# BIOTECHNOLOGY IN AGRICULTURE: AGRONOMIC AND ENVIRONMENTAL CONSIDERATIONS & REFLECTIONS BASED ON 15 YEARS OF GM CROPS

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## Abstract

Genetically-modified (GM) varieties of crops, notably soybean, maize, rape (canola) and cotton were first grown commercially in 1996. In 2010 they occupied 148 million ha in 29 countries, mostly in the Americas and Asia but with an obvious absence in Europe where their introduction has been controversial due to concerns about environmental impairment and adverse impacts on human health. This paper reviews the published literature on the agronomic and environmental impact of GM crops in the last 15 years (a related paper by Morse and Mannion reviews the socio-economic impact). Overall, the impact of GM crops has largely been agronomically and environmentally positive in both developed and developing world contexts. The often claimed negative impacts of GM crops have yet to materialise on large scales in the field. Agronomically, there have been yield increases per unit area, mainly due to reduced losses as a result of improved pest i.e. insect and weed control; in the case of conventional crops grown near GM varieties with insect resistance there have been benefits due to the so-called ‘halo’ effect. Environmentally, the decrease in insecticide use has benefitted non-target and beneficial organisms while surface and groundwater contamination is less significant; human-health problems related to pesticide use have also declined. Equally important is the reduced carbon footprint as energy inputs are reduced. Of particular note, however, is the recognition that the success or longevity of GM crops is reliant on the speed with which resistance develops in target weeds and insects. However, resistance to GM-based plant resistance is already being detected in some pest populations and this suggests that scientists and farmers cannot be complacent. Current GM approaches are relatively transitory as a means of combating pests, as are conventional pesticides, and good management will determine how long this strategy proves positive. However, GM is a comparatively new science and the possibilities are considerable.

**Key words**

Genetic modification, crop production, environmental impact, biotechnology, agriculture

## Introduction

Modern biotechnology involves the manipulation of organisms and their components, including genes, to improve their ability to perform specific tasks for human benefit. Born out of the discovery by Watson and Crick in the early 1950s (Watson and Crick, 1953) of the molecular structure of deoxyribonucleic acid (DNA), modern biotechnology has focused on genetic manipulation for agriculture, horticulture, environmental remediation, medicine and forensic science (see reviews in Mannion, 2007, Fukuda-Parr, 2006, Murphy, 2007 and Thomson, 2006). In terms of people-environment relationships the most significant developments have been in agriculture, especially since 1996 when the first genetically-modified (GM) staple crops became available commercially. Such developments have also been controversial and there has been a mixed reception of GM crops worldwide. Controversy centres on whether these crops have generated environmental, economic and/or social benefits or indeed caused environmental, economic and/or social problems the possibilities for which were highlighted by various authors in the early to mid-1990s (e.g. Mannion, 1995a,b and c; Morse, 1995, You *et al*; 1993 and Fox, 1993) as the first GM crops became available. The reality of these issues has been addressed in recent reviews by for example Ronald (2011), Lemaux (2008) and Barfoot and Brooks (2008) though socio-economic issues tend to be given precedence and these publications are aimed at a scientific/agriculture audience. An exception is the review by Lemaux (2009) which does focus on environmental issues related to GM; such an approach is adopted in this review with emphasis on agronomic and environmental factors, including considerations in relation to energy issues and carbon footprints. This review is also timely for the geography literature given the spatially varied impact of GM crops in relation to the developed and developing worlds and subsistent versus commercial agriculture, as well as the by now extensive experience obtained with this technology under 'real' conditions rather than being based solely upon experiments.

The fundamental question is: have GM crops caused environmental or ecological impairment or indeed improvement? It is also timely given the challenge being faced by world agriculture, notably a rapidly increasing population in a warming and uncertain world (see Fedoroff, 2010 and Fedoroff *et al.*, 2010 for commentaries). It is important to ascertain if past experience has any lessons for politicians and policy makers, especially as 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, 2009 and United Nations, 2009). This prompts questions as to how such a large increase, i.e. 36 to 39 per cent, can be fed adequately given the additional pressure it will place on the world's agricultural systems. Although some parallels can be drawn with the so-called 'Green Revolution' of the 1940s-1970s when global crop productivity was increased substantially through the development of new strains of maize, wheat and rice, the invention/use of crop protection chemicals, and irrigation, the world in 2010 is a very different place than in the early 1970s and it will be substantially different again by 2050. Such differences fall into four categories: first there is global climatic change which will necessitate considerable and ongoing adjustments in most if not all agricultural systems given uncertainty about the magnitude and spatial distribution of global warming and its impact on water availability; 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. Second, this will be a world in which the expansion of agriculture could cause further loss of natural/semi-natural ecosystems and thus decrease global sustainability for a host of reasons. Third, a substantial proportion of its population in emerging nations will continue to broaden its food requirements to include dairy and meat products, and fourth there will be continued population growth in a world in which poverty continues to be widespread, often with even greater divides between rich and poor. This is especially the case for agriculture in Africa (see comments by Sánchez, 2010). In addition policies relating to future agriculture need to embrace the findings of Wise *et al.* (2009) and Burney *et al.* (2010). The former have shown that increased crop yields decrease greenhouse gas emissions on a par with 'cleaner' energy technologies such as wind and solar energy while Burney *et al.* (2010) have demonstrated that all (and more) the greenhouse gas emissions from intensive agriculture are compensated for through land/ecosystem conservation i.e. intact forests, savannah etc and their soils continue to act as carbon stores but would become carbon sources if ploughed.

