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Impacts of GM crops on biodiversity

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Abbreviations: Bt, *Bacillus thuringiensis*; FSE, farm scale evaluation; GM, genetically modified; HT, herbicide tolerant; GR, glyphosate resistant or glyphosate tolerant

The potential impact of genetically modified (GM) crops on biodiversity has been a topic of general interest as well as specifically in the context of the Convention on Biological Diversity. Agricultural biodiversity has been defined at levels from genes to ecosystems that are involved or impacted by agricultural production. After fifteen years of commercial cultivation, a substantial body of literature now exists addressing the potential impacts of GM crops on the environment. This review takes a biodiversity lens to this literature, considering the impacts at three levels: the crop, farm and landscape scales. Within that framework, this review covers potential impacts of the introduction of genetically engineered crops on: crop diversity, non-target soil organisms, weeds, land use, non-target above-ground organisms and area-wide pest suppression. The emphasis of the review is on peer-reviewed literature that presents direct measures of impacts on biodiversity. In addition, possible impacts of changes in management practices such as tillage and pesticide use are also discussed to complement the literature on direct measures. The focus of the review is on technologies that have been commercialized somewhere in the world, while results may emanate from non-adopting countries and regions. Overall, the review finds that currently commercialized GM crops have reduced the impacts of agriculture on biodiversity, through enhanced adoption of conservation tillage practices, reduction of insecticide use and use of more environmentally benign herbicides and increasing yields to alleviate pressure to convert additional land into agricultural use.

Introduction

The potential impact of GM crops on biodiversity has been a topic of interest both in general as well as specifically in the context of the Convention on Biological Diversity. Agricultural biodiversity has been defined at levels from genes to ecosystems that are involved or impacted by agricultural production (www.cbd.int/agro/whatis.shtml). After fifteen years of commercial cultivation, a substantial body of literature now exists addressing the potential impacts of GM crops on the environment. This review takes a biodiversity lens to this literature, considering the impacts at three levels: the crop, farm and landscape scales. Within that framework, this review covers potential impacts of the introduction of genetically engineered crops on: crop diversity, biodiversity of wild relatives, non-target soil organisms, weeds, land use, non-target above-ground organisms and area-wide pest suppression.

The emphasis of the review is on peer-reviewed literature that presents direct measures of impacts on biodiversity. In addition, possible impacts of changes in management practices such as tillage and pesticide use are also discussed to complement the literature on direct measures. The focus of the review is on technologies that have been commercialized somewhere in the world, while results may emanate from non-adopting countries and regions. The most direct negative impact of agriculture on biodiversity is due to the conversion of natural ecosystems into agricultural land. In that context, the potential impacts of GM crops are most appropriately considered in relation to prevailing modern agricultural practices.[1,2] The categories of potential impacts of GM crops are similar to those of non-GM crops.[3,4]

Previous reviews have reached the general conclusion that GM crops have had little to no negative impact on the environment.[4,5] Most recently, the US National Research Council released a comprehensive assessment of the effect of GM crop adoption on farm sustainability in the US, that concluded, "[g]enerally, [GM] crops have had fewer adverse effects on the environment than non-[GM] crops produced conventionally".[6]

Crop Diversity

Modern agriculture is the result of a long process of plant domestication to create new and better agricultural produce for society.[1] Conventional breeding has focused on improving economic efficiency, and as such has narrowed the number and genetic basis of current crops. It has been estimated that 7,000 plant species have been used for human consumption,[7] but that just four crops (wheat, maize, rice and potato) provide one-half of the total world food production and 15 crops contribute two-thirds.[8] Crop genetic diversity is considered a source of continuing advances in yield, pest resistance and quality improvement. It is widely accepted that greater varietal and species diversity would enable agricultural systems to maintain productivity over a wide range of conditions.[9] Particularly in light of climate change, maintaining and enhancing the diversity of crop genetic resources is of increasing importance to ensure the resilience of food crop production.[10] A meta-analysis of studies on genetic diversity trends in

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Box 1. Gene flow in Mexico. Particular concerns have been raised about the potential impact of GM crops on diversity of crop landraces and wild relatives in centers of origin. In this light, the reported finding of transgenic DNA in maize landraces in a remote mountain area of Mexico garnered much attention.[16] Shortly after publication of these findings, the study was criticized for poor methodology and faulty analysis of results, likely arising from contamination of samples analyzed.[17] Editors of Nature, where the results were first published, concluded after publication that the original evidence presented, as well as subsequent analysis, was not sufficient to justify the publication of the original paper.[18] Any gene from commercial corn varieties, whether from GM varieties or not, may introgress into landraces. However, the potential impact of such introgression would depend on consequences, that is, whether or not the additional genetic material confers any fitness advantage or disadvantage. Consideration of the potential impacts should be made in the context of the background genetics of the GM variety, which may have a greater impact than the accompanying transgene.

crop cultivars released in the last century found no clear general trends in diversity.[11] While a significant reduction of 6% in diversity in the 1960s as compared with the diversity in the 1950's was observed, diversity in released varieties appears to have increased after the 1960s and 1970s.

With the introduction of GM crops, concern has been raised that crop genetic diversity will decrease because breeding programs will concentrate on a smaller number of high value cultivars.[2] Three studies have analyzed the impact of the introduction of GM crops on within-crop genetic diversity. A study of field genetic uniformity, a measure of genetic relatedness, in US cotton comparing 1995 to 2000, a year in which 72% of cotton acreage was planted to GM varieties, found a 28% reduction in uniformity across the US.[12] Similarly, a study of 312 glyphosate tolerant and conventional released cultivars or advanced breeding lines analyzed the coefficient of parentage, which measures the average degree of relationship among a population among other indicators of diversity within a population. The introduction of glyphosate tolerant varieties was found to have had little impact on diversity due to its incorporation into many breeding programs.[13] In contrast, the introduction of Bt cotton in India initially resulted in a reduction in on-farm varietal diversity due to the introduction of the technology in only a small number of varieties, which has been offset by more Bt varieties becoming available over time.[9] From a broader perspective, GM crops may actually increase crop diversity by enhancing underutilized alternative crops, making them more suitable for widespread domestication.[14] Transgenic approaches are being used to improve so called orphan crops, such as sweet potato.[15] Crop diversity may also be impacted by gene flow between crops and wild relatives if the gene flow reduces genetic diversity available for crop improvement[6] (See **Box 1**).

