that that the financial benefits have occurred in both the developed and developing world, with the latter earning 53% of the global income gain in 2006 (Million US$ 3,713), mainly through herbicide-resistant GM soybeans (Million US$ 1,828) and Bt cotton (Million US$ 1,715). In developed countries the income gain was mostly for herbicide-resistant soybeans (Million US$ 1,263) and insect resistant maize (Million US$ 992). This gain in income has occurred despite the increased cost of GM seed over that same period. Further evidence for economic benefit, albeit modest, is reported by Smale *et al* (2006) who reviewed 47 peer-reviewed papers on Bt cotton published since 1996. More recently Carpenter (2010) reviewed the results of 168 studies reported in 49 publications. In the developed world she identified 36 studies which clearly showed a statistically significant increase in yield for GM varieties versus non-GM, while for developing countries the corresponding figure was 88. Thus there was more than double the number of studies showing a significant yield increase for the developing world compared to the developed. In part this is a reflection of the fact that Carpenter reported more studies of GM crops in the developing world (107) compared to the developed (61); a balance in favour of the developing world that some may find surprising.

Thus GM crops can, at least in theory, contribute to the alleviation of poverty in developing countries through increased income for producers as well as addressing persistent problems of hunger (Juma, 2011). The reasons for these increases in producer income will vary from region to region as well as farm to farm (Finger *et al,* 2011), but can be categorized into three key areas. The first is the level of pesticide or herbicide used by farmers being generally reduced with GM crops having a degree of plant resistance relative to non-GM. In India reports have suggested that the level of insecticide being used for a particular type of insect-resistant cotton (Bt cotton) was up to two thirds less than what would normally be used on this crop (Qaim, 2003) although care has to be taken with these results as the research was based upon on-farm trials at 395 locations within seven states in India. The farmers selected were those who were willing to take part and had sufficient money to pay for all of the necessary materials. Hence there was a degree of selection based upon wealth and this raises the question as to whether or not they accurately reflect results that could be produced by poorer farmers. This is an issue that often emerges within published comparisons between GM and non-GM crops. To what extent is this assessing the impact of the technology and/or the skill of the farmer? But this is by no means limited to GM technology; the same could be said of any new technology. Indeed a reduction in the use of pesticide would be expected for any pest-resistant crop variety; whether it be bred via GM or conventional means. With the Bt cotton the reduction in pesticide usage is typically only seen with pesticide applications targeted against bollworm (Lepidopera), and pesticides to control other pests such as those in the Hemiptera (aphids, leafhoppers, cotton stainers etc) typically continue unchanged. In Argentina the reduction in pesticide use with GM crops was less than in India at 50% (Qaim *et al,* 2005). Again care has to be taken in interpreting these results as farmers adopting Bt cotton in Argentina were large-scale farmers who were comparatively better off in terms of finance and available resource than small-scale poorer farmers. Of relevance here is that developing countries are typically located in the tropics where pest pressures tend to be highest (Schemske *et al.,* 2009). Thus crops tend to suffer most from insect attack, especially as farmers may not have access to suitable, affordable and effective pesticides or means of application. How this will play out under conditions of climate change is a matter of much conjecture, and some authors have called for more attention to be placed on this pressing question (Gregory *et al*., 2009). Nonetheless, it is likely that a technology which helps to protect the crop against pest damage, even if from some pests and not others, and which requires no expertise in terms of correct application or indeed labour, would be popular amongst resource-poor farmers in the developing world.

Farmers' perception can also play an important role in the reduction (or not) in the volume of pesticide use and therefore the level of information made available to farmers is essential in decision-making. Whilst early reports following the introduction of Bt cotton in China indicated that savings through reducing the use of pesticide could be achieved, a later report from Pemsl *et al* (2005) suggested that this may not be uniform throughout China. They found that in some regions the volume of pesticide used remained high with as much as 30% directed at the pests targeted by the Bt toxin contained within the plant (i.e. mostly Lepidoptera) itself. Yang *et al.*(2005) report similar findings. Much of this is due to a lack of awareness as to the characteristics of the GM crops, but this is by no means the first time that farmers have proved to be unaware of the characteristics of new varieties and as a result managed them in an inappropriate way. Indeed the notion of 'Integrated Pest Management' which dates back to the 1950s had a combination of reduced insecticide application with the planting of plant resistant varieties as almost an archetypal example of the benefits of 'integration', yet effective adoption of this combination has been 'patchy' (Morse, 2009).

