Plant Biotechnology Journal

Plant Biotechnology Journal (2011) **9**, pp. 2–21

doi: 10.1111/j.1467-7652.2010.00565.x

Review article

The role of transgenic crops in sustainable development

Julian Raymond Park*, Ian McFarlane, Richard Hartley Phipps and Graziano Ceddia

School of Agriculture, Policy and Development, University of Reading, Reading, RG6 6AR, UK

Received 4 May 2010;
accepted 29 July 2010.

**Correspondence*
(Tel 00 44 118 378 6686;
fax 00 44 118 935 2421;
email j.r.park@rdg.ac.uk)

Keywords: transgenic, sustainable, biodiversity, economic, environment, social.

Summary

The concept of sustainable development forms the basis for a wide variety of international and national policy making. World population continues to expand at about 80 M people per year, while the demand for natural resources continues to escalate. Important policies, treaties and goals underpin the notion of sustainable development. In this paper, we discuss and evaluate a range of scientific literature pertaining to the use of transgenic crops in meeting sustainable development goals. It is concluded that a considerable body of evidence has accrued since the first commercial growing of transgenic crops, which suggests that they can contribute in all three traditional pillars of sustainability, i.e. economically, environmentally and socially. Management of herbicide-tolerant and insect-resistant transgenic crops to minimize the risk of weeds and pests developing resistance is discussed, together with the associated concern about the risk of loss of biodiversity. As the world population continues to rise, the evidence reviewed here suggests it would be unwise to ignore transgenic crops as one of the tools that can help meet aspirations for increasingly sustainable global development.

Introduction

Sustainable development permeates policy and action at the international, national and local level. Although the term sustainability has been used for several centuries, the unique relationship between the environment and societal actions was popularized by the book Silent Spring written in 1962 by Rachel Carson. The relationship between environment, economy and development has since grown in importance. The establishment of the International Institute for Environment and Development, the First Earth Day and the publication of the controversial ‘Limits to Growth’ (Club of Rome, 1972) all took place in the early 1970s. The World Watch Institute was established in 1975 and since 1984 has published annually the ‘State of the World’ reports. In 1980, the International Union for Conservation of Nature (IUCN) published its World Conservation Strategy with a section entitled ‘toward sustainable development’, which highlighted strong links between habitat destruction and poverty, population increase, social inequity and trade. The release of ‘Our Common Future’ in 1987, commonly known as the Brundtland report, brought the concept of sustainable development more widely into the public arena. Growing concerns about climate change led to the formation of the Intergovernmental Panel on Climate Change (IPCC) in 1988 and further international promises and conventions followed at both the 1992 (Rio de Janeiro) and 2002 (Johannesburg) summits. The Millennium Development Goals (MDGs) re-enforced a global desire to tackle the key sustainable development challenges related to growing population, poverty, hunger, health, damage and over exploitation of natural resources and biodiversity and concerns about the rate and severity of climate change. The recent substantive report ‘Agriculture at a Crossroads’ (IAASTD, 2009) noted, perhaps not surprisingly, that agricultural knowledge, science and technology are fundamental to meeting the MDGs, particularly related to poverty and livelihoods, although the report notes the general polarization in positions that individuals, organizations and indeed Governments adopt with respect to transgenic crops.

In 2009, the world population was 6.8 billion, and by 2025, the Population Reference Bureau expect it to increase to 8.1 billion (PRB, 2009). By 2050, it is predicted

© 2010 The Authors
Plant Biotechnology Journal © 2010 Society for Experimental Biology and Blackwell Publishing Ltd

that population will stabilize at just over 9 BN (UN Population Council, 2003). Thus, in the next 40 years, the world population is likely to grow by a further 37%. FAO estimated that 1.02 billion people were undernourished worldwide in 2009 (FAO, 2009). Paradoxically, an almost equal number suffer with obesity with the potential for associated diabetes and metabolic disease. With an increasing world population, the desire for economic development and increasing urbanization, the global demand for food will continue to grow. At the same time, climate change is leading to production uncertainties, and the reliance on fossil fuels in food production systems is of increasing concern. (RSC, 2009; Karlsson, 2009; UNCOD, 2008).

Against this backcloth, a range of transgenic crops have been developed, and a few are now being grown in many parts of the world; so far the crops are either herbicide-tolerant, giving farmers greater choice in crop management, or insect-resistant, reducing the need for spraying with pesticides. A variety of novel transgenic crops, some offering nutritional benefits and others that are tolerant of drought and other forms of stress, or higher yielding, are at advanced stages of testing. As well as performance testing, they are being tested from the point of view of environmental impact and biosecurity. Data from the biotech industry suggest that since wide-scale planting started in 1996, the area of transgenic crops grown globally has increased from 2 to 134 Mha in 2009 (James, 2009), of which 131 Mha are grown in eight countries: USA, Brazil, Argentina, India, Canada, China, Paraguay and South Africa. Other countries that include Uruguay, Bolivia, Philippines, Australia, Mexico, Spain, Chile, Columbia, Honduras, Bukina Faso, Czech Republic, Romania, Portugal, Germany, Slovakia and Poland grow between <0.1 and 0.8 Mha (Table 1). Currently, these crops are grown by 13.3 million farmers, who are attracted by the potential to reduce input costs as a mechanism for maintaining margins rather than expecting increases in yields *per se*. However, it is important to note that the largest numbers of farmers growing transgenic crops are small-scale producers (12.3 million of the 13.3 million growers of biotech crops in 2008 were small and resource-poor farmers), particularly in India, China, South Africa and Philippines (James, 2008). The principal transgenic crops are soya bean, maize, cotton and canola, which are modified for agronomic input traits such as herbicide tolerance (HT) and or insect resistance (*Bacillus thuringiensis-Bt*). On a global basis, transgenic crops are 77%, 26% and 49% of the total soya bean, maize and cotton areas, respectively (James, 2009). Currently, 60% of all transgenic crops grown have the single trait of HT. However, there has been a marked increase in use of transgenic crops containing stacked traits (HT and *Bt*), and these now contribute a higher proportion of the total area than crops modified for just *Bt*. Between 2007 and 2008, the area of transgenic maize grown in the USA with three inserted traits increased from 28% to 48% (James, 2008), and this trend is likely to increase. Recent work has focussed on the use of biotechnology to produce abiotic stress-tolerant and nutritionally enhanced food and feed with a range of new events being predicted by 2015 (Newell-McGloughlin, 2008; Stein and Rodriguez-Cerezo, 2009).

Table 1 Global area of biotech crops in 2008 by country (after James, 2009)

Country	Area (Mha)	Biotech crops
USA	64.0	Soya bean, maize, cotton, rape, squash, papaya, alfalfa, sugar beet
Brazil	21.4	Soya bean, maize, cotton
Argentina	21.3	Soya bean, maize, cotton
India	8.4	Cotton
Canada	8.2	Rape, maize, soya bean, sugar beet
China	3.7	Cotton, tomato, poplar, papaya, sweet pepper
Paraguay	2.2	Soya bean
South Africa	2.1	Maize, soya bean, cotton
Uruguay	0.8	Soya bean, maize
Bolivia	0.8	Soya bean
Philippines	0.5	Maize
Australia	0.2	Cotton, rape, carnation
Burkina Faso	0.1	Cotton
Mexico	0.1	Cotton, soya bean
Spain	0.1	Maize
Chile	<0.1	Maize, soya bean, rape
Colombia	<0.1	Cotton, carnation
Honduras	<0.1	Maize
Czech Republic	<0.1	Maize
Romania	<0.1	Maize
Portugal	<0.1	Maize
Poland	<0.1	Maize
Costa Rica	<0.1	Cotton, soya bean
Slovakia	<0.1	Maize
Egypt	<0.1	Maize

Despite the growth and use of transgenic crops in many areas of the world, some governments, organizations and individuals still hesitate to acknowledge that transgenic crops provide economic and environmental benefits that are unobtainable in a timely manner via non-transgenic advances in plant breeding. For example, Binimelis *et al.* (2009) reported the appearance in Argentina of a growing number of glyphosate-tolerant or glyphosate-resistant

© 2010 The Authors

weeds, with socio-environmental consequences apart from the loss of productivity. Hall and Moran (2006) described some of the organizations that believe that there are unacceptable risks associated with the release of transgenic crops, and some scientists have expressed caution about specific issues such as disturbance of nitrogen balance in soils (Gurian-Sherman and Gurwick, 2009). A balanced view is presented by the UK Royal Society (2009): 'The reality is that there is no technological panacea for the global challenge of sustainable and secure food production…new crop varieties and appropriate agro-ecological practices are both needed'.

The overall thesis of the paper is that if the growing world population is to be adequately fed, both in terms of quantity and quality, without further compromising the environmental services that the planet provides, then transgenic crops are a potential 'tool' giving options for ongoing sustainable development. This paper considers the contribution of transgenic crops in relation to the three recognized pillars of sustainability (economic, environmental and social), and where possible makes links to specific sustainable development goals and targets. In the Economic dimension, we examine the evidence that yield is maintained or enhanced relative to non-transgenic crops and that inputs are reduced; we also note the sharing of economic benefit between suppliers, farmers and consumers. In the Environmental dimension, we look first at the long-term environmental prospects for maintaining soil quality, reducing greenhouse gas emissions and conserving water supplies; Environmental dimension continues with environmental issues specific to transgenic crops: coexistence, biodiversity and emergence of resistance. In the Social dimension, we review implications for human health and nutrition before discussing the overall implications for sustainable development.

Economic dimension

The aim of the first of the eight United Nations Millennium Development Goals (UN, 2009) is to eradicate extreme poverty and hunger. As many of the poorest peoples and countries in the world are highly reliant on agriculture, then it is likely that developments in crop and animal husbandry will have a direct impact on achieving this goal (DFID, 2005) and lead to improved economic conditions. The eight goals are claimed to represent a partnership between developed and developing countries, which is conducive to both development and the elimination of poverty, and indeed Goal 8 relates directly to Global Partnerships for Development. An example of such a partnership is the initiative between the Bill and Melinda Gates and the Howard G Buffet Foundations who have provided US$ 50 million to research centres in Africa to help develop drought-tolerant crops. Although in a different economic context, farm incomes in developed countries have also been squeezed by rising input costs and volatile commodity prices and thus farmers are carefully evaluating their production systems including the use of transgenic crops to either reduce input costs and or increase production or product value/quality. In the following sections, the effects of transgenic crops are considered in relation to crop yield, inputs such as pesticides and their effects on overall profitability.

Yield impacts

The release of the first transgenic events with insect resistance (*Bt*) or HT (Schuler *et al.*, 1998; Bates *et al.*, 2005) was not engineered to increase yield directly, but experience has shown that, by reducing losses from pests and weed competition, these varieties have in many cases delivered increased yields when compared with conventional crops.

For *Bt* cotton, Fernandez-Cornejo and Caswell (2006) reported that the increases in cotton yields in the Southeast United States were associated with the adoption of HT and *Bt* cotton in 1997. The same authors quote a 2001 US government survey data showing that maize yield was 9% higher for *Bt* maize than for conventional maize. Gianessi (2008) reported the outcome of a study in Mississippi over 3 years, in which *Bt* cotton produced higher lint yields and had an economic advantage when compared with conventional cotton varieties. Although the transgenic varieties in years two and three had greater costs associated with insect control, the economic advantage associated with the transgenic cotton for the 3 years was $82, $24 and $53 per acre, respectively, when compared with conventional cotton varieties.