There is no doubt that food production must increase substantially in the next few decades. Are GM crops likely to be a key component? Or is their environmental impact too big a price to pay? Thus while much of the GM literature exists within agricultural/biological science, economics and development journals there is no doubt given the intersection of such a wide variety of disciplines that geographers have much to contribute to this important discourse. This paper considers published research on the environmental impact of GM crops between 1996 and 2010 to provide some insight into this controversial issue. However, it must be pointed out that a true assessment is hampered by misused and poorly reported data. This has been highlighted by Morse *et al.* (2012) in relation to economic advantages. In addition Waltz (2009) has highlighted problems of reporting potential adverse impacts of GM crops on organisms while there is an uncharted belief that it is easier to have work relating to adverse impacts rather than positive outcomes published. Moreover, divergent opinions about GM crop impacts are confusing as is illustrated by Bagla's (2010) report in the journal *Science*; this states that Monsanto have discovered resistance to Bt cotton in pink bollworms though the findings are disputed by other researchers!

## Background

The productivity of all types of arable agricultural systems is dependent on the manipulation of crops, and especially the environment, to channel nutrients, water and light into the crop plants. Traditional plant breeding involving cross breeding between individuals of a species or its close relatives to produce hybrids, soil preparation, weed, insect and disease control and water management are all employed to maximise crop production. 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. direct manipulation at the molecular level short circuits time-consuming and expensive conventional breeding. This is a much more targeted approach compared to the production of hybrids followed by extensive selection, and also allows for the inclusion of genetic material from a wide variety of sources and thus is not limited to the same species and its close relatives. In the early 1990s this led to commentators referring to the possibility of creating designer or bespoke crops. The traits pinpointed for enhancement were basic productivity i.e. increased production of sugar or starch, ripening control, disease, insect and herbicide resistance, plant architecture and tolerance to environmental stresses such as drought, frost and high salinity. Other possibilities included the engineering of plants to produce commercially valuable substances such as pharmaceuticals and biodegradable plastic. This approach also broadens the resource base from which improved crops can be developed because it allows genes or their components to be introduced from non-crop species e.g. bacteria, fungi, insects, animals etc. It is this latter capacity which has underpinned much concern about GM crops and their impact on ecosystem and human health.

The first GM crop was the Flavr Savr tomato (reviewed by Martineau, 2001) which was developed by Calgene and approved for marketing by the US Food and Drug Administration (FDA) in1994. The tomato was genetically modified to alter ripening and thus to increase the time fruits could remain on the vine to intensify the flavour before harvesting in contrast with conventional practice which involved harvesting while still green and then ripening artificially with ethylene while in transit. It enjoyed only limited success, partly because of opposition by anti-GM groups. Production ceased in 1999 though no adverse effects on consumers have been reported to date. Since then many crop plants have been genetically modified to express a range of advantages e.g. disease resistance in papaya, enhanced vitamin A production in rice, virus resistance in potato, and delayed ripening in cantaloupe melon. The list is long as examined in a recent compendium (see Copping, 2010).

However, these are relatively minor players in the world of horticulture/agriculture when compared with the major cereal crops, soybean, rape seed (canola), and cotton which were the next major commercial GM products. These were first grown commercially in 1995/6. In 2000 the area planted was 44.2 million ha; by 2005 some 90 million ha were planted with GM crops and in 2010 the area had increased to c.148 million ha in 29 countries (James, 2010). As shown in Figure 1, the biggest producer is the USA followed by Argentina and Brazil. Few European countries are represented, reflecting the fact that GM crops have been strongly opposed by environmental groups and few African countries are listed because, amongst other reasons, they are concerned about losing markets in Europe for their produce. These and related issues have been discussed by Kershen (2010). Herbicide-tolerant crops have been widely adopted, especially those which are glyphosate tolerant (see Dill *et al.*, 2008 for a review). The significance of the major GM crops in the context of global production is given in Figure 2 which shows that soybean in particular has been widely adopted and now occupies c50 per cent of the total global area on which the crop is grown.

<Figures 1 and 2 near here>

## Advantages and disadvantages: claimed and real

The claimed and real advantages and disadvantages of GM crops are many and varied. They can be divided into three categories which relate to direct agronomic issues i.e.

increased/decreased productivity per unit area, indirect environmental advantages/disadvantages and socio-economic advantages/disadvantages, though there is some blurring between these groups. For example, the production of crops resistant to pests is potentially an advantage economically through enhanced production per unit area and because fewer conventional chemical pesticides are necessary there are environmental and further economic advantages. Moreover, 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 lends stability to farm incomes and facilitates planning. In this paper the emphasis will be upon the agronomic and environmental considerations, and the key ones discussed are outlined in Figure 3. The socio-economic considerations are not covered here in any depth but often revolve around considerations of the following issues:

1. Changes in revenue and costs with growing GM versus non-GM varieties, and how this impacts upon gross margin (revenue - costs).

2. Role of GM varieties in poverty alleviation and how the economic impacts may vary across space and time. Also included here are the uses made by farmers of any increased profit arising from growing GM (e.g. for educating children)

3. Impacts of GM crops on labour costs and employment.

4. Dependency issues, as GM seed typically has to be purchased each year rather than be saved from the previous growing season. The high cost of GM varieties can also raise issues around credit availability and cost.