It is certainly the case that the planting of Bt-based varieties of cotton and other crops has been extensive and they now cover significant areas of land. Such an extent of insect resistant plants should place a selection pressure on the pests and encourage the multiplication of genes which allow the plant resistance to be overcome (van Emden, 1999). However there have been few studies which have proven such a response, at least for field populations of pests. Roush (1994) predicted that Bt-based plant resistance may be more effective at delaying the onset of resistance-breakdown compared with Bt sprays and the evidence to date suggests that this is correct. Gassmann *et al* (2011) provide a recent example from the US for such a breakdown in GM-based insect resistance. However, it must be stressed that this is not solely an issue for GM-based resistance as it has been well-documented with resistance bred via conventional (i.e. non GM) means. For a review of one type of non-GM based resistance to insect herbivores please see Jongsma and Bolter (1997). Thus while such a widespread breakdown in GM-based insect resistance would undoubtedly be problematic for farmers it has yet to occur. Indeed the apparent excess of pesticide use noted above for GM-based insect resistant crops has been explained in terms of poor extension information and training, in effect a market failure, rather than a diminution of the resistance. Pemsl *et al* (2005) have argued that it ignored the fact that those employed within the extension organisations were paid on the basis of pesticide sold and therefore they did not have an incentive to reduce pesticide use.

As discussed above, there is considerable global variation in the economic benefits of GM crops. In many countries, notably the USA, Brazil and Argentina the economic benefits have been minimal (but with significant environmental gains), but in others significant economic gains are manifest. Brookes (2005) has reviewed the economic performance of the HT soybean crop in Romania since it was introduced in 1999. Following the fall of communism a decade earlier, Romania's agricultural sector was also undergoing adjustment in relation to technology. HT soybean was adopted in the commercial sector but where weed control was variable, ranging from little herbicide use to as many as four applications per crop season. Brookes found that yield gains overall for HT soybean were considerable and ranged from 0.4t to 1t per ha, an increase of between 16 and 50% (average 31%). This was due to the much improved weed management necessary to combat an accumulated weed seed bank and reduced soybean plant damage due to inappropriate herbicide use. Moreover, the much reduced weed seed contamination in the harvest meant improved economic returns from soy oil producers. Further economic benefits derived from reduced production costs, particularly reduced herbicide costs. Brooks reports cost savings of between 28 and 29%, with average savings of Euro 61.5/ha and Euro 44.4/ha for farms below and above 5000ha respectively.

Economic benefits of GM crops also ensue from yield increases and the revenue they generate; if the price obtained by the farmer per unit of produce remains constant then any increase in yield will clearly generate more revenue. This relationship will vary spatially and temporally as crop outputs, local, regional and international markets and consumer choices change though some generalizations are possible as Carpenter (2010) has shown on the basis of 49 peer-reviewed publications relating to GM crop adoption. The results, from 12 countries (four developed and eight developing countries), show that GM crops, notably insect resistant and herbicide tolerant crops, have benefitted farmers in most cases due to increased yields and other cost savings when compared with conventional crops. Indeed, Carpenter's results show that greater crop yields have been achieved in developing rather than developed nations. In developing countries the average yield increases range from 16% for insect-resistant corn (maize) to 30% for insect-resistant cotton; in developed countries increases ranged from zero for HT cotton to 7% for HT soybean and insect resistant cotton. As noted above, such differences are probably due to relatively poor conventional pest control in developing countries. Carpenter does, however, point out that advantageous variation in 'background' (i.e. unmodified genes) germplasm in GM crops may also be important in improving crop yields. After all GM typically involves the transfer of only a few genes, albeit ones that instill important characteristics, and much can depend upon the vast majority of genes already present. If the variety is relatively poor in terms of desired agronomic characteristics then the few genes being transferred via GM may provide little benefit for the farmers and the GM variety may not produce such positive results (Bennett *et al*., 2005). Those same genes transferred to a variety with 'better background' may be perceived by the farmers as having a much more positive effect. The influence of such 'background' effects on perception of GM by farmers has been relatively under-explored.

Given that revenue is a function of yield and price, and as yield will fluctuate with environmental conditions, then revenue will also fluctuate. In India, for example, there are reports of Bt cotton yields increasing by 80% under high bollworm pressure and between 30 to 40% under moderate bollworm pressure (Qaim, 2003). As pest pressure will vary year on year then the apparent gains of growing an insect-resistant GM variety will also fluctuate. An important distinction must be made here between a theoretical notion of 'yield' i.e. what would be achieved under ideal growing conditions with no limits in place, and what the farmers actually experience. The latter is almost always significantly lower than the former; this is called the 'yield gap' (Lobell *et al*., 2009). GM instilled traits generally help mitigate some of the limits placed on achievement of the ideal yield, but no single trait will address all of the limits or indeed address any one limit in a perfect sense. Hence under conditions where all such limits have been removed it is likely that the GM variety will have an identical yield to a non-GM variety. Indeed it is theoretically possible that the yield of the GM variety may arguably be less than its non-GM counterpart because, for example, the production of insecticidal toxins may impose a metabolic 'cost' to the plant (Koricheva, 2002).