Farm-Scale Diversity

For the purposes of this review, impacts at the farm scale are considered to encompass any impacts on organisms that live primarily within the boundaries of the farm, including soil-organisms and weeds.

Non-target soil organisms. Plants have a major influence on communities of micro- and other organisms in soil which are fundamental to many functions of soil systems, such as nitrogen cycling, decomposition of wastes and mobilization of nutrients. The type and amount of nutrients released will affect both the numbers of organisms and their diversity.

The potential impact of Bt crops on soil organisms is well studied. A comprehensive review of the available literature on the effects of Bt crops on soil ecosystems included the results of 70 scientific articles.[19] The review found that, in general, few or no toxic effects of Cry proteins on woodlice, collembolans, mites, earthworms, nematodes, protozoa and the activity of various enzymes in soil have been reported. Although some effects, ranging from no effect to minor and significant effects, of Bt plants on microbial communities in soil have been reported, they were mostly the result of differences in geography, temperature, plant variety and soil type and, in general, were transient and not related to the presence of the Cry proteins. The review found that the respiration of soils cultivated with Bt maize or amended with biomass of Bt maize and other Bt crops was generally lower than from soils cultivated with or amended with biomass of the respective non-Bt isolines, which may have been a result of differences in chemical composition between Bt plants and their near-isogenic counterparts. Studies have shown differences in the persistence of Cry proteins in soil, which appear to be the result primarily of differences in microbial activity, which in turn is dependent on soil type, season, crop species, crop management practices and other environmental factors that vary with location and climate zones.

Studies published since the Icoz and Stotzky review have reached similar conclusions (See **Table 1**). Notably, two recent studies have investigated the potential impacts of Bt corn on snails, which had not been previously studied. The first study, using purified protein found no negative effect of the Bt toxin on the snail *H. aspersa* during the observed life stages.[20] Subsequent work using plant material and soil from fields where Bt corn had been grown in a no-choice feeding experiment showed reduced growth at long exposure times, which was considered a worst case scenario.[21]

Weeds. Crop production practices have significant effects on the composition of weed communities. Changes in the kinds of weeds that are important locally are termed weed shifts. Such shifts are particularly relevant for managing weeds in herbicide tolerant crop systems, in which tillage practices and herbicide use both play major roles in shaping the weed community. There are reports in the literature of fourteen weed species or groups of closely related species that have increased in abundance in glyphosate resistant crops.[6] At the same time, in a survey of corn, soybean and cotton growers in six states, between 36 and 70% of growers indicated that weed pressure had declined after implementing rotations using glyphosate resistant crops.[22]

The potential impact of herbicide tolerant crops and their management systems on weed biodiversity was studied as part of the Farm Scale Evaluations (FSE's), supported by the United Kingdom government. The trials were undertaken on over 60 fields of sugar beet, maize and oilseed rape in the UK, to allow the comparison of large-scale management systems of

Table 1. Recent results of studies on impact of Bt crops on soil organisms

Country	Organism	Species	Location	Experimental variable	Crop	Event (Protein)	Comparison Type	Effect	Reference
Germany	enchytraeids	*Enchytraeus albidus*	laboratory	survival, reproduction	Corn	Bt11 (Cry1Ab), MON88017 (Cry3Bb1)	no-choice diet of Bt or non-Bt near isoline	no significant differences for Cry3Bb1; significantly higher survival and significantly lower reproduction for Cry1Ab, likely to be caused by differences in plant components	117
US	soil microbes		field	microbial community function by quantification of extracellular enzymes	Corn	MON863 (Cry3Bb1)	Bt, non-Bt near isoline with insecticide, untreated non-Bt near isoline	no appearance of adverse effects on saprophytic microbial communities of soil and decaying roots or on decomposition	118
Portugal	soil microbes		field	numbers of culturable aerobic bacteria, activity of dehydrogenase and nitrogenase enzymes and ATP content	Corn	event 176 (Cry1Ab), MON810 (Cry1Ab)	Bt and non-Bt near isoline	the presence of Bt maize did not cause, in a general way, changes in the microbial populations of the soil or in the activity of the microbial community	119
US	earthworms	*Aporrectodea calignosa, Aporrectodea trapozoides, Aporrectodea tuberculata, Lumbricus terrestris*	field	biomass of juveniles and adults	Corn	Bt11 (Cry1Ab), MON810 (Cry1Ab), MON863 (Cry3Bb1)	MON810 and non-Bt near isoline, MON863 and non-Bt near isoline with and without insecticide seed treatment	no significant differences in biomass of juveniles and adults	120
China	earthworms	*Eisenia fetida*	laboratory	acute toxicity, weight, SOD activity, growth and reproduction	Cotton	GK19 (Cry1Ac)	no choice diet of Bt or non-Bt parent line, insecticide treated soil and sterile manure controls	no significant acute toxicity; average weight, numbers of cocoons and new offspring not significantly different	121
US	soil microbes		field	number of culturable bacteria, carbon substrate utilization, total soil DNA	Corn	MON810 (Cry1Ab)	Bt and non-Bt near isoline	altered functional activity *substrate metabolism) and structure of microbial communities, attributed to higher lignin content of Bt variety	122
Switzerland	soil meso- and macrofauna	Collembola, Acari and Clitellata	field	number of extracted organisms	Corn	MON810 (Cry1Ab), Bt11 (Cry1Ab), MON88017 (Cry3Bb1)	Bt and non-Bt near isoline	corn varieties had no impact on the soil fauna community	123

conventional and genetically engineered herbicide tolerant crops. Effects on weeds and associated arthropods and on detrital food webs were evaluated and presented in a series of papers published in the *Transactions of the Royal Society of London*.[23-32] These studies showed that for genetically engineered herbicide tolerant sugar beet and oilseed rape fewer weeds and weed seeds, whereas for genetically engineered herbicide tolerant corn, an increase in dicot weeds and weed seed was observed. The results on associated arthropods, detrital food webs and birds are discussed further in the relevant sections below.