5. Acceptability of GM produce to consumers, and this raises issues of labeling and exports from GM growing countries to other regions such as the European Union.

6. Impacts on human health. Two sides to this coin are often covered in the literature; the potential for negative impacts on health of GM produce and the growing of some GM varieties that are designed to be enriched in certain nutrients and vitamins.

<Figure 3 near here>

The GM traits in crops which are now most widespread are: herbicide tolerance, insect resistance, virus resistance, and delayed ripening. Moreover, 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. For example the agribusiness companies Monsanto and Dow Agrosciences have produced SmartStax maize with 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). The new product, approved for use in the USA and elsewhere in 2009, combines traits which were originally engineered individually.

## Agronomic considerations

Given that a major goal of genetic modification is increased yield, is there supporting evidence? There are claims and counter claims! Much hinges on whether reduced crop losses, due to internalised GM pesticidal activity rather than the use of chemical pesticides or internalised herbicide resistance which allows weed competitors to be reduced, can be considered as crop production increases. This is an interesting point as no major crops have as yet been genetically engineered specifically for enhanced productivity but the curtailment of losses because of the GM control of insect and/or weed competitors does lead to higher yields per unit area for farmers in developing and developing nations. Such gains are not confined to commercial farmers. 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 not adopting GM cotton; this means that in all cases losses through bollworm attack were substantially reduced. As Table 1 shows for farmers in India and China, those farmers adopting GM cotton experienced additional benefits such as reduced pesticide use and increased income. Both have advantages for environmental and socio-economic reasons as discussed below. Similar trends have been identified in resource-poor cotton farmers in South Africa (Morse and Mannion, 2009) and this success is leading to the adoption of GM cotton by smallholders elsewhere in Sub-Saharan Africa (Hillocks, 2009). James (2010) also cites gains by resource-poor farmers growing Bt maize in South Africa and the Philippines. However, drawing out an overall picture across the globe is difficult. A recent review by Finger et al. (2011) has pointed towards a spatial skew in the reporting of yield benefits from GM crops. Published studies to date are skewed towards some developing countries (notably India, China and South Africa) thereby increasing their representation within a meta-analysis of GM versus non-GM yield differences compared to the globally more important agricultural producing countries. Also, there is the problem of trying to draw out generalities when the data sources are so different in terms of their methodologies and assumptions as well as their objectives. Furthermore, an analysis based upon a series of short-term individual studies may not allow for the drawing out of longer term environmental effects.

<Table 1 near here>

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). Overall, peer-reviewed published literature indicates, indeed sometimes concedes, that GM crop output per unit area is in general greater than non GM output across a range of crops which have GM varieties (Finger et al., 2011). This must be considered a positive outcome. Figure 4 gives data compiled by PG Economics Limited (2009) on global increases in crop production resulting from the growing of GM varieties; for the period 1996 to 2006 and for the year 2006. The increase in production over this time has been substantial. In 2006 it was estimated that GM soybean had a 20 per cent increase in yield compared with non-GM varieties of the same crop, and the corresponding figures for cotton and maize were 15 per cent and 7 percent respectively. Given these figures, PG Economics Limited has stated that "the evidence presented derives from peer reviewed scientific journal articles and is representative of real impacts at the commercial and subsistence farm level". GM soybean and cotton have been particularly successful. Whilst most yield increases are due to pest reduction it is worth noting that in Argentina and Paraguay the cultivation of herbicide resistant soybeans has prompted the adoption of 'no-tillage' cultivation i.e. direct seed drilling without ploughing and in combination with fertilizer application. This practice not only reduces soil erosion but also conserves water and energy as well as enhancing carbon storage. It has reduced the overall production cycle for soybean so that land used for wheat production is now double-cropped with soybean.

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In relation to commercial maize production in the corn (maize) belt of the USA, where the major pest is the European corn borer (*Ostrinia nubilalis*; Lepidoptera), Hutchison *et al.* (2010) have examined production/economic data for the last 15 years. This work relates to both economic and ecological aspects of GM crop production. Economic gains amount to $6.8 billion for 5 states, of which $2.5 billion is attributed to Bt maize and $4.3 billion to non-Bt maize. A significant reason for the large non-Bt maize gains is attributed to the co-called ‘halo effect’ of Bt crops (see Tabashnik, 2010 for additional comments) i.e. the proximity of both crops mean that insect control extends beyond the Bt crop itself to neighbouring fields of non-Bt because of declines in pest populations. Additional factors relevant to non-Bt gains include the value of refugia i.e. islands/patches of non-Bt crop and the fact that non-Bt maize seed is c.30 per cent cheaper than the transgenic variety.

It is premature to judge the role of GM crops in relation to gains on marginal or compromised land or in relation to lands that might be brought into cultivation because crops with environmentally sensitive modifications have not yet become widely available. As Cominelli and Tonelli (2010) have discussed, the genetic mechanisms of plants to deal with abiotic stresses are complex and in the context of drought they result in either drought tolerance or drought avoidance; both traits are under investigation. Experiments by Monsanto with drought-resistant maize, which is engineered with a gene from the bacterium *Bacillus subtilis* to enhance drought tolerance, have shown between 6 and 10 per cent increase in yield and should be commercially available in 2012; other companies are also developing drought-resistant maize e.g. DuPont (see comments by Service, 2009 and Gilbert, 2010). Research is also focusing on the genetic engineering of salt tolerant crops; for example Li *et al* (2010) report on the production of a halophyte species of maize which in experimental plots achieved notably improved yield than conventional plants. Salt-tolerant crops would facilitate the revival of agriculture on cropland salinized by poorly-managed irrigation. However, both drought- and salt-tolerant crops could be environmentally detrimental by encouraging the spread of agriculture into remaining natural ecosystems.