While revenue is important even more so is gross margin (i.e. revenue minus costs). For the GM crops that instill a degree of resistance to insect pests there are the obvious savings on insecticide costs. Ronald (2011) refers to research by the US Department of Agriculture (USDA) on Bt corn (maize) (Fernandez-Cornejo and Caswell 2006) which shows that insecticide use was 8% lower per planted acre for Bt maize when compared with non-Bt maize. Naranjo and Ellsworth (2009) have reported profits of $200 million between 1996 and 2008 in Arizona where Bt cotton is grown in an integrated pest management (IPM) programme and where pesticide applications declined by c.70%. Indirect benefits can equally extend beyond the point of GM use as Hutchison *et al* (2010) have reported for non Bt maize cultivated in the US Mid-West; benefits worth millions of US dollars have accrued to non-GM farmers because of general pest suppression caused by the Bt varieties.

With the HT trait the situation is more complex. Gusta *et al* (2011) have reported economic benefits to farmers of HT canola (rape seed) in western Canada. Here the benefits, due to a combination of reduced costs and increased yields, amounted to between $Can 1.063 billion and 1.192 billion for the 2005-7 period. Farmers also reported that 'spillover 'benefits i.e. the easier and less costly weed control year on year once HT canola had been planted exceeded direct benefits. However, in Argentina costs were reduced in the production of HT soybean but yield did not increase (Pray and Naseem*,* 2007). The cost saving was due to reduced herbicide costs for the GM variety given that the 'total' herbicides used with such varieties tend to be off-patent and thus significantly cheaper than the more selective and expensive alternatives. Thus it is the GM-herbicide combination that brings about an apparent advantage to the farmer and not the GM crop *per se*. Of course, much depends upon what is included as a 'cost'. For farmers in the developed world where there is widespread use of machinery this may be relatively straightforward to estimate but in the developing world where production systems are based upon human and animal labour rather than machinery it may be more complex. Some of the labour may be hired but some may derive from the household or even friends and thus be 'free'. However, given that labour is a scarce commodity there are opportunity costs. Committing labour to crop production can mean it is unavailable for other activities. This trade-off is well reported within the rural development literature where projects have been promoting certain technologies, especially those that place an increased labour demand on households (e.g. Ellis, 1999). With GM crops the link to labour can operate in several conflicting directions. For example it can be 'labour saving' as with the HT varieties, although this may have ramifications within the local economy as labour is displaced. For example, reduction of labour was identified as a problem when

HT cotton was introduced into Western Australia (Russell, 2008). Crop weeding was originally undertaken by male Aborigine workers, but the introduction of HT varieties reduces the need for such workers, creating a loss of income for the neighbourhood. The community was happy with the reduction in the use of pesticide for Bt crops but this was not adequate compensation for loss of work. However, if GM crops increase yield this may create a greater demand for labour at the time of harvest. The latter has been noted, for example, with Bt cotton in South Africa (Bennett *et al*., 2003).

Given that GM seed costs more than non-GM seeds, and promise improved yields, then farmers may put more effort/input into the GM relative to the non-GM crop, a point highlighted by Stone (2007, 2011). Thus part of any increase in yield could be the result of altered or enhanced management rather than the GM trait per se. For example, Gouse et al. (2003) and Morse *et al* (2005a) acknowledged that irrigation and fertilizer use played significant roles in the improvement of yield from GM cotton grown in South Africa. While the quantities of fertilizer applied can be recorded and thus included in an econometric-based analysis of GM versus non-GM crops this may not necessarily take account of any greater care given by farmers when applying the fertilizer (side placement versus broadcast for example) to the GM varieties. Also, the impacts of growing GM crops may not always have a direct financial value. For example, when large scale farmers in South Africa were asked why they adopted Bt cotton, 25% cited that it gave them peace of mind and 18% cited improved crop and risk management (Gouse *et al.* 2003). Such factors may not directly influence gross margin but they can assist in terms of allowing resources to be invested into other crops and thus increase the gross margin for the farm overall. There are other socio-economic benefits of GM crop production. For example, the additional income from growing GM crops can have positive repercussions for communities as Ismael *et al* (2002a) and Morse *et al* (2005) have reported for subsistent cotton farmers in the Makhathini Flats of South Africa. Here there is evidence that additional income from growing Bt cotton was used to educate children and to improve farms.