The use of herbicides can also result in changes to weed communities through the development of herbicide tolerant weed

Table 1. (continued) Recent results of studies on impact of Bt crops on soil organisms

US	earthworms	*Aporrectodea caligonsa, Aporrectodea trapozoides, Aporrectodea tuberculata, Lumbricus terrestris*	field	biomass of juveniles and adults	Corn	Bt11 (Cry1Ab), MON810 (Cry1Ab), MON863 (Cry3Bb1)	MON810 and non-Bt near isoline, MON863 and non-Bt near isoline with and without insecticide seed treatment	no significant differences in biomass of juveniles and adults	120
China	earthworms	*Eisenia fetida*	laboratory	acute toxicity, weight, SOD activity, growth and reproduction	Cotton	GK19 (Cry1Ac)	no choice diet of Bt or non-Bt parent line, insecticide treated soil and sterile manure controls	no significant acute toxicity; average weight, numbers of cocoons and new offspring not significantly different	121
US	soil microbes		field	number of culturable bacteria, carbon substrate utilization, total soil DNA	Corn	MON810 (Cry1Ab)	Bt and non-Bt near isoline	altered functional activity *substrate metabolism) and structure of microbial communities, attributed to higher lignin content of Bt variety	122
Switzerland	soil meso- and macrofauna	Collembola, Acari and Clitellata	field	number of extracted organisms	Corn	MON810 (Cry1Ab), Bt11 (Cry1Ab), MON88017 (Cry3Bb1)	Bt and non-Bt near isoline	corn varieties had no impact on the soil fauna community	123

AUTHOR: Please refer for Box 1 & 2 within the body text.

Box 2. The importance of study design. There are several examples of study design leading to unwarranted conclusions on the impact of Bt crops on non-target above-ground invertebrates. **Monarch Butterfly:** Following an initial report of toxic effects of Bt corn pollen to Monarch butterfly larvae that was based on a no-choice laboratory feeding study,[61] numerous additional studies have been conducted, including both laboratory and field studies. Naranjo's analysis of the potential impact of Bt crops on non-target herbivore species was dominated by studies on the monarch butterfly, showing significant impacts in laboratory studies, but no impact in field studies.[48] This finding mirrors an earlier analysis of the impact on monarch butterflies, based on a collaborative research effort by scientists from several US states and Canada, which showed that risks in the field were negligible.[62] Green Lacewing: In a study by Dutton et al. the potential tritrophic effects of Cry1Ab-expressing Bt corn on green lacewing were studied in reference 63. Three different prey organisms were fed Bt or non-Bt corn leaves and were then fed to lacewing larvae. Lacewing larvae that fed on Bt-susceptible leafworms had significantly higher mortality and development time than those in the control treatment. These findings led to further research to explain the results. A follow-up study confirmed that the protein was transferred from prey to predator, and the biological activity of the Bt protein, for two of three prey organisms, spider mites and leafworms.[64] The concentrations of Cry1Ab was much higher in the spider mites, which had no effect on lacewing larvae. These additional experiments led researchers to believe that the effects of the Bt-fed leafworms were due to low quality pretty, since leafworms are susceptible to Cry1Ab protein.[65] **Caddisflies:** A 2007 paper suggested that Bt maize affects caddisflies.[66] In that study, two caddisfly species were fed either pollen or leaves from Bt and non-Bt corn in groundwater or streamwater. For one caddisfly species, Helicopsyche borealis, the higher tested concentration of Bt corn pollen was associated with increased mortality. The other species, Lepidostoma liba had greater than 50% lower frother rates when fed Bt corn littler compared with non-Bt corn litter, although mortality was not different. The Rosi-Marshall study has been criticized for not using appropriate controls.[67] Specifically, the study did not use non-Bt near isolines as the comparator, and therefore may have led to erroneous conclusions based on other factors that differ between corn hybrids. Further, no quantification of the Bt protein, or other chemical parameters in tested groundwater or streamwater was provided. As the level of Bt expression in pollen is quite low, the observed effects may have been due to other factors.[68] **Ladybird Beetle:** The results of 2009 paper that showed mortality to ladybird beetle at an intermediate tested concentration[69] have been questioned based on methodological flaws and inconsistencies.[70] The criticism cites a lack of quantification of exposure and unexplained high variability in mortality for control groups. In addition, the results contradict classical dose-response models, as mortality was lower at the highest tested concentration than at the intermediate concentration. The study also contradicts established findings that susceptible organisms suffer from sub-lethal effects long before direct toxic effects can be observed.

populations. The first confirmed report of a weed population expressing tolerance to an herbicide was in 1964, where field bindweed in Kansas was found to be resistant to 2,4-D. The US has the highest number of herbicide resistant weeds, with over 130 herbicide resistant weeds confirmed in the United States.[33] The first confirmed case of glyphosate resistant (GR) weeds was in Australia in 1996, prior to the commercialization of GR crops. The first confirmed case of glyphosate resistance in an area growing GR crops was in horseweed in Delaware in 2000.[34] Globally, GR weeds have been confirmed for 21 weeds in 15 countries. Most of these cases have been reported where GR crops are commonly grown. However, GR weeds have also been reported in California in almonds and roadsides, orchards in Oregon and nurseries in Michigan, none of which are related to GR crops.

The development of weeds resistant to glyphosate will likely require modification to weed control programs where practices in addition to applying glyphosate are needed to control the resistant populations.[35]

Landscape-Scale Diversity

For the purposes of this review, potential impacts at the landscape scale include land use, area-wide pest suppression and non-target above-ground invertebrates.

Land use. The most direct negative impact of agriculture on biodiversity is due to the considerable loss of natural habitats, which is caused by the conversion of natural ecosystems into agricultural land.[5] Increases in crop yields allow less land to be dedicated to agriculture than would otherwise be necessary. For example, it was estimated that if wheat yields in India had stagnated at 1961–1966 levels, farmers there would have had to cultivate an area almost three times greater to produce the same amount of wheat that was harvested in 1990.[36] A more recent analysis compared actual agricultural production between 1961 and 2005 with hypothetical scenarios where increases in food production were realized by expanding farmland instead of increasing yields, finding that between 864 and 1,514 million hectares would have had to be converted to agricultural production, depending on the living standard assumed.[37]

A large and growing body of literature has shown that the adoption of GM crops has increased yields. A recent review of results from 49 peer-reviewed publications reporting on farmer surveys from 12 countries that compare yields of adopters and non-adopters of currently commercialized GM crops showed increased yields for adopters.[38] Of 168 results comparing yields of GM and conventional crops, 124 show positive results for adopters compared to non-adopters, 32 indicate no difference and 13 are negative. Yield increases were greatest for developing country farmers. The average yield increases for developing countries range from 16% for insect-resistant corn to 30% for insect-resistant cotton, with an 85% yield increase observed in a single study on herbicide-tolerant corn (See **Table 2**). On average, developed-country farmers report yield increases that range from no change for herbicide-tolerant cotton to a 7% increase for herbicide-tolerant soybean and insect-resistant cotton.