Moreover, many studies have 'ignored' yield *per se* and concentrated on income and other factors, e.g. reduced pesticide use and associated cost adjustments, to assess GM crop success or otherwise. The logic for this is that farmers may not necessarily be interested in yield but in the gross margin (revenue - costs) if they wish to market the produce. Even with subsistence farmers the focus may be upon the production related to inputs such as labour rather than land. In such circumstances GM varieties can provide a degree of insurance for the farmers in that they may help to stabilise outputs in the face of environmental uncertainty given that the farmers have to commit inputs such as land and labour. These and other studies are discussed by Morse *et al.* (2012).

## Environmental considerations

While increased yields are a primary objective of GM technology in agriculture there are other potential advantages and disadvantages in relation to the environment. Given that insect and herbicide resistance are the major traits so far engineered into crop plants, patterns of use and costs of pesticide use are informative. Other issues include changes to the carbon footprint of agricultural systems using GM rather than non GM crops, the real and potential development of resistance by weeds and insects to herbicide and insecticide traits in crop plants (as might occur re chemical herbicides and insecticides), the spread of modified genes into wild species, harm to beneficial organisms especially insects, and the potential of crops engineered with tolerance to environmental stresses to expand agriculture into marginal areas at the expense of natural ecosystems.

Barfoot and Brooks (2008) have analysed available data on pesticide use in terms of quantity, reduced environmental impact and cost, as shown in Table 2. They show that for all the major GM crops herbicide and insecticide use declined substantially with a significant reduction in the Environmental Impact Quotient (EIQ). The latter 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. The greatest savings were for GM herbicide tolerant soybean in the USA and Argentina, GM herbicide tolerant canola (rape) in Canada, GM insect resistant maize in Canada, South Africa and Spain, and insect resistant GM cotton in China, Australia and the USA. In terms of the EIQ in developed and developing countries the difference was small: -6610 and -7166 respectively. A less obvious but still significant and beneficial impact of GM crops is a shift from more toxic to less toxic pesticides. One example of this is the shift from using metolachlor, a herbicide which contaminates groundwater and which may have adverse toxicological effects on aquatic organisms, to the much more environmentally-friendly glyphosate in GM soybean production, especially in the USA (Rivard, 2003). In the latter there has been an annual reduction of some 27,000 tonnes of active pesticide ingredient between 1996 and 2006 (Livermore and Turner, 2009).

<Table 2 near here>

Barfoot and Brooks (2008) also report on reductions in greenhouse gas emissions when GM crops replace conventional crops. This is due to energy saving by reduced pesticide use and the adoption of no-tillage methods which reduce the use of farm machinery and encourage carbon sequestration in the soil. In 2006, for example, fuel reduction due to GM crop cultivation resulted in saving carbon dioxide emissions of $1215 \times 10^6$ Kg which is approximately equivalent of taking 540,000 cars off the roads. An estimated further $13.5 \times 10^9$ Kg of carbon dioxide was saved through sequestration in the soil which is equivalent to removing six million cars from the roads.

While these data are positive in relation to GM crop cultivation the long-term, i.e. decadal, outlook may not be so positive if resistance to GM traits in either insect or plant pests develops. There are potential parallels with resistance which is known to have developed in plant and insect pests re conventional pesticides. Indeed, 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) and Owen (2009) states that globally 13 weed species are known to be glyphosate resistant; nine of these occur in the USA e.g. two species of *Conyza*, compositae, and two species of *Lolium* which are grasses (Powles, 2008a and b; see below). Should pest resistance to the herbicide and/or pesticide components of GM crops develop, crop efficacy will be relatively short lived; this will sacrifice a huge investment in scientific endeavour and finance and will require further approaches to the improvement of agricultural production. This and adequate crop management to limit the spread of resistance are the major concerns of many farmers in North America (see Harrington *et al*., 2009) and elsewhere. In contrast, Wu *et al.* (2009) report an advantageous repercussion 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.

One key to prolonging the efficacy of insect-resistant GM crops is good management which includes the use of refugia within GM crop fields i.e. the provision of areas planted with conventional non GM crops (see Raymond and Wright, 2009, and Tabashnik and Carrière, 2009, for reviews). The underpinning logic is that populations of insects with no or little potential resistance to Bt insect-resistant crop genes will survive in such refugia and breed; their offspring will then genetically dilute the potential of insect progeny from the overall cultivated area which may exhibit resistance. Different strategies in relation to size and distribution of refuges will be required by different GM crops and will vary between crops with single modified or stacked multiple modified genes. Refuge strategies must, therefore, be under continual review. Despite prescribed management techniques, the first case of insect resistance to Bt cotton was reported in 2008 (Tabashnik *et al.*, 2008) from the US states of Mississippi and Arkansas where the bollworm *Helicoverpa zea* is a pest. This strategy gives rise to other points which relate not so much to the science but to implementation. First, such a strategy may be straightforward to implement in well managed agribusiness concerns, i.e. large commercial farms in the developed world, but in small-scale subsistence farming in the developing world it requires outreach education which is not always possible or effective.