Many studies have explored the acceptability of GM foods to consumers, and unsurprisingly some have concluded that much depends upon whether consumers can see a clear benefit (Hossain *et al*., 2003). Indeed consumer acceptability, willingness to pay, attitudes and adequate labeling of GM foods appear to have had a much greater focus for research than have any direct economic impacts on this group. For example, Lusk *et al*. (2004) explored how benefits of GM influenced acceptance by consumers in the US, England and France but benefits were presented in terms of less environmental impact, health benefits and benefits for farmers in developing countries. In theory an enhanced production or distribution arising from growing GM crops should help lower prices for the consumer, or at least help limit price inflation. A headline in the Daily Telegraph newspaper published on the 24th January 2011 carried the stark message that "*Food prices could double without GM foods, scientists warn*". If true then this would clearly be a significant advantage for consumers but it is always difficult to prove such scenarios as the alternative would not exist.

SOCIAL IMPACTS

That there would be adverse effects of GM crops on human health has long been an argument deployed by opponents of GM and is said to occur in several ways (Malarkey, 2003; Pusztai *et al.,* 2003). First there is the use of genes conferring resistance to antibiotics as part of the process to produce GM crops. Typically a bacterial gene conferring resistance to antibiotics was included alongside the desired trait as a convenient 'marker'; thereby providing a cost effective and straightforward means of checking if the trait gene had been incorporated into the host genome (Goldstein *et al*., 2005). If the antibiotic resistance gene had been incorporated and was 'expressing' (i.e. working) then it was reasonably assumed that the desired trait gene would also have been incorporated. In retrospect this might seem like an odd choice but it should be noted that the genetics of antibiotic resistance were well known and there was much expertise and kit readily available to test for the presence of such resistance. In theory it may be possible to neutralize or remove such genes when they are *in situ*, but to date there are no techniques for this (Goldstein *et al*., 2005). Even so, the use of antibiotic resistance genes as markers has raised concern about the impact on gut bacteria and the possibility that they might incorporate the resistance genes and thus develop resistance to antibiotics. However, as Ronald and Adamchak (2008) discuss, this is unlikely because "…*many antibiotic resistance genes are already common in bacteria and have been in our food all along*". Other markers have been used, including genes that code for fluorescent proteins (Lippincott-Schwartz and Patterson, 2003) but other less controversial methods of providing marker genes which do not employ antibiotic resistance or fluorescence are now in use. Moreover, the risk is slight when compared with the over prescription of antibiotics for medical purposes.

Second, there are concerns that foods containing GM crop proteins might cause allergies. This argument would in theory apply to plants bred via conventional means and is not unique to GM varieties. As Herman (2003) has discussed, GM crops, including soybean, have been used in many processed foods and have not to date been shown to add any additional allergenic risk beyond the risks already apparent in non-GM equivalents. However, GM techniques have the potential to break down species barriers and thus it is possible that cereals may have genes inserted from legumes which mean that they may produce proteins; these in turn may generate allergic reactions in people. Conversely, it is possible that GM technology could be used positively in this context as a means of eliminating allergy-promoting proteins. Nevertheless, as new GM crops are produced in the future, especially through the transfer of genes between unrelated species, it is important that regulatory controls should require the investigation of possible adverse impacts. Interestingly, there have been few reports of allergies arising from Bt crops which involve the emplacement of bacterial genes in plant species (cases reported have been examined in Ronald and Adamchak, 2008). These and other health issues have been addressed by Lemaux (2008) and include the central issue of what happens to DNA when it is digested in animals or humans. Lemaux (2008) emphatically states that:

"*No reproducible data exist to show that transgene DNA in commercialized GE [genetically engineered] crops has unique behavior relative to native plant DNA*".

However, she draws attention to the controversial and unreproducible work of some researchers that have suggested adverse effects on the development and mortality of rats fed with HT soybeans. This raises a further issue relating to GM safety, notably the importance of rigorous and reproducible experiments which can be trusted by the public.

Indirectly the reduction of pesticide use in GM crop production has had positive health effects, especially the reduction of accidents with pesticides. In many developing countries small-scale farmers apply pesticide using knapsack sprayers, often with little protective clothing including suitable boots or gloves. In addition, pesticide is often stored in rooms where people live and in inappropriate containers such as soft-drink bottles. Comparing the incidence of pesticide poisoning in hundreds of Bt and non-Bt cotton farmers in the Yellow River basin of northern China, Pray *et al.* (2002) noted the relatively low value of 5% in the former and 2 to 29% in the latter. In a related study, which extended the data by two years, the results of Hossein *et al.* (2004) reinforced the earlier conclusions. They state that:

"*Farmers who grew only Bt cotton applied about 18 kg of formulated pesticide per ha, while farmers who grew only conventional cotton sprayed about 46 kg per ha. Nine percent of the farmers who exclusively used Bt cotton reported poisoning, while almost a third of the farmers who exclusively used non-Bt cotton reported poisoning*."