Table 2. Average percentage changes in yield by technology for developed and developing countries [(GM-conventional)/conventional][38]

Technology	Change in yield	# of results	Min.	Max.	Std. Err.
Developed Countries	6%	59	-12%	26%	1.0%
HT Cotton	0%	6	-12%	17%	3.8%
HT Soybean	7%	14	0%	20%	1.7%
HT/IR Cotton	3%	2	-3%	9%	5.8%
IR Corn	4%	13	-3%	13%	1.6%
IR Cotton	7%	24	-8%	26%	1.9%
Developing Countries	29%	107	-25%	150%	2.9%
HT Corn	85%	1			
HT Soybean	21%	3	0%	35%	11%
IR Corn	16%	12	0%	38%	4%
IR Corn (white)	22%	9	0%	62%	6.9%
IR Cotton	30%	82	-25%	150%	3.5%

Averages calculated across surveys, geographies, years and methodologies. A two-tailed t-test shows a significant difference between the average yields of developed and developing countries ($t = 7.48$, $df = 134$, $p < 0.0005$).

Researchers have estimated the benefit of these yield improvements on reducing conversion of land into agricultural use. Brookes et al. modeled the impact of the introduction of GE corn, soybean and canola on global production and prices, accounting for market effects on the planting decisions of farmers in adopting and non-adopting countries. Their analysis assumed yield impacts of between 0 (US) and 31% (Romania) for soybean, between 5 (US) and 24% (Philippines) for corn and 3.7 (Canada) to 6% (US) for canola. They estimate that 2.64 million hectares of land would probably be brought into grain and oilseed production if biotech traits were no longer used.[39]

A potential impact of increased productivity related to adoption of GM crops is an increase in crop acreage, by farmers deciding to increase acreage planted to GM crops at the expenses of other farming activities or through expansion into natural areas. Both effects have been observed in Brazil and Argentina, where the introduction of GM crops combined with an enabling policy environment and facilitated adoption of no-till and double-cropping to cause the expansion of soybean acreage into areas previously planted to other crops or used as pasture, as well as into some natural areas.[40,41] To the extent that soy was planted into degraded pastures, it may be seen as an environmentally friendly way of expanding arable land.[40]

Area-wide pest suppression. The most direct landscape-level effects of growing Bt crops would be expected for target pest species for which the crop is a primary food source and that are mobile across the landscape. Observations of target pest populations over time reveal a high level of variability that may be driven by Bt crops as well as other factors such as weather, local and distant cropping patterns, other crop management practices and pest population dynamics.[42,43] Area-wide pest suppression not only reduces losses to adopters of the technology, but may also benefit non-adopters and growers of other crops by reducing crops losses and/or the need to use pest control measures such as insecticides.[43]

Several studies have investigated the impact of the introduction of Bt corn and cotton on regional outbreaks of pest populations. Evidence of regional suppression of the target pests *Ostrinia nubilalis* and *Helicoverpa zea* in corn was gathered from an area of Maryland where Bt corn adoption was over 60%.[42] Moth trap records from 35 years were used to capture variability in pest populations both before and after the introduction of Bt corn. Moth activity was 63% and 48% lower than the long-term average for *O. nubilalis* and *H. zea*, respectively, declines that are believed to have led to pest management benefits in other host crops, such as soybean and vegetables.

Box 3. Biofuels. With the recent heightened interest in biofuels as an alternative to fossil fuels, concerns have been raised that the increased demand for crops such as corn that are currently used for biofuel production will lead to increased food prices and increased pressure to convert land into agricultural use. GM crops have the potential to alleviate these concerns by increasing productivity as well as by decreasing the greenhouse gas emissions of biofuel production processes. Biotechnology can increase yields in crops used as a feedstock, improve crop adaptation to marginal lands, increase the amenability of crops to bioprocessing, which in addition to the coproduction of feedstock and food, will all be necessary for meeting current biofuel goals.[113,114] In that context, the further development of pest management technologies that can increase yields, as well as those that increase yields under drought or saline conditions will contribute to the increases in productivity needed to meet the demands of both food and biofuel sectors. In addition, advances are being made to develop crops with improved processing characteristics, such as a corn variety which produces alpha-amylase enzyme that would otherwise have to be added during the processing of starch-based grain to convert available starch to fermentable sugars in the production of ethanol. Trials have shown that alpha-amylase corn can significantly reduce the amount of natural gas, electricity, water and microbial alpha-amylase required in the production of ethanol.[115] Achieving processing efficiences in the production of cellulosic ethanol with transgenic crops will allow the use of a greater share of harvested plants, use of crops that produce more biomass per acre and reducing the input intensity of feedstock production, which will reduce the ecological footprint of biofuel production.[116]

Populations of *O. nubilalis* are also observed to have declined in Midwestern US maize growing areas.[43] Also using long-term data, on larval and moth flight, researchers have found significantly different per capita population growth rates in areas with different levels of adoption. The analysis found that the majority of benefits of Bt corn adoption has accrued to non-adopters.

In an investigation of the impact of Bt cotton on populations of the target pests *H. zea* and *Heliothis virescens* in Washington County, Mississippi, data from adult pheromone trap captures from 1986 through 2005 were analyzed.[44] Despite yearly fluctuations, adult populations of both species were found to have declined annually since 1997. Declines in adult populations of *H. virescens* were dramatic, particularly over the years from 2000 to 2005, and may have been due to wide-scale plantings of Bt cotton among other factors.

In a ten year study across 15 regions of Arizona, researchers concluded that Bt cotton suppressed a major pest, *Pectinophora gossypiella*, independent of the effects of weather and regional variation.[45] Population densities were found to have declined only in regions where Bt cotton was abundant.