The management of resistance in relation to herbicide tolerance has been discussed by Owen (2009). One particular concern is the overwhelming reliance on the herbicide glyphosate; some 90 per cent of herbicide-resistant GM crops have modified genes for glyphosate resistance and are major crops, notably soybean, cotton, maize and canola, on millions of hectares in the USA, Canada, Argentina and Brazil (Figure 1). Should resistance become widespread serious crop and financial losses will ensue with implications for food supplies. Owen (2009) notes that the rate of resistance development is accelerating as six new species of weeds with glyphosate-resistant genes have been recorded in the USA between 2004 and 2008. This is an unsurprising occurrence given the huge increase in glyphosate use during this period but it is equally important to note that this is still a relatively small number. Indeed, it is perhaps surprising that the number is so low given the intense selection pressure. An equally important question to ask is how the resistance developed. Was it through survival of a proportion of a weed's population with naturally higher resistance which thus conferred advantage, or was it through cross breeding between GM crops and their wild relatives, or have there been weed transfers between related weed populations?

In any plant population there are variations in degree of tolerance/resistance to particular herbicides. Thus a proportion of any targeted weed population will exhibit some herbicide tolerance; natural selection will then occur over generations due to 'survival of the fittest' culminating in a high incidence of resistance to the regularly-used herbicide. Such development of resistance may be accelerated if there is poor management; if farmers, in attempts to economise, apply less than recommended herbicide doses; there will be more residual weeds with resistance, or if farmers apply high rates resistant mutants will be favoured. Herbicide-tolerant GM crops will be no less susceptible to this process as non-GM crops (see Powles, 2008a and b). It is possible, indeed likely, that the increasing use of glyphosate due to glyphosate-resistant crops may accelerate the development of resistance. Moreover, Dewar (2010) has pointed out, in the context of glyphosate-resistant maize, that such GM varieties could become a vital component of European (and other) agricultural systems given recent tightening of EU regulations regarding risks associated with herbicides (and pesticides in general). This makes the discovery and registration of new chemical pesticides extremely difficult though continued reliance on glyphosate is likely to accelerate the development of resistance and will require careful management practices such as rotations.

Owen (2009) has reviewed the various possibilities and realities of gene transfer between the major crops and their wild relatives. This is important because of the potential for the development of 'superweeds', an argument regularly cited in the debate against GM crops. There is evidence for gene flow between cultivated plants and wild relatives (see Ellstand, 2003) so it is not surprising that there is potential for gene flow between GM crops and their wild relatives and between related weed species. 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). The result is that weed management is more difficult in these crops; this adds an additional dimension to crop management which will detract from crop profits. Moreover, there is the likelihood of gene transfer between GM crops and their traditionally-bred counterparts. Actual cases have been reported for canola (oilseed rape) in which genes for both glyphosate and glufosinate herbicide resistance have been found in non GM canola crops (Legere, 2005). Transfers of this sort have implications for the juxtaposition of GM crop and non-GM crop cultivation. This is especially significant in relation to organic farming which precludes the use of GM crops as well as crop protection chemicals. Ensuring that no contamination can occur requires the maintenance of a buffer zone between the two which is a question of management and co-operation between farmers; other safeguards include staggering dates of planting, the use of varieties with differently timed life cycles i.e. different maturity dates (see Dlugosch and Whitten, 2008). However, it is ironic that GM crops which reduce or eliminate chemical pesticide use are not acceptable in organic farming systems when in fact they could contribute to yield increases in such systems (see discussion in Ronald and Adamachak, 2008).

The possibilities of GM crops becoming weeds themselves have recently been highlighted at a conference of the Ecological Society of America in August, 2010, reported by Gilbert (2010). A research group from the University of Arkansas examined traits from canola found at 288 sites in North Dakota, USA, and found that some 80 per cent had one GM trait. Approximately half were resistant to Monsanto's Roundup (the herbicide glyphosate) and the other half were resistant to Bayer's Liberty (the herbicide glyphosinate); even more surprising was the discovery of two individual plants with resistance to both. This means that an entirely new and 'un-engineered' trait had developed in the field. The high incidence of 'feral species' at widespread locations often at considerable distance from fields of engineered crops, and the appearance of a new trait, reflects inadequate management and considerable potential for the spread of genes as well as the relatively rapid development of resistance. In a recent review Warwick *et al* (2009) highlight the possibility of gene transfer through pollen and seed exchanges between crops and their wild relatives. They conclude that generalisations are inadequate and that investigations, ultimately informing regulatory bodies, are essential on a case-by-case basis. Precautions also need to be taken at the post-harvest phases of transport and processing to ensure that GM crops are not mixed with non-GM crops to ensure the accuracy of food labeling and the integrity of consumer choice.