Huang *et al.* (2005) have documented pesticide poisoning in Hubei and Fujian Provinces, China, where trials of insect-resistant rice were being undertaken. Their research compared 123 farmers producing GM rice with 224 farmers growing non-GM rice in 2002 and 2003; they showed that approximately11% of the latter had symptoms of pesticide poisoning with no cases within the GM group.

GM technology also offers other opportunities to provide health benefits. Of note is the potential for engineering the production or enhanced production of essential nutrients and vitamins in staple crops which could reach large populations (Sakakibara and Saito, 2006; Sauter *et al.*, 2006). To date one such variety has been produced - Golden Rice - a bio-fortified rice engineered to contain a high concentration of vitamin A. Deficiency in vitamin A occurs in millions of people, most commonly in children, in parts of Africa and Asia, and renders them susceptible to blindness; it affects between 250,000 to 500,000 children annually. Golden Rice is produced in two steps. The first involves modification of the indigenous rice gene which codes for beta-carotene (a building block of vitamin A) synthesis in rice leaves to extend production to the grain. The second stage involves the addition of genes from other species, e.g. the daffodil and the soil bacterium *Erwinia uredovora,* to increase beta-carotene concentrations (Golden Rice Project, 2009). The potential of Golden Rice has been evaluated by Stein *et al.* (2008) for India and they indicate that it would reduce the problem of vitamin A deficiency by at least 50% at modest cost. Despite its potential Golden Rice has not, however, proven to be a panacea for vitamin A deficiency. This is not because of adverse human or environmental effects, as none have so far emerged, but is largely quasi-political due to anti-GM protests and the introduction of increased regulatory hurdles.

Other nutritive deficiencies might also be addressed by genetic modification through biofortification i.e. the production of crops with high concentrations of essential nutrients (Bouis *et al.,* 2011). As White and Broadley (2009) have pointed out, two-thirds of the world's population lacks one or more essential mineral element, notably iron, zinc, copper, magnesium, calcium, iodine and selenium. How such deficiencies could be rectified is addressed by Gomez-Galera *et al.* (2010) who highlight the benefits of GM to produce mineral-rich crops. They state:

"*The major advantages of genetic engineering over conventional breeding are the diversity of the source of genetic information, the speed with which modified elite varieties can be generated and, perhaps most important for the future, the fact that nutritional traits for different vitamins and minerals can be stacked in the same plant without highly complex breeding programs*".

They report that the technology has been used to promote increased concentrations of iron, zinc and calcium in crop plants but that no such fortified crops have yet reached the marketplace. This they attribute to regulatory uncertainties and trade barriers to which must be added a reluctance to accept GM crops in some countries.

Another potential application of GM technology is molecular 'pharming' i.e. the use of plants to produce substances useful in human and animal health and for industrial purposes (Cockburn, 2004; Ramessar *et al*., 2008). In relation to human and animal health there are three categories of product: vaccines, recombinant antibodies and a heterogeneous group which includes substances such as blood products, enzymes and cytokines (Arntzen *et al.*, 2005, Floss *et al.* 2007; Molecular Farming, 2009). However, few such 'pharm' plants have so far been widely used. Edible vaccines to combat diseases such as hepatitis, diarrhea and rabies have been produced in crop plants (e.g. maize and potato) and trials have shown that their consumption does indeed promote anti-body formation in humans, although there are risks associated with this (Shama and Peterson, 2008). A major advantage of plant-derived vaccines is their low cost when compared with fermentation-based production and this should make them increasingly accessible to more of the world's population. However, in a world which is growing short of food and where there is a limit on availability of good land there is the potential for the same issues to arise as have occurred with the growing of crops to produce fuel. Indeed given the likely high economic value of the products of 'pharming' there is both an opportunity for farmers as well as a potential threat to the environment if forests are destroyed to make way for such crops.

Social aspects of GM crops extend beyond health issues. Qaim (2010) highlights that an increase in income for farmers growing GM crops provides increased employment opportunities which consequently boost rural transport and other businesses. In India it has been shown that Bt cotton produced more income for the female workers than male (Subramanian, 2008). The explanation for this was that more workers were required for harvesting, which is generally seen as female work rather than planting and weeding the crops which was the male domain.