In China, *Bt* cotton was first approved in 1997 and by 2004 accounted for 69% of cotton grown in China, with 100% adoption in Shandong province, where pest pressure was greatest (James, 2008). Approval came later in India, in 2002, but as early as 2006, India's *Bt* cotton area exceeded that of China, and in 2008 accounted for 80% of India's cotton output (James, 2009). Karihaloo & Kumar (2009) noted that between 2003–04 and 2006–07 cotton yields in India indicate a significant yield advantage of more than 30% with *Bt* cotton compared with conventional varieties with corresponding increase in farm income.

Yield enhancement varies depending on environment and the local intensity of pest and weed pressures. Commenting on yield increases obtained by *Bt* maize farmers in Spain, Gomez-Barbero *et al.* (2008) observed regional differences in yield between *Bt* and conventional maize ranging from −1.3% to +12.1%, with the yield advantage of *Bt* directly related to local pest pressure. They noted that *Bt* technology performed differently in the three regions studied, and this variability was explained by heterogeneity between farmers, differences in pest pressure, agro-ecological conditions and the fact that *Bt* technology may not yet have been introduced in varieties suitable for all regions.

Carpenter *et al.* (CAST, 2002) found that the trend in soya bean yields was continually upward through to 2001, a year in which 68% of the total soya bean area was planted with HT soya bean varieties. The study of Fernadez-Cornejo and McBride (2002) suggests that for HT soya bean, a 10% increase in adoption in the USA would lead to a 0.3% yield increase. At the same time, the yield effect seems to be compensated for by the higher seed prices as the authors found that a 10% increase in adoption would lead to no change in net returns on the farm, but the more recent data quoted above for the continuing increase in the numbers of farmers adopting HT soya bean suggest that farmers are finding sufficient benefits overall. Better results were obtained for HT corn where a 10% increase in adoption generated a 1.7% increase in yield and a 1.8% increase in net returns.

Commercial planting of HT soya beans in Romania between 1999 and 2008 was associated with an average increase in yields of 31% because of improved weed control, especially of difficult-to-control established weeds such as Johnson grass. A recent report on the sustainability of soya bean production in the USA (CAST, 2009) suggests that about 29 Mha of soya bean are grown each year in 31 states, covering about 22% of the total crop area of the United States. Of this, 92% is now glyphosate-resistant HT, and thus, it is essentially the 'conventional' growing system.

The Canola Council of Canada reported yield increases of up to 10% for transgenic compared with conventional varieties of canola. Direct comparison between mean yields of adopters versus non-adopters needs treating with caution as the adopters could be the more productive farmers anyway. HT Canola was grown commercially in Canada for the first time in 1997. Within 6 years of the transgenic varieties being available, over 90% of the area was HT Canola and the overall area of the crop grown had increased from 12 to 16 Mha. One of the main reasons for adoption was that HT canola is used as a 'cleaning crop'. In this way, the need for fallow is removed and farmers can have one more crop in the rotation. Phillips (2003) reported an economic benefit of C$ 28 per ha for HT over conventional. Gusta *et al.* (2010) suggested based on a survey of growers that this figure had increased to C$38 per ha.

These data suggest that across a range of agro-ecological zones, the four main transgenic crops have at worst been neutral in relation to yield and in many cases have increased yields.

Input impacts

Early transgenic events have been associated with improving the management of crops through pest resistance and/or weed control. This has often been associated with reduced pesticide use, or the use of cheaper pesticides with wider efficacy, thus having the potential to improve profitability. Qaim (2005), in a review of adoption of transgenic crops in developing countries, reported average pesticide savings between 33% and 77% for HT and insect-resistant (IR) events, commenting that the savings for HT soya beans are from the lower cost of glyphosate relative to other herbicides, while insecticide savings for *Bt* cotton are directly from reduction in quantity applied. Reporting in more detail, Qaim and Traxler (2005) noted savings of 24% in weed management costs in favour of HT soya bean when compared with conventional soya bean weed control programmes, commenting that glyphosate is usually cheaper than other herbicides. The benefits to Argentine farmers who had adopted HT soya beans was estimated to be $30 per ha based on a cost of the technology of $3 per ha, thus providing an additional margin of $27 per ha. The introduction of HT soya beans encouraged minimal tillage systems, which resulted in fewer tillage operations resulting in lower fuel input cost and reduced the time needed for harvesting, and consequently it has reduced labour and machinery costs by 14%.

For farmers in developing countries, Qaim reports that input savings alone outweigh the additional seed cost in all regions with high adoption rates, and in most cases, farm incomes are further enhanced by the improved yield because of more efficient control of crop losses.

As noted previously, farmers in developed countries, notably in the USA, pay more for HT soya bean seed than conventional seed. Bonny (2008) identifies the associated agro-economic effects that enable farmers in USA to offset this 'technology fee':

1. Ease of weed management using glyphosate as sole herbicide
2. Flexibility arising from longer period available for application
3. Reduced overall cost of herbicide treatments
4. Reduced risk of incomplete weeding
5. Easier crop rotation associated with less herbicide residue
6. Generally fewer herbicide treatments
7. Reduced labour and equipment costs
8. Opportunity for conservation tillage.

These advantages are offset by the cost of precautions to avoid build up glyphosate resistance, but the necessary precautions are now well understood. Responses to the build up of resistance in the context of HT soya bean production in Argentina were reported and discussed by Binimelis *et al.* (2009). Similarly, in commenting on the use of refuge areas as a strategy to delay the build up of insect resistance, Tabashnik (2008) noted that there had been a decade of resistance monitoring data for six major pests targeted by *Bt*, demonstrating the success of refuges; resistance had been detected in only one of the six pests and that only after 7–8 years. Seed suppliers have attempted to make provision of *refugia* a mandatory part of stewardship agreements with adopters particularly to comply with EU regulations, with only partial success. Strategies to minimize build up of resistance are discussed later in the paper.

It was noted at an early stage that transgenic crops have the potential to reduce the indirect application costs, such as reduced field operations and associated reductions in diesel usage (Phipps and Park, 2002). In the case study mentioned earlier of maize grown in Florida (Gianassi, 2008), there was a 79% reduction in insecticide use, and a corresponding $3.9 million per year increase in production value. The change in production costs was estimated to provide $1.3 million in net savings in insect control. Farmers in Florida would on average save $33 per ha. Gianessi further reports that in 2005, the use of HT soya beans was estimated to cost less than the effective alternative programmes by an average of $45 per ha, thus reducing farmer input costs by $1.17 billion on the USA's 26 Mha of HT maize.

The US National Centre for Food and Agricultural Policy (NCFAP) estimates that the cost advantage to the HT maize weed control programme in 2005 was $23.7 per ha in comparison with weed control programmes in conventional maize. Thus, with 11.3 Mha of HT maize planted in 2005, the aggregate net value to the US farmers of HT maize was estimated at $269 million. This figure has increased markedly as the area of HT maize has continued to increase.

In marked contrast with conventional canola crops in Canada where herbicide application rose by 29% between 1996 and 2000, the herbicide application rate in transgenic crops declined by 20%. Herbicide use per hectare in HT canola has remained consistently lower than conventional canola. The mean amount of herbicide applied in conventional canola from 1996 to 2000 was 0.69 kg/ha, which was significantly higher than the 0.34 kg/ha applied to HT canola (Brimner, 2004).

In addition to the above direct benefits, Beckie *et al.* (2006) reported that HT canola enabled Canadian farmers to plant earlier in the year, achieving higher yields from better utilization of snow-melt moisture and from reduced environmental stress during flowering. Early planting also introduced operational diversity, particularly in relation to weed management systems, which has lead to increases in overall economic performance (Gusta *et al.*, 2010).

Such changes in farming system with transgenic crops are common, and the glyphosate-resistant weed control package for soya beans has led to changes in rotation and fallowing practices. In Louisiana, conventional practice for many years has been to grow sugarcane for 3–5 years, followed by crop destruction and a fallow period when glyphosate is used to reduce Johnson grass levels. Research has shown that, instead of fallowing, the field can be planted with glyphosate-resistant soya beans, and the glyphosate usage will reduce the Johnson grass levels for the subsequent sugarcane crop while at the same time resulting in a profitable soya bean crop instead of a non-crop fallow period (Gianassi, 2008). Clewis and Wilcut (2007) also confirmed the economic advantage of weed management using strip tillage in transgenic cotton, compared with conventional crop and tillage systems. Their data showed that economically effective weed management can be obtained in both conventional and strip-tillage transgenic cotton production environments.

In relation to cotton in Argentina, Qaim *et al.* (2003) reported that *Bt* cotton could halve pesticide use while also increasing yield. However, Jost *et al.* (2008), considering the growth of transgenic cotton in Georgia, USA, suggested that although pesticide usage was reduced in transgenic crops, the overall economics when compared with conventional systems was not significantly different. It is also interesting to note that in villages in India, women earn more from *Bt* cotton as they traditionally do the picking and men do the spraying, the amount of which has been reduced because of the introduction of *Bt* cotton (Subramanian and Qaim, 2009). In addition, Raney (2006) has shown that even when allowing for the higher seed costs of transgenic varieties, the use of *Bt* cotton in Argentina, China, India, Mexico and South Africa increased yield of lint, revenue and profit and reduced pesticide costs.

More advanced transgenic cotton varieties such as Bollgard II, which contains two *Bt* genes and express two cry-proteins (Cry1Ac and Cry2Ab2), are now available and are becoming widely used. Gore *et al.* (2008) conducted experiments with two such varieties and confirmed that cotton yields suffer little damage even under extreme high pressure of bollworm infestation unlike those with a single gene insertion. Vitale *et al.* (2008) comments that experimental station results appear to be conservative in their assessment of Bollgard II because the observed pest densities were lower than that typically found under actual farming conditions.

In summary, the adoption of insect- and herbicide-tolerant varieties often leads to reductions in pesticide applications when compared to 'conventional systems', with resultant cost savings. Farmers will increasingly be able to purchase varieties with stacked traits to match specific agronomic issues they are facing (Stein and Rodriguez-Cerezo, 2009). The area of transgenic crops grown with stacked traits is increasing, and the use of such biotechnological innovations should lead to further reductions in pesticide use and increased yields.

Sharing of economic benefit

There has been considerable debate about the uptake and economics of transgenic crops in developing countries (Frow *et al.*, 2009; Sonnino *et al.*, 2009), although Brookes and Barfoot (2008) report that a common cost ratio applies across all the transgenic crops: that is, payments to the seed supply chain (including sellers of seed to farmers, seed multipliers, plant breeders, distributors and the transgenic technology provider) are typically about one-third of the net benefit. They provide an overview of the economic benefits for different countries between 1996 and 2007 (Table 2).