In the cotton growing area of the Imperial Valley, California, gossyplure-baited trap catch data for 1989 to 2003 were analyzed, which covered periods when different areawide control strategies were used to control pink bollworm.[46] Catches were significantly lower in 1998 to 2003 than in 1995 to 1997, except in 1999, although high populations in 1995 to 1997 may have been related to moth migrations from the large cotton acreages grown in the Mexicali Valley, which borders the Imperial Valley.

A study of the population dynamics of cotton bollworm from 1992 to 2007 covered six provinces in northern China, a major growing area of cotton and other crops which are also hosts to bollworm, such as corn, peanuts, soybeans and vegetables.[47] The analysis indicated that a significant decrease in regional outbreaks in multiple crops was associated with the planting of Bt cotton, which suggests a reduced need for insecticide sprays in general.

Non-target above-ground invertebrates. *Insect resistant crops.* The effects of GM crops on above-ground non-target invertebrates have been the subject of a large number of laboratory and field studies. By the end of 2008, over 360 original research papers had been published on non-target effects of Bt crops.[48]

Several reviews have summarized the literature. The overall conclusion of the reviews is that studies of the potential impact of Bt crops on non-target herbivores and beneficials have not detected significant adverse effects,[49] and no evidence of landscape-level effects. Laboratory and glass house studies have revealed effects on natural enemies only when Bt-susceptible, sublethally damaged herbivores were used as prey or host, with no indication of direct toxic effects. Field studies have confirmed that the abundance and activity of parasitoids and predators are similar in Bt and non-Bt crops.[50] The indirect impacts of Bt crops on beneficials, due to multitrophic exposure, loss of prey or reduction of prey quality, are considered to be negligible compared with the direct effects of agricultural practices.[42]

The first published quantitative review analyzed the results of 45 laboratory studies of the impact of insect resistant crops (including Bt and proteinase inhibitors) on 32 species of natural enemies, finding that 30% of studies for predators and nearly 40% of studies for parasitoids reported significant negative effects on multiple life history characteristics.[51] This review was later updated with subsequent published literature to include a total of 80 studies on 48 species, finding 21.2% negative results.[52] The Lovei et al. analysis has been criticized for using multiple non-independent measures of life history and behavioral traits, which can inflate the purported effects in the data, lack of consideration of prey/host mediated effects in tri-trophic studies, inclusion of studies with irrelevant or unrealistic experimental designs and generalization across Bt, proteinase inhibitors and lectins.[53]

Another series of quantitative reviews has been conducted based on a common dataset, originally compiled by Marvier et al. which covers impacts of Bt crops on invertebrates. Using meta-analysis, the results of 42 field-based studies of Bt corn and cotton were analyzed, showing that the abundance of non-target invertebrates was higher in Bt crops compared to non-Bt crops that had been treated with insecticides, although abundance was slightly lower compared to non-sprayed non-Bt crops.[54]

A later study used a modified version of the Marvier et al. database, examining the results of field-based studies for corn, cotton and potato by functional guild using meta-analysis.[55] Predators were found to be less abundant in Bt cotton compared to unsprayed non-Bt controls, and fewer specialist parasitoids of the target pest occurred in Bt corn compared to unsprayed non-Bt controls, though no significant reduction was detected for other parasitoids. The abundance of predators and herbivores was higher in Bt crops compared to sprayed non-Bt controls, the difference affected by the type of insecticide used. However, omnivores and detritivores were more abundant in insecticide treated non-Bt crops. The study found no uniform effects of Bt crops on non-target arthropods by functional guild, and that the impact of insecticide use was much greater than Bt crops.

A separate study analyzed the results of 25 laboratory studies that specifically looked at the impacts of Bt crops on honey bees,[56] also using meta-analysis. Bt proteins in lepidopteran or coleopteran resistant crops were found to have had no effect on the survival of larvae or adults.

Most recently, the Marvier et al. database was updated with literature published subsequent to the compilation of the original database.[48] The updated database included 135 laboratory-based studies on nine Bt crops from 17 countries and 63 field-based studies on five Bt crops from 13 countries, which were analyzed using meta-analysis techniques. Laboratory studies were found to have identified negative effects of Bt crops when organisms were exposed directly to Bt proteins, some of which were expected because of the relatedness of the non-target pest to the groups targeted by the Bt crop. In tri-trophic studies, the quality of prey or hosts was associated with negative effects, whereas no negative effects were found when unaffected, high quality prey or hosts were used. In general, laboratory studies identified greater levels of hazard than field studies, at least partially explained by differences in organisms studied, and frequently higher protein exposure in lab studies compared to exposure levels in the field. Field studies demonstrated few harmful non-target effects, with the non-target effects of insecticides being much greater than Bt crops. More recent literature on the non-target impacts of Bt crops are largely consistent with Naranjo's conclusions (See **Table 3**).

A modeling study of the potential impact of Bt corn on non-target butterfly and moth species in four European countries estimated mortality both within the field and at the field margin at varying distances from the crop edge. That study estimated low environmental impacts in all regions, with a calculated mortality rate of less than one individual in every 1,572 for the butterflies and one in 392 for the moth in the worst case scenarios.[57]

In a study of the landscape level effects of Bt cotton, population densities of ants and beetles in non-cultivated sites near agricultural fields were monitored for up to 5–6 years. The sequence of crops planted in neighboring fields, crops diversity and abundance were more frequently associated with greater insect density than characteristics of the non-cultivated sites. Results suggest that the farming of Bt cotton in neighboring fields frequently resulted in positive short- and long-term landscape effects on ants and beetles in non-cultivated sites, while Bt cotton planted farther away had less frequent negative short-term impacts.[58]

In a study of the impact of reduced use of broad spectrum insecticides in Bt cotton on secondary insect pests in China, mirid populations were found to be higher in Bt cotton fields compared to conventional cotton sprayed with conventional insecticides as well as in fruit crops in regions with higher proportions of Bt cotton.[59] In another analysis of the observed increase in secondary pests in Bt cotton in China, the rise and fall of mirid populations was found to be largely related to local temperature and rainfall.[60]

Herbicide tolerant crops. As described above, the UK Farm Scale Evaluations (FSE's) evaluated the effects of conventional and herbicide tolerant weed management systems on weeds and associated arthropods and on detrital food webs.[23-32] These studies showed that for genetically engineered herbicide tolerant sugar beet and oilseed rape, fewer weeds and weed seeds, and fewer insects from species that live in or on weeds, were observed. Increased numbers of detritivores were found in HT sugar beet and maize, with a corresponding increase in predators in sugar beet. Whereas for genetically engineered herbicide tolerant corn, an increase in dicot weeds and weed seed was observed, with a corresponding increase in seed-eating beetles.