One aspect of GM farming that has not been significantly discussed within academic literature has been the level of debt incurred by farmers. GM seed generally costs significantly more than non-GM, and hence could increase the amount of credit that farmers would have to take at the start of the season. For example, smallholder farmers in the KwaZulu Natal province of South Africa obtained credit from one source, that of Vunisa, a private company (Ismael *et al.,* 2002) whose loans were underwritten by the Landbank. Farmers were engaged in this before the introduction of GM crops, and cotton is a crop where it is difficult (but not impossible) to save seed for planting the next year. Hence farmers bought seed each year even before Bt cotton was introduced. This is an important point as it is often claimed that GM forces a 'lock in' by farmers as they have little choice but to go back each year and purchase the seeds from the same suppliers. This is especially problematic if farmers are presented with little choice as to where they can purchase GM seed. The implication is that prior to the introduction of GM farmers could save their seed and thus once they adopt GM it will result in greater dependency upon suppliers to provide the input each year. Given that local seed suppliers are ultimately connected back to those that own the varieties, mostly multinational companies, then concerns have been raised about the desirability of this. This however is not necessarily a new situation. The point regarding cotton has already been made but the hybrid seed industry, most notably for maize but also for wheat and rice amongst other crops, existed long before the advent of GM and such hybrids have to be purchased each year for best results. The same applies to other inputs such as pesticides and fertilizer of course. There is a significant difference in the sense that hybrid seed, fertilizer and pesticide may be produced by local companies rather than multinationals, but again this is not necessarily so. Hence while a dependency on a limited number of input suppliers can be perceived as an issue in that limits farmer choice (and hence power) it is by no means an issue restricted to GM seed.

Debt is often quoted as the cause of high suicide rates amongst farmers given that GM seed is more expensive than locally produced varieties. There is evidence from India, for example, for relatively high suicide rates amongst cotton farmers but there is little evidence to show that such rates have increased since the introduction of GM (Haper, 2011; Gruère and Sengupta, 2011). The high cost of purchasing GM seed may contribute but the issue and control of loans is also important, plus the availability of support to farmers to help them manage debt. Related to this is the availability of spurious GM seeds (Ramaswami *et al*., 2012) which are sold by unscrupulous merchants; such seeds generally give low returns which makes loan repayment problematic. Some indications suggest that smallholder farmers have found some ways of avoiding repaying the loans, such as using different family names (Gouse, 2009). Moreover, debt in itself is by no means solely an issue for GM as a technology. There is a wealth of literature on micro-finance, both credit and savings, in the developed and developing worlds and issues regarding the setting of an appropriate interest rate, poor repayments , appropriate use of the funds, sustainability of the credit providers, impact, policy, subsidies and so on are well-explored. Brau and Woller (2004) provide a primarily 'developed world' review of microfinance, but Morduch (2000) and Copestake (2007) provide critical analyses relevant to the developing world. The high cost of GM seed sits alongside other relatively high-cost technologies, including fertilizers, machinery, irrigation, hybrid varieties and so on and all of these have a risk associated with them.

DISCUSSION

This review of published work indicates that overall GM crops have created benefits for farmers since they were first grown in 1996 and it indicates where vigilance is needed to avoid problems. In relation to both agronomic and environmental issues, published data reflect positive gains from GM crops. However, caution is necessary when drawing generalisations because of the relatively limited places on a global scale where monitoring has been undertaken, differences in monitoring approaches, and the disparate nature of the studies (Finger *et al.,* 2011).

Agronomically, small- and large-scale and low and high technology agricultural enterprises have benefitted from increased production per unit area of cultivated land. Much of the increased productivity is due to reduced losses caused by pests (insects and weeds) rather than the resultof increased crop productivity. Additional gains have also been obtained through the so-called 'halo effect' where gains have occurred in non-GM crops grown near GM crops which reduce pest populations beyond their immediate area.

The environmental benefits are also significant. Where insect-resistant crops are cultivated there has been a reduction in pesticide use. This gives rise to environmental benefits e.g. the preservation of non-target and often beneficial insects and diminished risks of water contamination. It also generates socio-economic advantages e.g. reduced financial outlay for pesticide purchase and application and improved farmer health (see Morse *et al.,* 2011). Some GM crops, notably HT maize and soybean, promote no or reduced tillage practices; this is also environmentally positive insofar as it reduces soil erosion and nutrient loss. In the USA and Argentina, for example, Carpenter (2011) observes that HT soybean cultivation has reduced the number of tillage operation by at least 25 per cent and as much as 58 per cent. Reductions in tillage and pesticide use have broader benefits because they reduce inputs of fossil fuels and so reduce the carbon footprint of food production.