Suggestions that increased yields from farmland would lead to decreased cultivation and thus leave land available for 'nature' (e.g. Matson and Vitousek, 2006) have not proved true. There is no evidence which relates to GM crops specifically but Ewers *et al* (2009) report that where yields have increased the released land is put to other economic uses. For example, in many developing countries where yields of staple crops have increased the released land has been used to grow other crops and in many developed countries little change was observed, possibly due to subsidies. On a positive note, however, Ewers *et al.* note that in countries where yield increases per unit area were high forest loss was reduced i.e. loss of natural ecosystems through land conversion to agriculture was less intense. It is not unreasonable to expect that increased yields due to GM crops would follow similar patterns. There is no evidence to suggest that GM Bt crops have adverse affects on beneficial organisms such as honey bees as, for example, Duan *et al.* (2008) assert on the basis of their re-examination of 25 laboratory-based studies directed at honey-bee mortality in Bt crops. GM crops may have a beneficial effect on non-target organisms. For example, Marvier *et al* (2007) examined the results of 42 field experiments and state that "non-target invertebrates are generally more abundant in Bt cotton and Bt maize fields than in non-transgenic fields managed with insecticides". They also found that some non-target invertebrates were less abundant in GM fields than in control untreated fields. In contrast, Lu *et al.* (2010) have examined the impact of Bt cotton crops over a ten-year period in six provinces of northern China and have found that the populations of mirid bugs (Heteroptera: Miridae), non-target insects, have increased sufficiently so that they are now considered a serious pest in other regional crops, e.g. cereals, vegetables and fruit, grown by more than 10 million small-scale farmers. Such studies have not, however, led to GM crops being banned i.e. policy change as has occurred in Germany. Studies on laboratory force-feeding trials of ladybirds and daphne 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. These results constituted a primary factor in a ban imposed in 2009 on the cultivation of GM corn variety MON810 by the German Federal Office of Consumer Protection and Food Safety. Their content and its significance has been addressed by Ricroch *et al* (2010) who have examined the experimental conditions and resulting data and who conclude that numerous flaws in experimental design undermine substantially the findings of Schmidt *et al* (2009) and Bohn *et al* (2008) and that their review of some 41 related studies published in 2008 and 2009 report no or very limited impact of GM corn MON810 on non-target organisms. Ricroch *et al* (2010) advise that the use of such selective, and possibly flawed, evidence is unacceptable and 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 general public and the media so that they are well informed.

All of the studies referred to above are concerned with plant/animal communities above ground. However, the adoption of GM crops and associated management practices has the potential to alter below ground biotic communities (i.e. fungi and bacteria) and processes. Few studies have addressed these issues. Powell *et al.*(2009) 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 biota and characteristics of litter decomposition. Their results show that following a minor initial disturbance of soil biota equilibrium was restored rapidly and whilst this may reflect resilience long-term studies are necessary to test this resilience further. In relation to litter decomposition, the results show no discernible trends; some reduced decomposition with increased soil organic matter was noted in some plots but not all.

## Discussion

This survey of published work indicates that there have been advantages of GM crop production at least during their first 15 years of cultivation, though there are cautionary tales for the future.  In terms of both agronomic and environmental considerations, the analyses undertaken so far point towards a positive gain from growing GM crop varieties relative to their non-GM counterparts. However, there are issues surrounding the relatively narrow set of places on the globe where such studies have taken place and the disparate nature of the studies that have been undertaken (Finger et al., 2011). Great care does have to be taken to avoid an over-generalisation over space and indeed time.

Agronomically, high- and low-technology, small- and large-scale agricultural systems have benefitted from increased production per unit area of cultivated land.  This is due to reduced losses from pest impact in the field rather than increased biological productivity by the crop itself.  Further gains in productivity have been noted through the so-called ‘halo effect’ whereby GM crops result in a reduction of pests in nearby non-GM crops.  Both are welcome outcomes.

The environmental benefits are also noteworthy and numerous.  Most important, especially in relation to insect resistant crops, is the reduction in pesticide use.  Apart from environmental benefits such as the preservation of non-target and often beneficial insects and reduced risks of water contamination, this has socio-economic benefits e.g. cost cuts and improved farmer health (see Morse *et al.,* 2011).  The promotion of no or reduced tillage cultivation in some regions, facilitated by HT crops such as maize and soybean, is also environmentally positive as it curtails soil erosion and soil nutrient loss.  This has occurred in the USA and Argentina, where Carpenter (2010) notes that HT soybeans have resulted in a decrease in the number of tillage operations of between 25 per cent and 58 percent.  The reduced use of pesticides and the adoption of no tillage also have broad environmental implications since they reduce the input of fossil fuel and thus reduce the carbon footprint. This should be a target for all agricultural systems.

However, published work indicates that there are environmental disadvantages of GM crops. The most significant is the real and potential development of resistance in pests to herbicides and insecticides. Evidence from North America especially indicates that weed resistance to specific herbicides is increasing. 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. Although evidence to date for the development of resistance in the target insects of Bt crops is limited, this may accelerate in the future.

Given the multifaceted nature of the impacts (positive or negative) of GM crops and the granularity of these across space then geographers are 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 having the term ‘genetically modified’ within the topic, but barely a dozen of these appeared within the top 20 geographical journals. The vast majority of thee publications occur within the biological and agricultural science and economics literatures. Admittedly this is a fairly simple indicator given that geographers do publish very widely but even so it does hint of a much lower degree of engagement from geographers than one may expect or indeed demand.