Table 2 Economic impact of transgenic crops: 1996–2007, US$M

Country	Cumulated economic benefit 1996–2007, US$M
United States	19789
Argentina	8184
China	6740
India	3181
Brazil	2933
Canada	1643

Adapted from Brookes and Barfoot (2009).

Extensive *ex post* studies of transgenic crop adoption have been conducted for *Bt* cotton in Argentina, China, India, Mexico and South Africa (Raney, 2006). Yield improvement, higher revenue and lower pesticide costs are widely reported for *Bt* cotton, producing in most cases significant net benefit after accounting for higher seed prices. Other large-scale transgenic crops include HT soya beans, grown in Argentina, Brazil and Paraguay. James (2009) reported that in 2009, about 77% of worldwide soya bean production was transgenic and that the cumulative benefits in Argentina between 1996 and 2005 were US$20 BN.

Overall, the evidence strongly suggests that in both developed and developing countries, the adoption of transgenic crops can increase the farmer's income. The increase in income to small-scale farmers in developing countries can have a direct impact on poverty alleviation and quality of life, a key component of sustainable development. Bennett *et al.* (2006) compared the performance of over 9000 *Bt* and non-*Bt* cotton farm plots in Maharashtra in India and reported that *Bt* cotton varieties had a significant positive impact on average yields and on the economic performance of cotton growers. However, they note that not all farmers had benefited from increased performance of *Bt* varieties because of regional variations in agro-climate conditions and thus yield. Bennett *et al.* (2006) reported similar results following a 3 year study in South Africa of resource-poor smallholder cotton farmers. Their results conclusively show that adopters of *Bt* cotton have benefited in terms of higher yields, lower pesticide use, less labour for pesticide application and substantially higher gross margins per hectare. They go on to note 'that the smallest producers are shown to have benefited from adoption of the *Bt* variety as much as, if not more than, larger producers.' This suggests that transgenic crops do have a key role to play in poverty alleviation and thus international development goals.

Environmental dimension

The MDGs are overarching in their nature, although Goal 7 refers specifically to environmental sustainability. This illustrates the recognition by the international community of the strong links between environment and economy and the fact that continued economic development and the state of the environment are very closely linked (Arrow *et al.*, 1995; IAASTD, 2009, UNDP-UNEP 2009). The most important comprehensive international plan of action is Agenda 21 (UNCED, 1992), which relates to all areas in which human's effect their environment. The following sections discuss how transgenic technology may have an impact on environmental sustainability.

Land use and soil quality

Within Agenda 21, there is a section on the conservation and management of resources for development. Managing fragile ecosystems by combating desertification and drought is a focus within this section. Desertification is a recognized worldwide environmental issue. The most recent action to tackle this issue resulted in the United Nations Convention to Combat Desertification in those countries experiencing serious drought and/or desertification, particularly in Africa (UNCCD, 2008). The aims of this convention are to combat desertification and through international partnerships to prepare long-term national action plans to link land use and livelihood to the target of sustainable development and to mitigate the effects of climate change, and UNCCD is the only legally binding convention focused on combating desertification.

The main mechanisms by which transgenic crops have contributed directly to land and soil quality is that they are conducive to minimum and no-till soil management techniques. These reduce the potential for soil erosion and increase the storage of organic matter in the soil, which will in turn help to retain soil moisture. Given an appropriate combination of herbicides and crops that are resistant to those herbicides, no or minimum or conservation tillage can be practiced, which reduces soil erosion and associated loading of pesticides, nutrients and sediments into the environment and decreases direct energy input required for crop production. However, it should be noted that no-till can lead to increases in both pesticide and fertilizer requirements, particularly in the initial years of adoption.

The use of HT canola in Canada is mainly because it allows the use of canola as a cleaning crop within the rotation. Thus, the need for fallow and mechanical weeding is removed, meaning that over the rotation, the overall crop productivity increases in relation to inputs such as chemicals, fertiliser and mechanization. Similarly, the American Soya bean Association strongly supports adoption of transgenic soya beans (Docket No. APHIS 2007-0019) and in particular describes the associated conservation tillage crop production methods as having decreased soil erosion because of wind and water by 90%, and greatly reduced consumption of fuel required for US soya bean production.

In relation to soil biological properties, studies with reduced tillage have shown that these systems achieved considerable success in enhancing soil quality and preventing soil erosion (Christoffoleti *et al.*, 2007) and that when HT crops were grown under these conditions, soils showed that HT maize and cotton maintained higher levels of soil organic carbon and nitrogen when compared with conventional crops (Christoffoleti *et al.*, 2008). Results from these studies indicate positive differences attributable to the interaction of conservation practices and glyphosate-resistant crop.

Crop residues are the primary source of soil carbon enrichment, and root exudates govern which organisms reside in the rhizosphere. Therefore, any change to the nature or quality of returned crop residues could modify the dynamics of the composition and activity of organisms in soil. It has been suggested that *Bt* crops may change the microbial dynamics, biodiversity and essential ecosystem functions in soil, because they usually produce insecticidal Cry proteins through all parts of the plant. It is therefore crucial that risk assessment studies on the commercial use of *Bt* crops consider the impacts on organisms in soil. However studies, reported from China by Liu *et al.* (2008), have shown that *Bt* rice has no adverse effect on rhizosphere soil microbial community composition and concluded that the Cry1Ab gene had no measurable adverse effect on the key microbial processes or microbial community composition.

Icoz and Stotsky (2008) reviewed the effect of *Bt* crops on soils. The review discusses the available data on the effects of Cry proteins on below-ground organisms, the fate of these proteins in soil, the techniques and indicators that are available to study these aspects. They conclude that the use of IR *Bt* crops, expressing highly specific *Bt* proteins, had no marked effects on woodlice, collembolans, mites, earthworms, nematodes, protozoa, and the activity of various soil enzymes and represented an opportunity to replace the use of broad-spectrum insecticides.

Linking directly to the issue of desertification, some of the transgenic events in the pipeline related to drought- and salt-tolerant varieties are likely to enable the cultivation of crops in areas where yields are currently low or indeed in areas where cultivations has been abandoned. The problems associated with soil salinization, which affects 20%–50% of the global irrigated farmland, have been reviewed by Geissler *et al.* (2008).

Slowing of deforestation and the designation of forests for biodiversity conservation is one of the targets of the MDGs. While the original transgenic events were not primarily designed to increase yield, yield increases have in many cases occurred. However, it is anticipated that in the medium term, events in the pipeline are likely to have more significant impact on yield, and this could lessen the pressure to further expand agricultural production into natural forest areas.

In summary, transgenic crops have enabled and encouraged some farmers to adopt conservation tillage techniques, thus reducing soil erosion and potentially improving soil quality through a gradual accumulation of organic material in the soil. Emerging technologies are likely to enhance the potential for cropping in arid and saline environments, potentially bringing degraded areas back into production. Drought is the most significant environmental stress in agriculture worldwide, and improving yield under drought conditions is a major goal of plant breeding. A review by Cattivelli *et al.* (2008) of improvements in drought tolerance considers the new insights into the complexity of plant mechanisms enabled by genomics, but there is still a large gap between yields in optimal and stress conditions. Minimizing the 'yield gap' and increasing yield stability under different stress conditions are of strategic importance in guaranteeing food for the future. In the longer-term modifications aimed more specifically at stabilizing yields in stressed environments and increasing yields in more productive regions may help to offset the demand for the conversion of further forested lands to arable production, this seeming an inevitable consequence of the expanding world population.

Greenhouse gases

The first major international treaty established to tackle the emission of greenhouse gases (GHG) was the United Nations Framework Convention on Climate Change (UNFCCC, 1998). The objective of this treaty was to achieve 'stabilization of greenhouse gas concentrations in the atmosphere at a low enough level to prevent dangerous anthropogenic interference with the climate system'. The recognition of the importance of legally binding targets led to the Kyoto Protocol, which required the developed countries to reduce greenhouse gas emissions to an average of 5.2% below their 1990 emissions levels by 2008–2012.

The use of transgenic crops has the potential to reduce GHG via several mechanisms. If less pesticide is required, then this will reduce emissions because of a reduction in emissions related to their manufacture. Lower rates of application will reduce the amount of fuel required, and if this is combined with lower levels of cultivation, for instance related to minimum tillage or no till, then GHG savings could be significant (Phipps and Park, 2002). Subsequent ISAAA reports have suggested significant savings in carbon equivalents. For instance in 2007, they estimated savings of 1.1 BN kg of CO_2 because of the usage of less sprays. However, they also estimated an additional saving of 13.1 BN kg CO_2 in cases where the use of herbicide-tolerant varieties had facilitated the use of min-till systems (ISAAA, 2009).

The UN Food and Agriculture Organization (FAO, 2008) have quantified the contribution of conservation tillage to carbon sequestration. They state that soil carbon sequestration during the first decade of adoption of best conservation agricultural practices is 1.8 tons CO_2 per hectare per year, with better cycling of nutrients and avoiding nutrient losses among the key benefits to farmers. Thus, in systems where transgenic crops enable wider use of conservation tillage systems, this is likely to be accompanied by reductions in GHG emissions.

Glover *et al.* (2008) reviewed the relevance of biotechnology in the context of climate change. They note that the agricultural sector accounts for 16%–18% of Australia's net greenhouse gas emissions, which includes nitrous oxide (primarily from fertiliser applications), methane (primarily from livestock) and carbon dioxide. As a net emitter, agriculture needs to reduce emissions and/or increase carbon storage. This is a particular challenge in intensive cropping systems. Agricultural soils can act as a sink for carbon storage, and stored carbon can be increased by growing trees, changing cultivation and other cropping practices.

There has also been considerable interest in the use of transgenic crops for biofuel production to provide greener energy, thus providing a renewable fuel with related greenhouse gas savings. Current transgenic events probably do not have sufficient advantage over conventional varieties to overcome the generally poor financial balance of growing crops for biofuels (Ceddia *et al.*, 2009; Ninni, 2009). Edgerton (2009) has however suggested that the development of transgenic crops modified for drought tolerance will provide increased yields in drier areas and increased average yields in rain-fed systems by reducing the effects of sporadic drought and by decreasing water requirements in irrigated systems. This development could help biomass from non-food crops grown on marginal land to be viable as biofuel feedstock.

In summary, there is increasing evidence that suggests that the use of transgenic technology has had direct and indirect benefits in relation to GHGs. Brookes and Barfoot (2009) estimate that between 1996 and 2007, the use of transgenic crops reduced carbon dioxide emissions by 7090 million kg. They estimated that this was equivalent to taking 3.6 million cars off the roads for 1 year. Further, medium-term varietal developments and the wider adoption of conservation tillage in combination with transgenic crops suggest they do have the potential to help meet the targets set as part of the Kyoto protocols.

Water

The MDGs aim to halve the number of people without access to safe drinking water, halve the proportion of people without access to basic sanitation and develop integrated water resource management and efficiency plans by 2015. The International Code of Conduct on the Distribution and Use of Pesticides (FAO, 2005) aims to form voluntary standards for public and private use of pesticides. This code aims to ensure efficient use of pesticides and the establishment of national regulations on pesticide use and where possible to minimise risk to both human health, biodiversity and to reduce the risk of water pollution.