However, published work indicates that there are environmental disadvantages of GM crop. The real and potential development of resistance in pests to herbicides and insecticides is of primary significance. Research in North America indicates that resistance to specific herbicides is increasing in some weed species. This appears to have been the most significant adverse environmental impact of GM crops and there is considerable potential for the development of herbicide resistance in weeds in the future. Similar problems are beginning to occur in some insect pests of Bt crops and there is much scope for future problems. Both problems can be limited through careful management.

In terms of socio-economic impacts of GM crops, the technology has an increasing relevance throughout the food security pillars of Figure 1, but as illustrated by this review the emphasis for research has tended to rest at the availability end of the chain. The 'access' and 'use' pillars of food security have received far less attention, with the notable exceptions of consumer acceptability of food and issues related to health impacts (notably research designed to show that GM food is safe). Many other facets of access and use have received far less attention, maybe because no 'unusual' impacts are expected for GM crops. For example, why should GM crops generate any especial issues with regard to transportation? Nonetheless there are some notable (and relative) gaps here. For example, just what are the benefits experienced by consumers of GM crops? Is there evidence for an economic gain that goes beyond 'marginal' or is there evidence for better nutrition (as with Golden Rice)?

The evidence to date regarding the economic impacts of GM crops is mixed. In some places and contexts they have increased gross margin while in others they have not (Finger *et al*., 2011). This should not be all that surprising as GM is far from being a 'magic bullet' that guarantees success. GM is an umbrella term that refers to a suite of technologies for isolating and transferring a small number of genes. What matters is the use to which that technology is put, and much depends here upon human judgement and skill. Placing these single genes into a genetic 'background' that is not especially advantageous will not help. Similarly, the conferring of a characteristic to a plant grown in any environment where that characteristic provides no discernible advantage will also not help. Given that GM seed is usually more expensive than non-GM seed then the absence of an advantage may result in a gross margin that is no different to what the farmer would get with non-GM varieties. It is a nonsense to say that the GM technology is 'bad' in such circumstances'; it is the use to which it was put that was at fault.

Nonetheless, while noting the caveat in the previous paragraph there is evidence that under some circumstances GM varieties have provided an economic advantage for farmers, including small-scale farmers of the developing world. There is also some evidence that those farmers have used the extra income wisely as an investment in livelihood. A reduction in application of insecticides has also been shown to provide benefits to human health alongside environmental benefits for non-target organisms. Would it be expected that these benefits would be seen by all farmers everywhere? The answer is no; but then can it be said that all farmers have benefitted from machinery, fertilizer or irrigation? Again, the answer is no. It has been well-established for many years that there are inequalities in the capacities of farmers to gain from new technologies. To expect GM to somehow be different is at best naive. It is not and cannot be expected to be a panacea. Indeed one of the criticisms that can be levelled at both extremes of the GM debate is their poor expectation management.

The facets of food security shown in Figure 1 have long been present, although with intensifying globalisation some of them are taking on greater importance. The global trade in produce has existed for centuries, but with increasing population and wealth the intensity of such trade measured in terms of volumes, economic value and indeed speed of delivery has increased. Similarly the 'availability' end of the food security chain covers very familiar topics. Therefore it is important to note that GM technology has not changed the chain in any way; the topics remain the same. All it has done is to provide some new emphases.

GM crops provide a step-change in the ability to produce new crop varieties. While many of the socio-economic issues surrounding GM crops are no different to those of conventionally bred new crop varieties (Lipton and Longhurst, 2011) there are also some important differences. Part of the difference is related to the intensity of the trait. Hence while pest-resistant varieties have been available for some time, and these do help reduce pesticide usage, the introduction of Bt into some crops where pesticide use has until now been very high it has made a significant difference very quickly. However, the socio-economic advantages and problems associated with the pest resistance arising from GM are not different in form from those that arise from resistance bred through conventional means. For the most part (but not exclusively) this is because convention resistance has tended to rely upon an enhancement of toxins in plant tissue, and the Bt gene does much the same. The Rothamsted Research approach with their GM wheat referred to above acts in a quite different mode. Similarly conventional breeding has long been used to help with traits such as drought resistance, storability, ease of processing or even nutritional status. It has also been the case that some new crop varieties may have a different taste or texture than more familiar varieties and thus be rejected by farmers. GM has not added anything new in this regard. It is simply a new way of doing what plant breeders have long been doing and with much the same aims.

The use of HT GM varieties does introduce a new package, but even here the socio-economic impacts are not that dissimilar in form to those occurring prior to GM introduction. Thus it can be argued that HT varieties combined with herbicide can help reduce labour demands and costs (good for the farmer) but at the same time may displace labour (bad for the labourers and their families). It is important to note that this has always potentially been the case with herbicide use; as a technology it is designed to replace the need for human labour to weed by hand or with machines. Herbicides have been available for decades and provide the vast bulk of weed control in richer parts of the world. Admittedly the HT-herbicide package may do an effective job in terms of weed control compared with the use of alternatives such as pre-emergent herbicides, but the basic objective is the same.