The Farm-Scale Evaluations have been criticized for leading to inappropriate conclusions about the environmental impacts of genetically engineered crops.[2,71,72] The FSE was not designed to test the direct effect of the genetically engineered trait itself, but rather the broader herbicide and crop management practices. Glyphosate and glufosinate as used in conjunction with genetically engineered herbicide tolerant sugar beet and oilseed rape provided highly effective weed control, which resulted in fewer weeds and weed seeds. Not surprisingly, the effects on various groups of arthropods followed the effects on the abundance of their resources. It has been noted that the introduction of other technologies that increase control of weeds is routine and occurs without public debate.[71]

Other studies on the non-target impacts of herbicide tolerant crops have come to similar conclusions. The effects of genetically engineered herbicide tolerant soybeans and corresponding weed management strategies on various soybean insects were the focus of a study from 1996 to 1998 in Iowa. Weed management systems that allowed more weed escapes typically had higher insect population densities.[73] Springtail numbers were similar to or higher in herbicide tolerant crops than those in conventional plots.[74]

The potential impact of GM HT canola on bees was studied in a two year field trial (2001 and 2002) and one year semi-field trial (2002) in Canada.[75] No differences in larval survival, adult recovery and pupal weight were detected in a comparison of colonies in conventional and GM canola fields. A significantly higher amount of hemolymph protein was found in one of two years in newly emerged bees from GM fields compared to conventional fields. Authors conclude that the results suggest that transgenic canola pollen does not have adverse effects on honey bee development.

In a study of the potential impact of GM HT soybean weed management on soybean insect pest populations in South Georgia in 1997 and 1998, few differences in pest population densities were observed. Observed differences were associated with soybean maturity grouping on some dates, and were not associated with the GM HT trait.[76]

A two year study of the impact of the deployment of herbicide tolerant corn on corn arthropods compared weeds, insect herbivores and their natural enemies in plots treated either with glyphosate or conventional pre-emergence herbicides. Despite significant differences in weed abundance, there were very few significant differences in the arthropod groups monitored.[77] These results contrast with prior findings of the same study comparing plots treated with glyphosate to plots with no herbicide treatment.[78]

Table 3. Recent results of research on potential impact of Bt crops on non-target above-ground organisms

Country	Organism	Species	Location	Experimental variable	Crop	Protein/Event	Comparison Type	Effect	Reference
US	caddisflies, crane fly larva, aquatic isopod	*Lepidostoma* spp. , *Pycnopsyche* cf. *scabripennis* (Rambur), *Tipula* (*Nippotipula)* cf. *abdominalis* (Say), *Caecidotia communis* (Williams)	laboratory	head width, dry mass, survival	Corn	MON810 (Cry1Ab), MON810/MON863 (Cry1Ab/Cry3Bb1)	Bt and non-Bt near isoline, single trait and stacked	no bioactivity of Cry1Ab protein in senesced corn tissue after 2 weeks of environmental exposure; growth of trichopterans not negatively affected, reduced growth rates of tipulid crane fly, reduced growth and survivorship of isopod on Bt near-isoline but not on stacked near-isoline	125
Poland	bird cherry-oat aphid, green lacewing	*Rhopalosiphum padi* L., *Chrysoperla carnea* Steph.	greenhouse/laboratory	population, feeding, moulting date	Corn	MON810 (Cry1Ab)	Bt and non-Bt near isoline	no significant differences	126
South Africa	*Lepidoptera*	15 *species*	field	infestation, damage	Corn	MON810 (Cry1Ab)	Bt and non-Bt near isolines	incidence of infestation and infestation levels generally lower in Bt fields than non-Bt fields	127
India	sucking insects, foliage feeder and predators	*Amrasca biguttula biguttula*, *Bemisia tabaci*, *Aphis gossypi*, *Thrips tabaci*, *Myllocerus undecimpustulatus*, *Chrysoperla* spp., *Orius* spp., *Coccinella* spp. *Brumus* spp., *Vespa* spp., *Lycosa* spp., *Aramews* spp.	field	densities, time of first appearance	Cotton	Bollgard (Cry1Ac), Bollgard II (Cry1Ac/Cry2Ab)	Bt and non-Bt cultivars with and without insecticide	similar densities and no difference in time of first appearance of non-target insects	128

Given the flexibility of herbicide treatment offered by the herbicides used in herbicide tolerant crops, some have proposed novel weed management systems that crops can be managed for enhanced weed and insect biomass without compromising yields in order to increase food and shelter for farmland birds and other wildlife.[79,80]

Stacked insect resistant/herbicide tolerant crops. Only one study was located that addressed the potential impacts of stacked crops on non-target above-ground invertebrates. In a 2 year farm-scale evaluation of 81 commercial fields in Arizona, insecticides used on conventional cotton was related to reduced diversity of non-target insects. However, the effects of cultivation of cotton, whether transgenic or not, were found to result in similar effects on biodiversity compared with diversity in adjacent noncultivated sites.[81]

Birds. The authors of the FSE reports suggest that the observed decreases in weed seeds and insects might reduce the number of birds that feed on these insects and seeds, though the results of a bird survey that was conducted on a sub-set of fields used in the FSE were not published until 2007. The bird survey results were in accord with differences in food availability found in the FSE.[82] Specifically, a greater abundance of granivores was found on conventional than genetically engineered herbicide tolerant sugar beet, as well as on genetically engineered herbicide tolerant maize after application of herbicides to the GM HT field. No differences were detected in spring oilseed rape. In the subsequent winter season, granivores were more abundant in the fields where conventional sugar beet had been grown than on the GM HT fields. Several bird species were found to be more abundant on maize stubbles following GM HT treatment.

Indirect Indicators

Changes in tillage practices. The introduction of herbicide tolerant crops has been associated with the increased adoption of conservation tillage practices, which decreases run-off, increases water infiltration and reduces erosion. Trends in the adoption of conservation tillage have been studied in the US and Argentina, the largest growers of herbicide tolerant crops.