This is an important issue for farmers in Asia, North and Central America and Europe, and agriculture accounts for 86%, 49% and 38% of total annual water withdrawal, respectively. Agricultural practices have a considerable impact on water quality as both fertilisers and pesticides may pollute water courses, thus reduction in pesticide use is likely to improve water quality. Industry data suggests that between 1996 and 2007, there has been an accumulated saving in pesticide of 359 000 metric tons of active ingredient, which equates to a 17.2% reduction in associated environmental impact, in part because of the lower toxicity rating of glyphosate, the key herbicide used for transgenic crops modified for HT (James, 2008).

Many of the herbicides used in conventional crop production systems in the USA have led to their detection in streams, rivers and reservoirs at levels exceeding the maximum contaminant level or health advisory level for drinking water (Thurman *et al.*, 1992). With the commercial introduction of transgenic HT crops in the USA in the late 1990s, it was possible to replace some of the persistent residual herbicide with short half-life contact herbicides that may be more environmentally benign (Fernandez-Cornejo and Caswell, 2006). A recent 4-year study conducted by Shipitalo *et al.* (2008) would support this hypothesis. It showed that the use of transgenic soya bean and maize crops modified to be tolerant to either glyphosate or glufosinate and completely or partially replacing the residual herbicides normally used in conventional crop production systems reduced the environmental impact of herbicide use.

Work reported from Australia (Crossan and Kennedy, 2004) has also shown that the introduction of HT crops can greatly reduce the probability of surface run-off and reduce the risk of water contamination when compared with herbicides used with conventional crops. They reported that the precautionary guideline value for diuron would be exceeded eight times out of ten, whereas a cotton farmer is 500 times more likely to win the lottery (probability one in 10 million) than exceed the precautionary guideline value for glyphosate (probability 1 in five billion 1.9×10^{-10}).

In summary, there is a body of field evidence to indicate that the use of HT crops can significantly reduce surface run-off of herbicides when compared with herbicides used in conventional crops and that this can reduce the need and costs associated with the treatment of drinking water.

Coexistence

Adventitious presence (the accidental or unintentional inclusion of foreign matter) can be problematic and may occasionally lead to economic consequences. There are specific issues relating to coexistence and the possibility that a transgenic crop may have a negative impact on the purity of surrounding crops (Brookes and Barfoot, 2003). Serious concerns related to coexistence have been persistently voiced by some member states of the European Community (EU, 2003). These are generally issues within the productive agro-ecosystem rather than having larger-scale ecological impacts.

Kershen and McHughen (2006) included discussion of coexistence in a review of economic concerns arising from adventitious presence of foreign matter in an agricultural commodity consignment. With regard to approved transgenic crops, the main issues were not food safety or environmental protection but contract specifications and consumer preferences. Langhof *et al.* (2008) noted that although maize has no wild relative in Europe, the introduction of transgenic maize has created the need for rules to keep its adventitious presence in conventional or organic maize below an acceptable level. As in the case of certified seed production, separation by distance is the most common safeguard. Langhof *et al.* conducted field trials and found as expected that outcrossing rates decreased with increasing separation distance, confirming the finding of Messeguer *et al.* (2006) that about 20 m is sufficient to maintain the adventitious presence as a result of pollen flow below the EU tolerance threshold of 0.9%. Rong *et al.* (2007) reported similar tests of separation distances for transgenic and non-transgenic rice, noting that although rice pollen is capable of dispersing at least 100 m from its source, extremely low frequencies of transgene flow occurred, with <0.01% in all cases at a separation distance of 6.2 m.

Messean *et al.* (2006) provide a comprehensive review of coexistence of transgenic and non-transgenic crops in European agriculture, with case studies of seed and crop production of maize, sugar beet and cotton (maize being the only major transgenic crop authorized for cultivation in the EU). Simulations suggested that after the introduction of transgenic rape in a region, adventitious presence will not increase significantly after the second rotation, unless farm-saved seed is used, which would lead to continuous subsequent increase in adventitious presence. For maize, simulations suggested that coexistence in seed production is feasible for a threshold of 0.5% with little or no change in current practice; coexistence of non-transgenic seed with transgenic maize crops would require the isolation distance to be increased from the current 200–300 m to 400–600 m.

Beckie and Hall (2008) reviewed a number of methods for predicting pollen-mediated gene flow in the context of EU concerns surrounding coexistence of transgenic with conventional crops. They concluded that seed growers should be able to achieve adventitious presence well below 0.3% using simple, inexpensive and reliable assays, based on North American experience. Contribution to adventitious presence by oilseed rape volunteers is best mitigated by careful management, including not growing conventional rape on fields previously planted with transgenic cultivars; with rape, gene flow via seeds, not pollen, may be a greater source of adventitious presence. Beckie and Hall found that experimental results and modelling predictions for outcrossing in rape, maize and wheat reveal that an extended isolation barrier is only required between fields of less than about 5 ha to maintain gene flow below the EU threshold; and even for these small fields, a 50 -m barrier is sufficient. This is contrary to most recommendations, which Beckie and Hall believe to be excessively cautious.

Davison (2010) highlighted inconsistency among member states of the EU in the formulation of coexistence regulations on buffer zones and isolation distances, in spite of the creation of the European Coexistence Bureau established jointly by DG Agriculture and EC Joint Research Centre 's Institute for Prospective Technological Studies. Devos *et al.* (2008) noted that it was the European policy of subsidiarity that allowed member states to stipulate distances ranging between 15 and 800 m ostensibly to ensure <0.9% of transgenic maize in conventional maize, commenting on the irony that by introducing coexistence regulations, the EU created a further barrier to the cultivation of transgenic crops. In a subsequent review, (Devos *et al.*, 2009) explored whether national or regional strategies comply with the stated principle that measures should be both science-based and proportionate, concluding that some of the proposed isolation distances are excessive from a scientific basis, out of proportion to heterogeneity in the agricultural landscape and enforce an unreasonable economic disadvantage to farmers by limiting their choice of crop.

Biodiversity

The United Nations Convention on Biological Diversity (CBD; http://www.cbd.int) established at the Earth Summit in Rio de Janeiro in 1992 has three objectives, 'the conservation of biological diversity, the sustainable use of its components and the fair and equitable sharing of the benefits arising out of the utilization of genetic resources'.

Under the CBD treaty, nations are expected to identify the important components of biological diversity that require conservation, to prevent the introduction of, or to eradicate alien species and to control any risks posed by genetically modified organisms. In relation to targets set under the CBD, it is unlikely that transgenic crops will have a direct measurable positive or adverse effect at a regional scale. However, if the indirect impact of growing transgenic crops is to reduce the ongoing expansion of agricultural zones into non-cultivated ecosystems, then the growing of transgenic crops may help to facilitate the achievement of the wider biodiversity targets.

The implications of transgenic crop introduction for biodiversity are complex and have been the subject of considerable research and debate. (Roy *et al.*, 2003; Velkov *et al.*, 2005; Ferry and Gatehouse, 2009). There is a school of thought that questions whether sufficient biodiversity can be preserved when any farming is carried out on a large scale; Altieri (2004) claimed that there is a form of agrobiodiversity by which traditional methods are used, yields remain stable and food security is adequately protected, but Altieri does not suggest how this could alleviate hunger in developing countries or indeed meet the challenges of rising demand for food.

In the United Kingdom, where the average agricultural system can be described as high output, a 4-year study of the effect that weed management practices associated with transgenic HT crops on wildlife was conducted by UK government agency DEFRA, 1999–2002. A key finding was that biodiversity impacts between transgenic and non-transgenic crops were no greater than the impact of growing different species of conventional crops (ACRE, 2004). A 2-year farm-scale evaluation in Arizona of *Bt* cotton (Cattaneo *et al.*, 2006) reported negative effects on ant diversity and positive effects on beetle diversity, but here again the impacts of the transgenic crop were no greater than those of the non-transgenic crop.

Threats and opportunities facing UK biodiversity were assessed in a wide-ranging foresight exercise (Sutherland *et al.*, 2008); it was noted that a trend towards carbon and water conservation and pollution control will involve changes in conservation management practice, with significant consequences for biodiversity. On this scale of resource management, the minor impacts of transgenic crops on biodiversity are unlikely to be an obstacle to their adoption.

Weed and insect resistance management

The risk that weeds may become resistant to herbicide is well known. A collaborative monitoring study (Heap, 2010) identified 194 herbicide-resistant species in 19 herbicide groups. Of the 194, 19 species show resistance to glycines, including glyphosate. Strategies have accordingly been developed to manage the cultivation of glyphosate-tolerant transgenic crops so as to delay the emergence of resistant weeds. Hurley *et al.* (2009a,b,c) described the weed management programmes, best management practices and the economic effects for growers of transgenic maize, cotton and soya beans. Based on farm surveys in USA, they reported that the emergence of resistant weeds reduced the economic benefit of growing these herbicide-tolerant crops by up to about one-third. The adoption of HT soya beans and no-tillage agriculture in Argentina has increased the use of glyphosate as the main tool to control weeds. This has helped to reduce the density of many weed species but has increased the density of some others that were previously not always part of the community (Qaim and Traxler, 2005). Overall, two weed management practices were considered effective: the use of a residual herbicide with glyphosate and the rotation of crops.

Field studies of soya bean crops in northern and southern regions of USA reported by Scursoni *et al.* (2006) indicate that limited use of glyphosate has little long-term effect on weed diversity. Some of the new weed species found in the fields sprayed with glyphosate on no-till crops have shown a higher tolerance to glyphosate; in Missouri and farther south, long growing seasons allow weeds that emerge and grow late to escape single glyphosate treatments, and this may reduce crop yields substantially if not treated. In contrast, in Iowa and farther north, a single glyphosate application inhibits weeds sufficiently to maintain high soya bean yields obtained from transgenic crops modified to be resistant to glyphosate, but still permits expression of highly effective species richness. Thus, in northern temperate agro-ecosystems, one-pass glyphosate management systems in HT crops may serve agronomic and environmental needs simultaneously. The timing of pesticide application may have a bigger impact on biodiversity than the direct influence of the transgenic crop *per se.* For instance in North America, Bertram and Pedersen (2004) found that the impact on the weed community is mainly because of the changes in the management system (i.e. rotations, tillage systems and herbicides strategies) than the transgenic trait *per se*.

May *et al.* (2005) found that the use of HT sugar beet provided greater flexibility to manipulate weed populations. They found that without yield loss, the transgenic options enhanced weed seed banks and autumn bird food availability compared with conventional management and provided early season benefits to invertebrates and nesting birds.

The US Environmental Protection Agency has published a risk assessment procedure focused on plants expressing insecticidal proteins available in the commercial market, evaluated for potential non-target invertebrate risks (US

EPA, 2007). This relates to concerns that the use of broad-spectrum herbicides such as glyphosate could reduce weed seed availability and thus predation by a range of insects and also fears that IR varieties would have a negative impact on non-target species. Initial assessments are laboratory based using surrogate non-target organisms; if potential toxicity is identified, field experiments are then undertaken. Duan *et al.* (2009) used meta-analyses to test whether laboratory studies are consistent with field studies and reported findings that supported the validity of EPA's tiered approach, provided that the laboratory studies exposed non-target organisms to a full variety of ecological contexts, including indirect exposure via an intervening trophic level.