Thus there is something of a conundrum when analysing the socio-economic impacts of GM in that there is much overlap with the impacts that have long been identified with other technologies introduced into agriculture. Mechanisation, for example, has wrought the greatest impact on labour requirements by allowing much more to be produced with less labour. Even issues such as credit or the need for farmers to buy-in seed produced by someone else each year are by no means unique to GM. The need to make credit available to farmers at a reasonable price and how to help farmers manage that credit has a long history. Indeed it is surprising how little linkage is made in the literature between GM and this wealth of experience with other agricultural technologies that underpin much of what is shown in Figure 1. It is here that agricultural scientists can make a significant contribution to the analysis and ultimately to policy development. It is indeed a landscape that has a rich potential.

Given the multifaceted nature of the impacts, both positive and negative, of GM crops and the granularity of these across space geographers are especially well placed to make a contribution to the discourse, yet there seems to have been little engagement from this discipline. A search of articles using Web of Knowledge in June 2011 yielded a total of 12,869 papers containing the term 'genetically modified', but only a dozen appeared within the top 20 geographical journals. The majority of these publications occur within the biological, agricultural science and economics literatures. Whilst this is a fairly simple indicator given that Geographers publish widely it still hints at a much lower degree of engagement from geographers than might have been expected or indeed demanded.

CONCLUSIONS

Today's risk-averse society is reluctant to embrace new technology unless it is 100 per cent safe, a condition which is most unlikely. Thus the major issue focuses on the degree of risk which is socially acceptable. As this review shows GM crops do indeed carry risks but their advantages outweigh the risks so that they should be considered a valuable asset in the fight to increase global food production. The gains are particularly noteworthy in relation to agronomic and environmental considerations; since their commercial planting in 1996 they have made a positive contribution to arable productivity in all regions which grow them and to both commercial and subsistent farmers. However, investigations into the benefits and drawbacks of GM crops are fraught with difficulties. This is because the introduction of a GM crop may be accompanied by a number of other innovations such as improved use of fertilizer or water management for which it is not generally possible to account quantitatively. Socio-economic benefits are less clear cut than agronomic and environmental benefits, especially in relation to debt issues; it is unclear at present what effects it may have had on society and whether it is worse for farmers producing GM crops than those producing conventional varieties. In contrast trends are generally positive in relation to human health, notably fewer deaths and accidents with chemical pesticides.

However, as in the case of other innovations such as pesticide use, GM crop adoption should not be without regulatory safeguards which were spurred by the once spurned Rachel Carson's epic *Silent Spring* (1962). Subsequent to the recognition that pesticides such as DDT could impair food chains and have short-and long-term adverse ecological effects within and beyond farm boundaries government institutions have been created to oversee/regulate such innovations in order to monitor and guarantee food safety. It is essential that such institutions should be allowed to monitor GM crops, beginning with laboratory and then with field trials, and that their findings should be easily accessible to politicians and the public; knowledge, understanding and practicality in terms of risks (not only of GM crops but artificial fertiliser, new pesticides, water quality etc) rather than unfounded rumour and rhetoric are essential for both the pro-and anti-GM lobbies. Published literature to date indicates that if GM crops pose any risk it is their ability to facilitate the expansion of agriculture to transform remaining areas of natural ecosystems considered unsuitable for agriculture by the production of drought-, salt-, heavy metal-tolerant etc crops through GM. Conversely, however, such crops might facilitate the reclamation of lands impaired and rendered unproductive through poor crop management, benefits which complement those already established such as soil and carbon conservation.

To date the major disadvantage of GM crops is the development of resistance in target organisms; a development already detected in some target plants and insects. Careful knowledge-based management is vital in order to limit such resistance and thus to preserve the gains in productivity afforded by GM crops.

Debates surrounding the advantages and disadvantages of GM crops are set to continue, possibly even more intensively that in the last two decades due in part to the rise of so-called 'synthetic biology' (Benner and Sismour, 2005). This involves the creation of bespoke genes or even genomes from their basic chemical components which are designed to express specific attributes and which may then be inserted into cells. This means that scientists would no longer be constrained to finding desired genes in nature and a host of new developments might ensue. The understanding of gene components, gene assembly and expression is developing rapidly though knowledge about the various impacts of GM crops is only slowly expanding. There is need for an acceleration of field studies, and it is here that geographers and those interested in sustainable development can play a major role. What is needed is a willingness to engage with all of the facets of GM crops; from the social and economic through to the environmental and political. The challenge is great but then so is the need.

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