In the US, soybean growers were already adopting conservation tillage practices prior to the introduction of glyphosate

Table 3. (continued) Recent results of research on potential impact of Bt crops on non-target above-ground organisms

Hungary	rove beetles	21 species	field	abundance, species richness, diversity and similarity	Corn	MON810 (Cry1Ab)	Bt and non-Bt near isoline	no influence on overall community structure; no significant differences for non-aphidophagous predators and parasitoids; significantly and marginally significantly higher abundances for predators with aphids in their diet in isogenic maize in 2 of 3 years.	129
France	moth	*Cotesia marginiventris*	laboratory	rates of parasitism, host suitability, developmental periods, off-spring longevity, size and sex ratio	Corn	MON810 (Cry1Ab)	no choice purified protein in artificial diet; no choice plant tissue	no effect of purified protein at evaluated concentrations; exposure via Bt maize tissue affected developmental times, adult size and fecundity	130
Switzerland	spider mite, ladybird beetle	*Tetranychus urticae*, *Stethorus punctillum*	laboratory	development, adult survival and reproduction	Corn	MON88017 (Cry3Bb1)	no choice Bt and non-Bt near isoline	no differences for *T. urticae*; female *S. punctillum* fed Bt corn had shorter pre-oviposition period, increased fecundity and increased fertility, otherwise no differences for *S. punctillum*	131
Spain	leafworm, ground beetle	*Spodoptera littoralis*, *Poecilus cupreus*	laboratory	development, mortality, adult weight	Corn	Event 176 (Cry1Ab)	no choice Bt and non-Bt near isoline	no differences in developmental time of larvae and pupae, adult weight or larval and pupal mortality of P. cupreus	132
China	beet armyworm	*Spodoptera exigua*	laboratory	development, food utilization and population performance	Cotton	NC33B (Cry1Ac)	no choice Bt and non-Bt near isoline	longer larval life-span and lower pupal weight, higher survival rate and adult fecundity, significantly lower consumption, frass and relative growth rate observed in three successive generations	133
Germany	spiders, carabid beetles	50 species of spiders, 57 species of carabid beetles	field	activity abundance	Corn	MON810 (Cry1Ab)	Bt and non-Bt near isoline with and without insecticide	significantly different activity abundances observed for spiders and carabid beetles in one of three years	134

tolerant soybean, using other post-emergence selective herbicides which became available in the 1980's and 1990's.[83] Already by 1989, 30% of US soybean acreage was under conservation tillage. Herbicide-tolerant crops facilitated adoption by making it easier and less risky to adopt conservation tillage and no-till. Between 1996 and 2008, adoption increased from 51 to 63% of planted acres.[6] In particular, the adoption of no-till in full-season soybean, which leaves the most crop residue on the soil surface, is

Table 3. (continued) Recent results of research on potential impact of Bt crops on non-target above-ground organisms

Switzerland	ladybird beetle	*Adalia bipunctata*	laboratory	larval/pupal mortality, development time, overall body mass accumulation		Cry1Ab, Cry3Bb1	no choice diet with solutions including either purified protein solution or solution with empty vector cassette	significantly higher mortality for Cry1Ab at all concentrations; marginally significantly higher mortality for Cry3Bb1 at intermediate concentration; no differences in development time and body mass of newly emerged adults	69
Germany	plant bugs	Six taxa, of which *Trigonotylus caelestialium* was most abundant	field	density	Corn	MON88017 (Cry3Bb1)	Bt and non-Bt near isoline	no evidence of negative impact on most abundant plant bug	135
US	carabid beetles	15 species	field	abundance and diversity	Corn	MON810 (Cry1Ab)	Bt and non-Bt near isoline	no negative effects	124
Switzerland	aphids	*Aphis gossypii*	laboratory	nymphal developmental time, number of nymphs produced, reproductivie rate, total fecundity per female, adult longevity, total longevity, instrinsic rate of population increase	Cotton	BG-1 (Cry1Ac)	Bt and non-Bt near isoline	no effect	136
US	arthropods	16 arthropod taxa	field	abundance	Corn	DAS-01507 (Cry1F)	Bt and non-Bt near isoline	no significant impact on community abundance or abundance of individual taxa	137
Canada	ground beetles	39 species	field	abundance	Corn	MON810 (Cry1Ac)	Bt and non-Bt near isoline with and without insecticide	no effect on total beetle abundance or species richness; negative effect for 3 of 39 species by year combinations examined	138

estimated to have increased from 27% in 1995 to 39% of planted acreage according to the latest surveys by the Conservation Tillage Information Center.[84]

The results of the CTIC are reinforced by two additional independent surveys. A survey of corn, cotton and soybean growers in six states (Illinois, Indiana, Iowa, Mississippi, Nebraska and North Carolina) found that the percentage of growers using no-till and reduced-till systems was increased as a result of the adoption of glyphosate-resistant (GR) crops. Tillage intensity declined more in continuous GR cotton and GR soybean (45 and 23%, respectively) than in rotations that included GR corn or non-GR crops.[85] A survey of 610 soybean growers across

Table 3. (continued) Recent results of research on potential impact of Bt crops on non-target above-ground organisms

India	ladybird beetle	*Cheilomenes sexmaculatus*	laboratory	larval and pupal periods, larval survival, weights of male and female larvae, adult emergence, weights of male and female adults		Cry1Ab, Cry1Ac	no choice purified protein or aphids fed purified protein	reduced larval survival and adult emergence from direct exposure, attributed to long term exposure; no effect of indirect exposure through aphids	139
Germany	planthoppers and leafhoppers	5 taxa, *Zyginidia scutellaris* most prevalent	field	abundance	Corn	MON810 (Cry1Ac)	Bt and non-Bt near isoline with and without insecticide	no consistent differences for *Z. scutellaris* between Bt and untreated non-Bt; decrease in *Z. sculettaris* for treated non-Bt compared to untreated non-Bt	140
US	midge	*Chironomus dilutus*	laboratory	mortality and dry weight	Corn	MON863 (Cry3Bb1)	Bt and non-Bt near isoline	significant decrease in survival at intermediate concentration tested; no effect on growth of surviving larvae	141
Switzerland	green lacewing	*Chrysoperla carnea*	laboratory	larval development and survival, pupal development time and survival and adult dry weight		Cry1Ac and Cry1Ab	purified protein	no effect	142
Spain	ladybird beetle	*Stethorus punctillum*	laboratory	survival and development	Corn	Bt176 (Cry1Ab), MON810 (Cry1Ab)	Bt and non-Bt near isolines	no effect on survival or development time to adulthood or fecundity	143
US	green lacewing, flower bug	*Chrysoperla carnea*, *Orius tristicolor*	field	abundance	Cotton	Bollgard (Cry1Ac)	Bt and non-Bt, with and without insecticide	no significant difference between Bt and unsprayed non-Bt; significantly lower abundance for insecticide-treated fields in one of two years	144