## Conclusion

In a risk-averse society technological innovations are only welcome when the technology is considered to be 100 per cent safe! In reality no technology is 100 per cent safe so adoption depends on what degree of risk is acceptable. GM crops are not without risk yet, in terms of their environmental implications, the conclusion based on this review of published work is overwhelmingly positive. Research to date indicates that in their 15 years of existence GM crops have contributed positively to arable agricultural production in all the regions to which they have been introduced whether to commercial or subsistent farmers. Avoiding the pitfalls of the past in relation to agricultural innovation was spurred by the once spurned Rachel Carson's epic *Silent Spring* (1962). Governmental bodies have since been created to oversee/regulate such innovations and their diligence has considerably improved food safety. Perhaps one message this sends, especially for anti-GM Europe, is that such regulatory bodies should be given credit for the food and environmental safety they have so far achieved and allowed to examine the pros and cons of GM crops. Broad publication of their findings could then be made available through scientific and political channels to be juxtaposed with often poorly-founded anti-GM rhetoric. The worst case scenario based on current evidence is that GM crops may compromise environmental conservation because potentially they could facilitate the expansion of agriculture into areas of natural ecosystems presently deemed unsuitable for agriculture. Field and laboratory evidence collected so far indicate that GM crops have not compromised environmental processes or components. Indeed there are many positive impacts including reduced soil/nutrient losses in the field as well as soil and energy conservation. The major drawback is the development of resistance in target organisms; this has already occurred in some plant and insect species and the rapidity at which it spreads is a function of crop management. Benefits from GM crops may indeed improve the food security of many without environmental impairment if appropriate crop management practices are implemented.

Finally, there is no doubt that the debates over the benefits and problems of GM crops will not go away in the immediate future. Indeed it is likely that the debate will become more intensive with the impending rise of what are called 'synthetic biology' (Benner and Sismour, 2005). Here bespoke genes or even genomes are created from their basic chemical components and designed to deliver certain attributes and inserted into cells. The result is that biologists are no longer limited to the genes one finds in nature and a whole new vista of possibilities opens up. Clearly the pace at which new knowledge about genes and what they do is accelerating but an understanding of the impacts of engineered organisms in the field, including the socio-economic impacts, lags well behind this. There is need for an acceleration of field studies, and it is here that physical geographers, and their human geography colleagues, can play a major role.

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Table 1. Data on resource-poor cotton farms growing Bt cotton in India and China in 2008 (based on PG Economics, 2010).

| COUNTRY | YIELD INCREASE (due to reduced losses) | PESTICIDE REDUCTION | FINANCIAL GAIN $/Ha |
| --- | --- | --- | --- |
| India | 31% | 39% | 257 |
| China | 8%-10% | 60% | 224 |

Table 2. Data on pesticide reduction in GM crops 1996-2006 (based on data in Barfoot and Brooks, 2008).

| 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

Figure 1. Global Area of Biotech Crops in 2010: by Country (based on James, 2010).

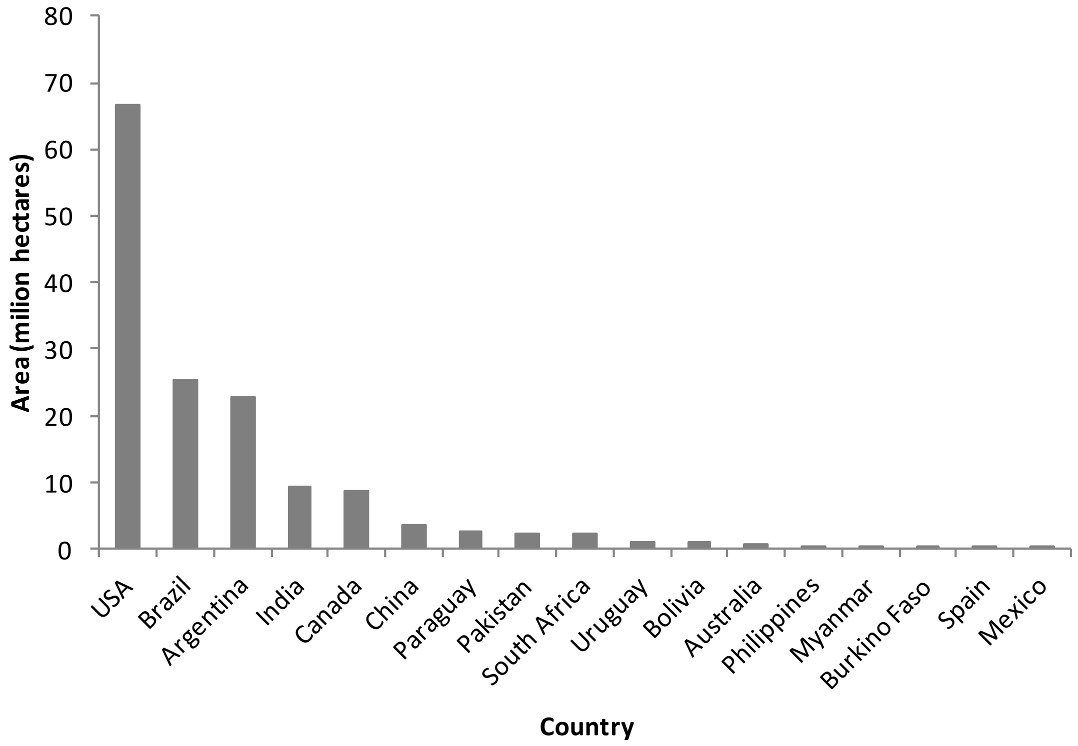

Figure 2. The extent of major GM crops in relation to global production in 2010 (based on James, 2010).