Monsanto maintain a website for insect-resistant MON810 YieldGard^{TM} maize (Monsanto, 2010). The website includes guidance for adopters on insect resistance management, and EU requirements for compliance. The advice for the *correct* use of MON810 maize is that the adopter must plant a refuge maintained and managed in the same way as the crop: it must be planted at the same time, irrigated in the same way and receive the same inputs. At least 20% of the hectares must be planted with maize hybrids that do not contain *Bt* technology, and the refuge area can be treated with insecticides only when corn borer pressure exceeds economic thresholds. Monsanto initiated a surveillance monitoring programme based on farm surveys (Monsanto, 2008), from which it was found that 18% of farmers planting MON810 in Spain in 2008 did not plant a refuge, an improvement on the 26% who did not plant refuges in 2007. In spite of these levels of non-compliance, monitoring did not reveal any resistance in insect populations.

Bt maize has been grown at the Vaalharts irrigation scheme in the Republic of South Africa since 1998, but Kruger *et al.* (2009) reported that refuge compliance was initially low, and farmers who did provide refuges generally preferred a permitted refuge option where 5% of the main crop area is planted to conventional maize. This practice seems to have allowed exposure of migrating larvae to sub-lethal doses of *Bt* toxin. Stem borer damage to *Bt* maize was first observed during 2005/2006, and during 2007/2008, stem borer infestation required the use of sprayed insecticides. Kruger *et al.* commented that farmers had become over-confident in *Bt* technology and ceased to monitor the crop for infestation; Kruger *et al.* concluded that non-compliance with refuge requirements contributed to selection pressure leading to insect tolerance to the toxin.

Sanvido *et al.* (2007) reviewed the environmental effects of 10 years of commercial cultivation of transgenic crops, including the loss of natural habitats caused by conversion of natural ecosystems into agricultural land, seen in relation to the environmental impacts of modern agriculture that has been practised over many decades. They opened their review by observing that the approval of transgenic crop varieties is more rigorously regulated than that of conventionally bred crops. They reached the firm conclusion that data available up to 2009 provided no scientific evidence that the commercial cultivation of transgenic crops has caused any impacts beyond those caused by conventional agricultural management practices. They noted that a truly precautionary policy towards approval of transgenic varieties should compare the risk of adoption against the risk of non-adoption.

In relation to insecticides, the more targeted application of the insecticidal chemical (plant expression as opposed to spray application) may limit the exposure level of many field arthropods. Beneficial, non-target arthropods can become exposed to insecticidal proteins produced in transgenic plants in several ways: by feeding on the plant parts themselves or through feeding on target or non-target herbivorous insects. Pilcher *et al.* (2005) studied the effect of *Bt* maize on non-target arthropods and found no significant effect on abundance of generalist predators. Mulligan *et al.* (2006) studied the potential impact of insect-resistant oilseed rape on an ecologically important beneficial predator, compared with the potential impact of the most widely used UK pesticide in rape cultivation. Neither genetic modification nor conventional pesticide treatment negatively affected the life history parameters of the beneficial insect. The result suggests that the cultivation of insect-resistant transgenic crops will have no greater impact than present cultivation methods.

Lu *et al.* (2010) conducted field trials over 10 years in a region of China where *Bt* cotton is widely grown and where the associated reduction in pesticide spraying has allowed unrestrained build-up of the population of mired bugs, which damaged not only the cotton crop but also adjacent fruit crops. Lu *et al.* concluded that comprehensive risk management is necessary to ensure sustainability of transgenic technologies. Lövei *et al.* (2009) reviewed numerous reports of the impact of *Bt* crops in laboratory settings and recommended widening the scope of environmental risk assessment. Shelton *et al.* (2009) agreed the importance of risk assessment of transgenic insect-resistant crops but were critical of the statistical methods employed by Lovei *et al.*

© 2010 The Authors

In summary, Baucom and Holt (2009) identified a need for collaboration between applied weed scientists and evolutionary ecologists, observing that weed adaptation to agricultural systems provides a view into the process of evolution as well as a challenge to food supply, particularly the processes involved in the evolution of herbicide resistance. An alliance of practical weed science with hypothesis-driven ecology may lead to better understanding not only of mutations that give weed persistence but also the genetic involvement in constraint of weed populations.

Social dimension

The social dimension is of paramount importance in the MDGs, particular relating to health, education, poverty reduction and human disease control. While early transgenic events were not engineered to have a direct impact on these factors, their take-up and use has had indirect effects in many areas, and new events and those in the pipeline may aid disease prevention and lead to health benefits (Newell-McGloughlin, 2008; Stein and Rodriguez-Cerezo, 2009). Earlier sections in this paper discussed the potential for transgenic crops to increase incomes and thus to alleviate poverty. Literature suggests that as incomes rise, people are able to access better education and health care, which thus impacts on the social dimension of sustainability (and indeed this principle underlies the MDGs). In the following sections, we consider indirect and direct human health effects of growing of transgenic crops.

Indirect health impacts

Indirect health effects will mainly arise from changes in the frequency of use and reductions in pesticide toxicity. In relation to toxicity, the Environmental Impact Quotient (EIQ) is a useful measure as it considers risks to farm workers and consumers as well as ecological risks (Brimner *et al.*, 2005). Pesticides with high EIQ values are considered to have a higher risk of potential impacts than those with low EIQs. Multiplied by the amount of pesticide applied, the EIQ can be used to calculate the potential environmental impact (EI) of individual pesticides or pest management programmes involving several active ingredients.

In Australia, with reference to *Bt* cotton, Knox *et al.* (2006) considered the impact of the transgenic proteins Cry1Ac and Cry2Ab on EIQ values. While the average insecticide EI for conventional cotton was 135 kg a.i./ha, the value for the *Bt* variety with two inserted genes was only 28 kg a.i./ha. Results of the EI evaluation indicate that there was a net reduction of at least 64% in EI from growing *Bt* cotton compared with conventional non-transgenic cotton.

In Canada, the growth of HT canola varieties increased from 10% in 1996, when the technology was first introduced, to 80% of the total area in 2000. From 1995 to 2000, the amount of herbicide-active ingredient applied/ha of canola declined by 43% and the EI per ha declined by 37%. Since 1996, herbicide use has shifted from broadcast applications of soil-active herbicides to post-emergence applications of herbicides with broad-spectrum foliar activity. The decline in herbicide use and EI since the introduction of HT varieties was because of increased use of chemicals with lower application rates, a reduced number of applications and a decreased need for herbicide combinations (Brimner *et al.*, 2004).

It is also worth noting that the introduction of HT soya beans, in particular, has changed patterns of use of chemical herbicides with glyphosate now being the most dominant herbicide, accounting for 92% of herbicide use on soya bean. It is classified internationally as a toxicity class IV pesticide, less toxic than many of the previously utilized herbicides.

Workers can be exposed to pesticides through direct skin contact or inhalation during application. Such exposure also may occur when safety periods between application and harvest are ignored or when pesticides are overused or used improperly. Pesticides from aerial spraying may also drift into neighbouring areas and expose residents. Research has indicated reduced incidence of pesticide poisonings in South Africa since the introduction of transgenic crops (Bennett *et al.*, 2006) and that reduced pesticide use has had health benefits among Chinese farmers (Huang *et al.*, 2002).

Direct health impacts

To date, direct health benefits have been relatively limited, although transgenic events in the pipeline could potentially have considerable health benefits. *Bt* varieties of maize were produced to protect plants against the European Corn Borer, which if pest levels are high can reduce crop yield by about 10%. There is a direct relationship between European Corn Borer infestation and ear rot, which is a result of secondary fungal plant infections of *Fusarium*, which results in greatly elevated levels of mycotoxins often in the form of fumonisin. The accumulation of mycotoxins in food and feed represents a major threat to human health and is linked to oesophageal cancer and neural tube defects. Major economic losses are associated with the effect of mycotoxins on human health and animal productivity. In the USA, Munkvold *et al.* (1999) showed that the fumonisin content of maize grain produced from *Bt* varieties was greatly reduced when compared with grain from conventional varieties. The conclusion is that the use of *Bt* maize not only has the potential to increase grain yield in areas where there is high infestation of European Corn Borer but will provide safer food and feed for humans and animals.

Work is also well advanced in the development of transgenic crops that will have a direct impact on health. For example, Chu *et al.* (2008) has shown that the most potent peanut allergens can be silenced in transgenic plants. Newell-McGloughlin (2008) lists examples of developments that improve protein quality, modify carbohydrates and fatty acids, add micronutrients and introduce functional secondary metabolites.

Nutrition

There are well-known dietary benefits associated with very long-chain omega-3 polyunsaturated fatty acids, originally identified with fish oils. Oilseed plants rich in omega-3 fatty acids, such as flax and walnut oils, contain only the 18-carbon omega-3 polyunsaturated fatty acid alpha-linolenic acid, which is poorly converted by the human body, but Damude and Kinney (2008) showed that is now possible to use genetic engineering to produce oilseeds such as soybean and canola that have nutritional properties similar to fish oils. Studies have shown that the use of oil from transgenic soya in which the fatty acid metabolic pathways have been modified can increase the n-3 VLC-PUFAs of chicken meat (Rymer and Givens, 2009).

Mayer *et al.* (2008) note that the desired traits for biofortification may not be present at all in a food crop; the best-known example being Golden Rice, in which the carotenoid biosynthetic pathway has been reconstituted in non-carotenogenic endosperm tissue, as a means to deliver provitamin A. The inability of governments worldwide to agree to distribute Golden Rice stirs strong emotions and little progress in terms of growth has been made despite the properties of Golden Rice being well known. (Golden Rice Project 2000).

Stevens and Winter-Nelson (2008) examined the acceptance of provitamin A-biofortified maize through taste tests and a trading experiment conducted in Maputo, Mozambique. These results indicate that orange maize meal is an acceptable product to many consumers. Such potential developments are of huge potential significance as Black *et al.* (2008) estimate that 600 000 children die each year from vitamin A deficiency. Clearly, these aspects relating to health and nutrition are a fundamental part of the MDGs.

Nutrition has already been enhanced via biotechnology with quality protein maize (QPM), developed specifically to improve amino acid composition with the aim of reducing malnutrition in parts of Sub-Saharan Africa. Krivanek *et al.* (2007) report that the International Maize and Wheat Improvement Centre (CIMMYT) has collaborated with IITA in Ibadan, Nigeria, and National Agricultural Research Systems (NARS) to develop a broad range of QPM cultivars. Breeding and dissemination is making good progress, with commercial cultivars released in 17 countries.

In conclusion, it appears that in relation to the social dimension of sustainable development, transgenic crops can have indirect impacts on health particularly via reduction in the handling and use of pesticide. However, ongoing developments in biotechnology, particularly related to the nutritional modification and enhancement of food, have the potential to radically improve human health and nutrition in both developing and developed countries.