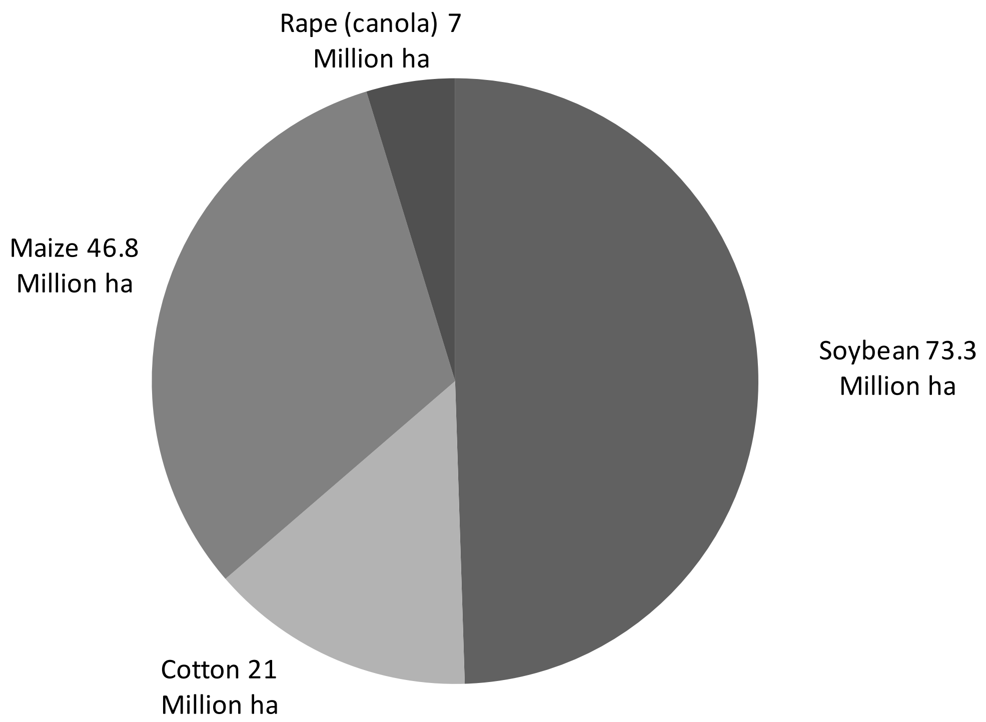

Figure 3. Outline of some of the benefits and associated problems of GM crops discussed in the paper.

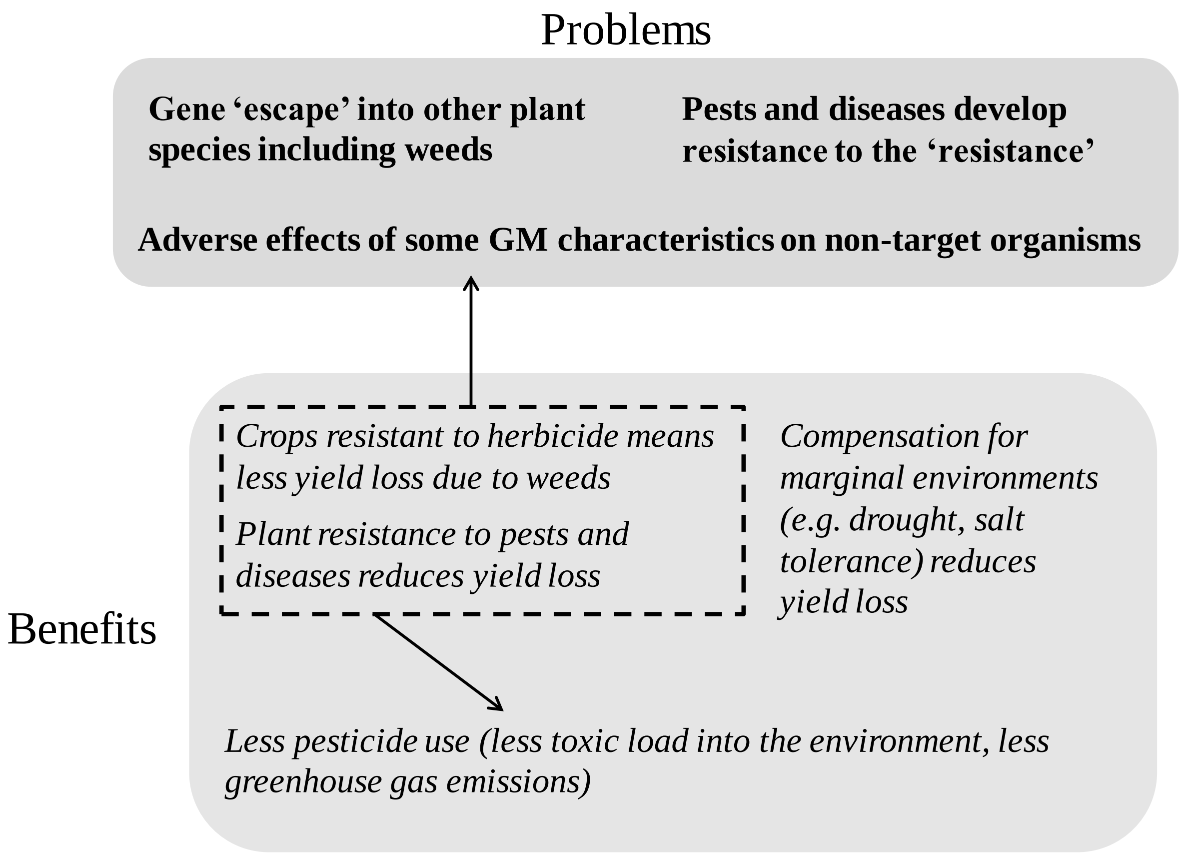

Figure 4. The volumes added to global soybean, maize, cotton and canola crop outputs through the use of GM varieties for the period 1996-2006 (PG Economics, 2009).