Discussion and conclusions

It is acknowledged that the world will face a number of serious challenges if development is to proceed on a sustainable pathway. Indeed, many people in the world still live in extreme poverty and are without adequate nutrition, health and education. World population continues to grow at 80 M per annum, and it has been estimated that the requirement for food will double by 2050. However, there is little or no scope to expand the existing agricultural footprint without further damaging natural ecosystems. Climate change threatens to reduce productivity in many regions and is itself driven by the use of fossil fuels that provide a great deal of the motive power in intensive and productive agricultural systems.

To meet these challenges humankind is likely to require a range of productive options and tools if wider-scale social deprivation and environmental degradation is to be avoided. Crop biotechnologies appear to provide such a range of tools and have started, and may continue, to contribute to sustainable development. In this paper, we have reviewed a wide range of literature that suggests transgenic crops can contribute to international targets and goals related to sustainable development. For instance, China has invested very extensively in biotechnology with the aim of ensuring food security. For example, work is well advanced with rice varieties that are tolerant of drought and other stresses (Huang *et al.*, 2009).

However, the growing of transgenic crops continues to be controversial despite the 134 Mha grown in 25 countries, the cumulative area grown since 1996 being over 2 BN ha. Fears and claims of possible adverse effects of biotech foods and crops on humans and the environment have yet to be substantiated; no ill effects have been documented after 12 years of extensive cultivation in diverse environments, and after the consumption of biotech foods by more than a billion humans and by a larger number of animals. Lemaux (2008) offers an extensive review of ways in which research using rDNA methods has 'opened the door' to changing agricultural crops in ways not previously possible. Although she recognizes the need to proceed with caution, Lemaux sees a responsibility to utilize the technology where it can improve human health, preserve the environment and assist in providing adequate nutrition.

Looking further into the future, Ridgwell *et al.* (2009) note that crop plants exert an important influence over the climatic energy budget, because of differences in their albedo (solar reflectivity) compared to soils and natural vegetation. They propose a bio-geoengineering approach to mitigate surface warming, in which crop varieties having specific leaf glossiness and canopy morphological traits are specifically chosen to maximize solar reflectivity. They estimate the near-term potential for bio-geoengineering to be a summertime cooling of more than 1 °C throughout much of central North America and mid-latitude Eurasia, equivalent to seasonally offsetting approximately one-fifth of regional warming because of doubling of atmospheric CO_2.

The review undertaken here suggests there have been potential benefits since the release of transgenic crops and that these can be evidenced in each of the three key dimensions of sustainable development.

Economic dimension

Poverty alleviation is a cornerstone of sustainable development and is critical to progress the MDGs. Most of the evidence suggests that at worst, transgenic crops are cost neutral, although the bulk of evidence suggests an economic benefit across the range of countries growing them. Analysis by Brookes and Barfoot (2008) suggests that the cost of accessing transgenic technology worldwide in 2006 was US$2687M, leaving farmers worldwide with net benefit of US$6915M. Of these totals, they estimate that farmers in developing countries pay only US$742M for the technology and achieve benefits of US$3713M, a cost/benefit ratio of 5 to 1. Advantages relate to input savings and in some cases increases in crop yield and quality.

Some researchers have attempted to quantify the longer-term economic consequences of adopting transgenic crops. The work by Wesseler *et al.* (2007) on take-up in the then EU-15 suggested that there were good economic reasons for adopting *Bt* and HT maize immediately when evaluating at the national economy or farm level. They went on to suggest that the early adoption by Spain of *Bt* maize led to an economic advantage of €135M, while the decision of France not to adopt over the same 5 -year period meant a lost economic opportunity of about €310M.

Environmental dimension

Soil erosion, desertification, climate change, water related issues and biodiversity are all of international importance in relation to sustainable development, and evidence suggests that transgenic crops can have positive impacts in many of these areas.

For instance, transgenic crops have the potential to reduce soil erosion via association with lower levels of cultivation. Currently available transgenic events are all related to the modification of pesticide use, and this has the potential to reduce the environmental loading and in particular the movement of highly toxic pesticides into water. When combined with reductions in field operations associated with multiple pass spraying, this can lead to reductions in the amount of GHGs emitted. In these key areas, transgenic crops are already having benefits, and it is likely that these will continue to accumulate as the areas being grown expand.

Biodiversity impacts related to transgenic crops are not as easy to quantify. Losey *et al.* (1999) caused alarm with results of a test in which pollen from *Bt* maize was fed to monarch butterfly caterpillars, from which the caterpillars died; several independent investigations subsequently showed the risk of harm to those butterflies in the field to be vanishingly small (Conner *et al.*, 2003). The farm-scale evaluation in the United Kingdom illustrated some biodiversity benefits related to HT maize but some negative impacts for other crops (i.e. spring or winter oilseed rape and sugar beet). Overall, it seems that in many cases, it is the type and management of the overall agricultural system that has an overriding impact on biodiversity, rather than the transgenic nature (or not) of the seed planted.

Social dimension

The MDGs are a clear driving force in relation to sustainable development. Transgenic crops are having health benefits at the simplest level as farmers are using and handling less highly toxic pesticide. The evidence related to increased income in developing countries also shows that this leads to increased benefits in relation to nutrition, health and education, all key development goals. In addition, events in the pipeline suggest much more tangible benefits related to nutritionally enhanced foods, for instance Golden Rice.

In conclusion, although many individuals and organizations continue to question the need for, and the benefits of transgenic crops, the challenges facing farmers in relation to feeding an ever increasing world population from a diminishing resource base continue and indeed are growing. Transgenic crops certainly do not provide a 'silver bullet' in relation to sustainable development, but the research evidence presented here suggests that they provide a suite of tools that need to be and should remain available to food producers. The recent 'Agriculture at a Crossroads' (IAASTD, 2009) also appears to advocate multifunctional systems with a range of technologies and systems being used to by agriculturalists. Many scientists believe new transgenic events in the medium term could provide further benefits. Those events in the pipeline through to 2015 mainly expand the *Bt* and HT options across a wider range of species and will be related to the stacking of traits. Stein and Rodriguez-Cerezo (2009) predict a total of 124 events by 2015 with 15 new rice events and eight related to potatoes.

Beyond 2015, it is difficult to predict what will come to market and when, or indeed what the nature and extent of international and national regulatory frameworks relating to transgenic crops will be. However, it is likely that new crop events related to nutritional benefits, nitrogen use efficiency, drought and salt tolerance and yield enhancement will be available by 2020 by which time the world population is predicted to be about 8 BN, 1.3 BN more than today. International agreement to responsibly deploy all safe tools, including transgenic crops at our disposal to minimize environmental impact while maximizing output, would have a major global impact in relation to sustainable development.

Acknowledgements

This research was undertaken at the University of Reading with the support of Monsanto Plc.

References

ACRE (2004) Advice on the implications of the farm-scale evaluations of genetically-modified herbicide-tolerant crops. http://webarchive.nationalarchives.gov.uk/20080727101330/http://www.defra.gov.uk/environment/acre/advice/pdf/acre_advice44.pdf (accessed 1 July 2010).

Altieri, M.A. (2004) Linking ecologists and traditional farmers in the search for sustainable agriculture. *Front. Ecol. Environ.* **2**, 35–42.

Arrow, K., Bolin, B., Costanza, R., Dasgupta, P., Folke, C., Holling, C.S., Jansson, B.-O., Levin, S., Mäler, K.-G., Perrings, C. and Pimentel, D. (1995) Economic growth, carrying capacity, and the environment. *Science* **268**, 520–521.

Bates, S., Zhao, J.-Z., Roush, R.T. and Shelton, A.M. (2005) Insect resistance management in GM crops: past, present and future. *Nat. Biotechnol.* **23**, 57–62.

Baucom, R.S. and Holt, J.S. (2009) Weeds of agricultural importance: bridging the gap between evolutionary ecology and crop and weed science. *New Phytol.* **184**, 741–743.

Beckie, H.J. and Hall, L.M. (2008) Simple to complex: modelling crop pollen-mediated gene flow. *Plant Sci.* **175**, 615–628.

Beckie, H.J., Harker, K.N., Hall, L.M., Warwick, S.I., Sikkema, P.H., Clayton, G.W., Thomas, A.G., Leeson, J.Y., Séguin-Swartz, G. and Simard, G.-J. (2006) Decade of herbicide-resistant crops in Canada. *Can. J. Plant Sci.* **86**, 1243–1264.

Bennett, R., Morse, S. and Ismael, Y. (2006) The economic impact of genetically modified cotton on South African smallholders: yield, profit and health effects. *J. Dev. Stud.* **42**, 662–677.

Bertram, M.G. and Pedersen, P. (2004) Adjusting management practices using glyphosate-resistant soybean cultivars. *Agron. J.* **96**, 462–468.

Binimelis, R., Pengue, W. and Monterroso, I. (2009) 'Transgenic treadmill': responses to the emergence and spread of glyphosate-resistant johnsongrass in Argentina. *Geoforum* **40**, 623–633.

Black, R.E., Allen, L.H., Bhutta, A.Z., Caulfield, L.E., de Onis, M., Ezzati Majid, E., Mathers, C. and Rivera, J. (2008) Maternal and child undernutrition: global and regional exposures and health consequences. *Lancet* **371**, 243–260.

Bonny, S. (2008) Genetically modified glyphosate-tolerant soybean in the USA: adoption factors, impacts and prospects. A review. *Agron. Sustain. Dev.* **28**, 21–32.

Brimner, T.A., Gallivan, G.J. and Stephenson, G.R. (2005) Influence of herbicide-resistant canola on the environmental impact of weed management. *Pest Manag. Sci.* **61**, 47–52.

Brookes, G. (2003) Farm level impact of using roundup ready soybeans in Romania. http://www.pgeconomics.co.uk/pdf/GM_soybeans_Romania.pdf (accessed 6 January 2009).

© 2010 The Authors

Brookes, G. and Barfoot, P. (2008) Global impact of biotech crops: socio-economic and environmental effects, 1996–2006. *AgBioForum* **11**, 21–38.

Brookes, G. and Barfoot, P. (2009) GM crops: global socio-economic and environmental impacts 1996–2007. http://www.pgeconomics.co.uk/pdf/2009globalimpactstudy.pdf (accessed 24 September 2009).

Brundtland Commission (1987) Our common future, World Commission on Environment and Development. Published as Annex to General Assembly document A/42/427, Development and International Co-operation: Environment. http://www.un-documents.net/a42r187.htm (accessed 5 March 2009).

Carpenter, J., Felsot, A., Goode, T., Hammig, M., Onstad, D. and Sankula, S. (2002) *Comparative Environmental Impacts of Biotechnology-derived and Traditional Soybean, Corn, and Cotton Crops*. Ames, IA, USA: Council for Agricultural Science and Technology (CAST). ISBN 1-887383-21-2.

Carson, R. (1962) *Silent Spring*. ISBN 978-0-141-18494-4.

CAST (2009) The sustainability of US soyabean production. http://www.cast-science.org (accessed 21 August 2009).

Cattaneo, M.G., Yafuso, C., Schmidt, C., Huang, C.-Y., Rahman, M., Olson, C., Ellers-Kirk, C., Orr, B.J., Marsh, S.E., Antilla, L., Dutilleul, P. and Carrière, Y. (2006) Farm-scale evaluation of the impacts of transgenic cotton on biodiversity, pesticide use, and yield. *Proc Natl Acad Sci USA* **16**, 7571–7576.

Cattivelli, L., Rizza, F., Badeck, F.-W., Mazzucottelli, E., Mastrangelo, A.M., Francia, E., Mare, C., Tondelli, A. and Stanca, A.M. (2008) Drought tolerance improvement in crop plants: an integrated view from breeding to genomics. *Field Crops Res.* **105**, 1–14.

Ceddia, M., McFarlane, I., Park, J. and Phipps, R. (2009) Sustainability of GM-feedstock biofuel for Europe. ICABR Conference, Ravello, 2009.

Christoffoleti, P.J., de Carvalho, S.J.P., Lopez-Ovejero, R.F., Nicolai, M., Hidalgo, E. and da Silva, J.E. (2007) Conservation of natural resources in Brazilian agriculture: implications on weed biology and management. *Crop Prot.* **26**, 383–389.

Christoffoleti, P.J., Galli, A.J.B., Carvalho, S.J.P., Moreira, M.S., Nicolai, M., Foloni, L.L., Martins, B.A.B. and Ribeiro, D.N. (2008) Glyphosate sustainability in South American cropping systems. *Pest Manage. Sci.* **64**, 422–427.

Chu, Y., Faustinelli, P., Ramos, M.L., Hajduch, M., Stevenson, S., Thelen, J.J., Maleki, S.J., Cheng, H. and Ozias-Akins, P. (2008) Reduction of IgE binding and nonpromotion of *Aspergillus flavus* fungal growth by simultaneously silencing Ara h 2 and Ara h 6 in peanut. *J. Agric. Food. Chem.* **56**, 11225–11233.

Clewis, S.B. and Wilcut, J.W. (2007) Economic assessment of weed management in strip- and conventional-tillage nontransgenic and transgenic cotton. *Weed Technol.* **21**, 45–52.

Conner, A.J., Glare, T.R. and Nap, J.-P. (2003) The release of genetically modified crops into the environment: part II. Overview of ecological risk assessment. *Plant J.* **33**, 19–46.

Crossan, A. and Kennedy, I. (2004) *Are there Environmental Benefits from the Rapid Adoption of Roundup Ready Cotton in Australia*. Sydney, Australia: University of Sydney.

Damude, H.G. and Kinney, A.J. (2008) Engineering oilseed plants for a sustainable, land-based source of long chain polyunsaturated fatty acids. *Lipids* **42**, 179–185.

Davison, J. (2010) GM plants: science, politics and EC regulations. *Plant Sci.* **178**, 94–98.

Devos, Y., Demont, M. and Sanvido, O. (2008) Coexistence in the EU – return to the moratorium on GM crops? *Nat. Biotechnol.* **26**, 1223–1225.

Devos, Y., Demont, M., Dillen, K., Reheul, D., Kaiser, M. and Sanvido, O. (2009) Coexistence of genetically modified (GM) and non-GM crops in the European Union. A review. *Agron. Sustain. Dev.* **29**, 11–30.

DFID (2005) Growth and poverty reduction: the role of agriculture. http://www.dfid.gov.uk/Documents/publications/growth-poverty-agriculture.pdf (accessed 20 August 2010).

Duan, J.J., Lundgven, J.E., Naranjo, S. and Marvieu, M. (2009) Extrapolating non-target risk of *Bt* crops from laboratory to field. *Biol. Lett.* http://dx.doi.org/10.1098/rsbl.2009.0612 (accessed 16 December 2009).

Edgerton, M.D. (2009) Increasing crop productivity to meet global needs for feed, food, and fuel. *Plant Physiol.* **149**, 7–13.

EU (2003) *Legislation on Genetically Modified Organisms*, 2003/556/EC.

FAO (2005) International code of conduct on the distribution and use of pesticides (Revised Version) Food and Agriculture Organisation of the United Nations, Rome, 2005.

FAO (2008) Soil carbon sequestration in conservation agriculture: a framework for valuing soil carbon as a critical ecosystem service. http://www.fao.org/ag/ca/doc/CA_SSC_Overview.pdf (accessed 25 February 2009).

FAO (2009) The state of food insecurity in the world 2009. Electronic Publishing Policy and Support Branch Communication Division FAO. http://www.fao.org/docrep/012/i0876e/i0876e00.htm (accessed 23 April 2010).

Fernadez-Cornejo, J. and McBride, W.D. (2002) Adoption of bioengineered crops. USDA Agricultural Economic Report No. (AER810) 67 pp, May 2002.

Fernandez-Cornejo, J. and Caswell, M. (2006) First decade of genetically engineered crops in the United States. USDA, ERS, Economic Information Bulletin No. 11, Washington.

Ferry, N. and Gatehouse, A.M.R. (eds) (2009) *Environmental Impact of Genetically Modified Crops*. Wallingford, UK: CAB International.

Frow, E.K., Ingram, D., Powell, W., Steer, D., Vogel, J. and Yearley, S. (2009) The politics of plants. *Food Security* **1**, 17–23.

Geissler, N., Hussin, S. and Koyro, H.-W. (2008) Interactive effects of NaCl salinity and elevated atmospheric CO2 concentration on growth, photosynthesis, water relations and chemical composition of the potential cash crop halophyte Aster tripolium L. *Environ. Exp. Bot.* **65**, 220–231.

Gianessi, L.P. (2008) Economic impacts of glyphosate-resistant crops. *Pest Manag. Sci.* **64**, 346–352.

Glover, J., Johnson, H., Lizzio, J., Wesley, V., Hattersley, P. and Knight, C. (2008) *Australia's Crops and Pastures in a Changing Climate – Can Biotechnology Help?* Canberra: Australian Government Bureau of Rural Sciences.

Golden Rice Project (2000) Golden Rice is part of the solution. http://www.goldenrice.org (accessed 1 July 2010).

Gomez-Barbero, M., Berbel, J. and Rodriguez-Cerezo, E. (2008) Adoption and performance of the first GM crop introduced in EU agriculture: *Bt* maize in Spain. JRC report EUR 22778EN. http://

croplife.intraspin.com/Burtech/papers/ID_305.pdf (accessed 20 April 2010).

Gore, J., Adamczuk, J.J., Catchot, A. and Jackson, R. (2008) Yield response of dual-toxin *Bt* cotton to Helicoverpa zea infestations. *J. Econ. Entomol.* **101**, 1594–1599.

Gurian-Sherman, D. and Gurwick, N. (2009) No sure fix: prospects for reducing nitrogen fertilizer pollution through genetic engineering. Union of Concerned Scientists.

Gusta, M., Smyth, S.J., Belcher, K., Phillips, P.W.B. and Castle, D. (2010) Economic benefits of genetically modified herbicide tolerant canola for producers. (in press).

Hall, C. and Moran, D. (2006) Investigating GM risk perceptions: a survey of anti-GM and environmental campaign group members. *J. Rural Stud.* **22**, 29–37.

Heap, I.M. (2010) International survey of herbicide resistant weeds. http://www.weedscience.org (accessed 30 June 2010).

Huang, J., Hu, R., Fan, C., Pray, C.E. and Rozelle, S. (2002) *Bt* cotton benefits, costs, and impacts in China. *AgBioForum* **5**, 153–166. Available at: http://www.agbioforum.org.

Huang, J., Sun, S.-J., Xu, D.-Q., Yang, X., Bao, Y.-M., Wang, Z.-F., Tang, H.-J. and Zhang, H. (2009) Increased tolerance of rice to cold, drought and oxidative stresses mediated by the overexpression of a gene that encodes the zinc finger protein ZFP245. *Biochem. Biophys. Res. Comm.* **389**, 556–561.

Hurley, T.M., Mitchell, P.D. and Frisvold, G.B. (2009a) Characteristics of herbicides and weed-management programs most important to corn, cotton and soybean growers. *AgBioForum* **12**, 269–280.

Hurley, T.M., Mitchell, P.D. and Frisvold, G.B. (2009b) Weed management costs, weed best management practices, and the Roundup Ready^{TM} Weed management program. *AgBioForum* **12**, 281–290.

Hurley, T.M., Mitchell, P.D. and Frisvold, G.B. (2009c) Effects of weed-resistance concerns and resistant-management practices on the value of Roundup Ready^{TM} crops. *AgBioForum* **12**, 291–302.

IAASTD (2009) *Agriculture at a Crossroads*. Synthesis Report. Washington DC: Island Press.

Icoz, I. and Stotsky, G. (2008) Fate and effects of insect-resistant *Bt* crops in soil ecosystems. *Soil Biol. Biochem.* **40**, 559–586.

ISAAA (2009) GM crops: global socio-economic and environmental impacts 1996–2007. http://www.pgeconomics.co.uk/pdf/2009globalimpactstudy.pdf (accessed 6 October 2009).

James, C. (2008) Global status of commercialised Biotech/GM crops. ISAAA Brief 39. Ithaca, NY, ISAAA.

James, C. (2009) Global status of commercialised Biotech/GM crops. ISAAA Brief 41. Executive Summary. http://www.isaaa.org/resources/publications/briefs/41/executivesummary/default.asp (accessed 23 April 2010).

Jost, P., Shirley, D., Culpepper, S., Roberts, P., Nichols, R., Reeves, J. and Anthony, S. (2008) Economic comparison of transgenic and nontransgenic cotton production systems in Georgia. *Agron. J.* **100**, 42–51.

Karihaloo, J.L. and Kumar, P.A. (2009) *Bt* cotton in India – A status report (second edition). Asia-Pacific Consortium on Agricultural Biotechnology (APCoBA), New Delhi, India.

Karlsson, R. (2009) A global Fordian compromise – and what it would mean to the transition to sustainability. *Environ Sci & Pol.* **12**, 190–197.

Kershen, D. and McHughen, A. (2006) Adventitious presence: inadvertent commingling and coexistence among farming methods. Council for Agricultural Science and Technology (CAST) Commentary QTA 2005-1.

Knox, O.G.G., Vadakattu, G.V.S.R., Gordon, K., Lardner, R. and Hicks, M. (2006) Environmental impact of conventional and *Bt* insecticidal cotton expressing one and two Cry genes in Australia. *Aust. J. Agr. Res.* **57**, 501–509.

Krivanek, A.F., De-Groote, H., Gunaratna, N.S., Diallo, A.O. and Friesen, D. (2007) Breeding and disseminating Quality Protein Maize (QPM) for Africa. *Afr. J. Biotechnol.* **6**, 312–324.

Kruger, M., Van Rensburg, J.B.J. and Van den Berg, J. (2009) Perspective on the development of stem borer resistance to *Bt* maize and refuge compliance at the Vaalharts irrigation scheme in South Africa. *Crop Prot.* **28**, 684–689.

Langhof, M., Hommel, B., Hüsken, A., Schiemann, J., Wehling, P., Wilhelm, R. and Ruhl, G. (2008) Coexistence in maize: do non-maize buffer zones reduce gene flow between maize fields? *Crop Sci.* **48**, 305–316.

Lemaux, P.G. (2008) Genetically engineered plants and foods: a scientist's analysis of the issues. *Annu. Rev. Plant Biol.* **59**, 771–812.

Liu, W., Lu, H.H., Wu, W., Wei, Q.K., Chen, Y.X. and Thies, J.E. (2008) Transgenic *Bt* rice does not affect enzyme activities and microbial composition in the rhizosphere during crop development. *Soil Biol. Biochem.* **40**, 475–486.

Losey, J.E., Rayor, L.S. and Carter, M.E. (1999) Transgenic pollen harms monarch larvae. *Nature* **399**, 214.

Lövei, G.L., Andow, D.A. and Arpaia, S. (2009) Transgenic insecticidal crops and natural enemies: a detailed review of laboratory studies. *Environ. Entomol.* **38**, 293–306.

Lu, Y., Wu, K., Jiang, Y., Xia, B., Li, P., Feng, H., Wyckhuys, K.A. and Guo, Y. (2010) Mirid bug outbreaks in multiple crops correlated with wide-scale adoption of *Bt* cotton in China. *Science* **328**, 1151–1154.

May, M.J., Champion, G.T., Dewar, A.M., Qi, A. and Pidgeon, D. (2005) Management of genetically modified herbicide tolerant sugar beet for spring and autumn environmental benefit. *Proc. Biol. Sci.* **272**, 111–119.

Mayer, J.E., Pfeiffer, W.F. and Beyer, P. (2008) Biofortified crops to alleviate micronutrient malnutrition. *Curr. Opin. Plant Biol.* **11**, 166–170.

Meadows, D.H. (Earth Island 1972) *Limits to Growth: A Report for the Club of Rome's Project on the Predicament of Mankind*. ISBN 0856440086.

Messean, A., Angevin, F., Gomez-Barbero, M., Menrad, K. and Rodriguez-Cerezo, E. (2006) New case studies on the coexistence of GM and non-GM crops in European agriculture. European Commission Joint Research Centre report EUR 22102.

Messeguer, J., Peñas, G., Ballester, J., Bas, M., Serra, J., Salvia, J., Palaudelmàs, M. and Melé, E. (2006) Pollen-mediated gene flow in maize in real situations of coexistence. *Plant Biotechnol. J.* **4**, 633–645.

Monsanto (2008) Annual monitoring report on the cultivation of MON 810 in 2008. https://yieldgard.eu/en-us/YieldGardLibrary Grower/2008 YieldGard Monitoring Report.pdf (accessed 29 June 2010).

© 2010 The Authors

Monsanto (2010). *User Guide for the Production of YieldGard, Roundup Ready and YieldGard with Roundup Ready Maize*. https://yieldgard.eu/en-us/(accessed 29 June 2010).

Mulligan, E.A., Ferry, N., Jouanin, L., Walters, K.F.A., Port, G.R. and Gatehouse, A.M.R. (2006) Comparing the impact of conventional pesticide and use of a transgenic pest resistant crop on the beneficial carabid beetle *Pterostichus melanarius*. *Pest. Manag. Sci.* **62**, 999–1012.

Munkvold, G.P., Hellmich, R.L. and Rice, L.G. (1999) Comparison of fumonisin concentrations in kernels of transgenic *Bt* maize hybrids and non-transgenic hybrids. *Plant Dis.* **81**, 556–565.

Newell-McGloughlin, M. (2008) Nutritionally improved agricultural crops. *Plant Physiol.* **147**, 939–953.

Ninni, A. (2009) Policies to support biofuels: a re-appraisal of the European experience. Icabr Conference, Ravello 2009.

Phillips, P. (2003) The economic impact of herbicide tolerant canola in Canada. In *The Economic and Environmental Impacts of Agbiotech: A Global Perspective* (Kalaitzanondakes, N., ed.), pp. 119–140. New York: Kluwer.

Phipps, R.H. and Park, J.R. (2002) Environmental benefits of genetically modified crops: global and European perspectives on their ability to reduce pesticide use. *J. Anim. Feed Sci.* **11**, 1–18.

Pilcher, C.D., Rice, M.E. and Obrycki, J.J. (2005) Impact of transgenic *Bacillus thuringiensis* corn and crop phenology on five nontarget arthropods. *Environ. Entomol.* **34**, 1302–1316.

PRB (2009) 2009 World population data sheet. Population Reference Bureau http://www.prb.org/Publications/Datasheets/2009/2009wpds.aspx (accessed 23 April 2010).

Qaim, M. (2005) Agricultural biotechnology adoption in developing countries. *Am. J. Agric. Econ.* **87**, 1317–1324.

Qaim, M. and Traxler, G. (2005) Roundup Ready soybeans in Argentina: farm level and aggregate welfare effects. *Agric. Econ.* **32**, 73–86.

Qaim, M., Cap, E.J. and de Janvry, A. (2003) Agronomics and sustainability of transgenic cotton in Argentina. *AgBioForum* **6**, 41–47.

Raney, T. (2006) Economic impact of transgenic crops in developing countries. *Curr. Opin. Biotechnol.* **17**, 1–5.

Ridgwell, A., Singarayer, J.S., Hetherington, A.M. and Valdes, P.J. (2009) Tackling regional climate change by leaf Albedo bio-geoengineering. *Curr. Biol.* **19**, 146–150.

Rong, J., Lu, B.-R., Song, Z., Snow, A.A., Zhang, X., Sun, S., Chen, R. and Wang, F. (2007) Dramatic reduction of crop-to-crop gene flow within a short distance from transgenic rice fields. *New Phytol.* **173**, 346–353.

Roy, D.B., Bohan, D.A., Haughton, A.J., Hill, M.O., Osborne, J.L., Clark, S.J., Perry, J.N., Rothery, P., Scott, R.J., Brooks, D.R., Champion, E.T., Hawes, C., Heard, M.S. and Firbank, L.G. (2003) Invertebrates and vegetation of field margins adjacent to crops subject to contrasting herbicide regimes in the farm scale evaluations of genetically modified herbicide–tolerant crops. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* **358**, 1879–1898.

Royal Society (2009) Reaping the benefits: science and the sustainable intensification of global agriculture. http://royalsociety.org/document.asp?tip=0&id=8825 (accessed 15 Dec 2009).

RSC (2009) The vital ingredient: chemical science and engineering for sustainable food. http://www.rsc.org/images/FoodReport_tcm18-142397.pdf (accessed 24 August 2010).

Rymer, C. and Givens, D.I. (2009) The effect of feeding steariodonic acid enriched soya oil to broilers on the fatty acid composition and sensory characteristics of chicken meat. *Br. Poult. Abstr.* **5**, 44.

Sanvido, O., Romeis, J. and Bigler, F. (2007) Ecological impacts of genetically modified crops: ten years of field research and commercial cultivation. *Adv. Biochem. Eng. Biotechnol.* **107**, 235–278.

Schuler, T.H., Poppy, G.M., Kerry, B.R. and Denholm, I. (1998) Insect-resistant transgenic plants. *Trends Biotechnol.* **16**, 168–175.

Scursoni, J., Forcella, F., Gunsolus, J., Owen, M., Oliver, R., Smeda, R. and Vidrine, R. (2006) Weed diversity and soybean yield with glyphosate management along a north–south transect in the United States. *Weed Sci.* **54**, 713–719.

Shelton, A.M., Naranjo, S., Romeis, J., Hellmich, R., Wolt, J., Federici, B., Albajes, R., Bigler, F., Burgess, E., Dively, G., Gatehouse, A., Malone, L., Roush, R., Sears, M. and Sehnal, F. (2009) Setting the record straight: a rebuttal to an erroneous analysis on transgenic insecticidal crops and natural enemies. *Transgenic Res.* **18**, 317–322.

Shipitalo, M.J., Malone, R.W. and Owens, L.B. (2008) Impact of glyphosate-tolerant soybean and glufosinate-tolerant corn production on herbicide losses in surface run off. *J. Environ. Qual.* **37**, 401–408.

Sonnino, A., Dhlamini, Z., Santucci, F.M. and Warren, P. (2009) *Socio-economic Impacts of Non-transgenic Biotechnologies in Developing Countries*. Rome: Food and Agriculture Organization of the United Nations.

Stein, A.J. and Rodriguez-Cerezo, E. (2009) The global pipeline of new GM crops. A JRC Scientific and Technical report.

Stevens, R. and Winter-Nelson, A. (2008) Consumer acceptance of provitamin A-biofortified maize in Maputo, Mozambique. *Food Policy* **33**, 341–351.

Subramanian, A. and Qaim, M. (2009) Village-wide effects of agricultural biotechnology: the case of *Bt* cotton in India. *World Dev.* **37**, 256–267.

Sutherland, W.J. *et al.* (2008) Future novel threats and opportunities facing UK biodiversity identified by horizon scanning. *J Appl. Ecol.* **45**, 821–833.

Tabashnik, B.E. (2008) Delaying insect resistance to transgenic crops. *PNAS* **105**, 19029–19030.

Thurman, E.M., Goolsby, D.A., Meyers, M.T., Mills, M.S., Pomes, M.I. and Kolpin, D.W. (1992) A reconnaissance study of herbicides and their metabolites in surface water in the mid-western United States using immunoassay and gas chromatography/mass spectrometry. *Environ. Sci. Technol.* **26**, 2440–2447.

UN (2009) Millennium Development Goals. http://www.un.org/millenniumgoals/ (accessed 24 August 2010).

UN Population Council (2003) Demographic prospects 2000–2050 according to the 2002 revision of the United Nations population projections. *Popul. Dev. Rev.* **29**, 139–145.

UNCCD (2008) Desertification – coping with today's global challenges. http://www.unccd.int/meetings/global/hlpd/docs/HLPD-Report-2008.pdf (accessed 11 March 2009).

UNDP-UNEP (2009) *Mainstreaming Poverty – Environment Linkages into Development Planning: A Handbook for Practitioners*. http://www.unpei.org/PDF/PEI-full-handbook.pdf (accessed 24 August 2010).

UNCED (1992) Agenda 21. UN Conference on Environment and Development. http://www.unep.org/Documents.Multilingual/Default.asp?documentID=52 (accessed 6 October 2009).

UNFCCC (1998) *Kyoto Protocol to the United Nations Framework Convention on Climate Change*. http://unfccc.int/resource/docs/convkp/kpeng.pdf (accessed 25 February 2009).

United Nations (2009) Convention to combat desertification [online]. http://www.unccd.int/convention/menu.php (accessed 21 June 2009).

US EPA (2007) *White Paper on Tier-Based Testing for the Effects of Proteinaceous Insecticidal Plant-Incorporated Protectants on Non-Target Arthropods for Regulatory Risk Assessments*. Washington D.C.: U.S. Environmental Protection Agency.

Vitale, J., Glick, H., Greenplate, J., Abdennadher, M. and Traoré, O. (2008) Second-generation *Bt* cotton field trials in Burkina Faso: analyzing the potential benefits to West African farmers. *Crop Sci.* **48**, 1958–1966.

Wesseler, J., Scatasta, S. and Nillesen, E. (2007) Maximum incremental social tolerable irreversible costs (MISTICs) and other benefits and costs of introducing transgenic maize in the EU-15. *Pedobiologia* **51**, 261–269.