19 states found that growers of GR soybeans made 25% fewer tillage passes than growers of conventional soybean.[86]

The introduction of glyphosate-tolerant soybeans is also cited as a contributing factor in the rapid increase of no-till in Argentina, where adoption of no-till increased from about 1/3 of soybean acreage in 1996 to over 80% in 2008. Other factors that also contributed to the expansion of no-till in soybean are: favorable macroeconomic policies, reduction in price of herbicides and continued research and promotion efforts.[87] A 2001 survey of 59 soybean growers in Argentina found that the number of tillage operations was 58% lower on glyphosate-tolerant acreage than on conventional soybean fields.[88]

Whether the introduction of herbicide tolerant crops has caused an increase in the adoption of conservation tillage or vice

Table 3. (continued) Recent results of research on potential impact of Bt crops on non-target above-ground organisms

India	predatory spiders, ladybird beetles, green lacewing, ichneumonid parasitoid	*Clubiona* sp., *Neoscona* sp., *Cheilomenes sexmaculatus*, *Chrysoperla carnea*, *Campoletis chlorideae*	field	abundance	Cotton	Bollgard (Cry1Ac)	Bt and non-Bt, with and without insecticide	no effect on predatory spiders, ladybird beetle or green lacewing; significant reduction in cocoon formation and adult emergence of *C. chlorideae*	145
UK	aphids, parasitic wasps	*Rhopalosiphum maidis*, *Cotesia marginiventris*	laboratory	performance	Corn	Bt11 (Cry1Ac), MON810 (Cry1Ac), Event 176 (Cry1Ac)	Bt and non-Bt near isolines	no difference in mean relative growth rates in individual comparisons; significantly more nymphs on transgenic lines than respective near isolines; differences might be partially explained by higher amino acid levels in Bt lines	146

versa, has been the subject of several studies. In an analysis of farmer decision-making using national survey data for 1997, researchers found that conservation tillage adoption led to adoption of glyphosate tolerant soybeans, but that glyphosate tolerant soybean adoption did not lead to increased adoption of conservation tillage.[89] However, more recent surveys have shown a positive two way relationship. Using data from 1998 to 2004, a simultaneous relationship was found between the adoption of conservation tillage and the adoption of herbicide tolerant cotton in Tennessee.[90] A broader study of herbicide tolerant cotton producers used state level data from 1997 to 2002 also found a simultaneous relationship between adoption of herbicide tolerant varieties and conservation tillage.[91]

Changes in pesticide use. The pest management traits that are embodied in currently commercialized GM crops have led to changes in the use of pesticides that may have impacts on biodiversity. If the planting of GM pest-resistant crop varieties eliminates the need for broad-spectrum insecticidal control of primary pests, naturally occurring control agents are more likely to suppress secondary pest populations, maintaining a diversity and abundance of prey for birds, rodents and amphibians.[4] In addition to the studies on the non-target impacts of GM crops compared to conventional practices, many studies have quantified changes in pesticide use since the introduction of GM crops. In a review of farmer surveys that report changes in yields and production practices, 45 results show decreases in the amount of insecticide and/or number of insecticide applications used on Bt crops compared to conventional crops in Argentina, Australia, China, India and the US.[38] The reductions range from 14 to 75% in terms of amount of active ingredient and 14 to 76% for number of applications. A small sample survey in South Africa observed a reduction in the number of insecticide sprays in one of two years studied and an insignificant difference in the other year. There are no results indicating an increase in insecticide use for adopters of GM insect resistant crops.

Fewer surveys have captured changes in herbicide use in GM herbicide tolerant crops, perhaps because the impact of GM herbicide tolerant crops has largely been a substitution between herbicides that are applied at different rates, and therefore, changes in the amount of herbicide used is a poor indicator of environmental impact. Indeed, studies show both increases and decreases in the total amount of herbicide active ingredient applied per acre.[81,88,92,93] Several studies have been done to apply environmental indicators to observed changes in pesticide use related to the adoption of both insect resistant and herbicide tolerant crops, which all show a reduction in the environmental impact of pesticides used on GM crops (See **Table 4**).

Conclusion

Knowledge gained over the past 15 years that GM crops have been grown commercially indicates that the impacts on biodiversity are positive on balance. By increasing yields, decreasing insecticide use, increasing the use of more environmentally friendly herbicides and facilitating the adoption of conservation tillage, GM crops have already contributed to increasing agricultural sustainability.

Overall, the review finds that currently commercialized GM crops have reduced the impacts of agriculture on biodiversity, through enhanced adoption of conservation tillage practices, reduction of insecticide use and use of more environmentally benign herbicides and increasing yields to alleviate pressure to convert additional land into agricultural use.

The key findings of the review are:

Table 4. Summary of results of studies that quantify environmental impacts of pesticide use changes

Country	Technology	Data source	Crop year	Indicator	Result	Reference
Argentina	Bt cotton	farmer survey	2001	amount of insecticide used (kg/ha) by toxicity class	reductions of 47% and 78% for toxicity classes 1 and 2; no significant chance for less toxic classes 3 and 4	147
Argentina	HT soybean	farmer survey	2001	amount of herbicide use (kg/ha) by toxicity class	reductions of 83% and 100% for toxicity classes 2 and 3; increase of 248% in the use of less toxic class 4	88
US	HT cotton	farmer survey	2000	pesticide leaching potential (PLP/ha)	25% lower for herbicides used on HT cotton	93
US	HT/Bt cotton	farmer survey	2000	pesticide leaching potential (PLP/ha)	42% lower for herbicides used on HT/IR cotton; 5% lower for insecticides used on HT/IR cotton	93
South Africa	Bt cotton	farmer survey	1998/99–2000/01	biocide index	reductions between 40% and 62% for total insecticide use	148
US	HT soybean	USDA NASS Chemical Usage	1994–96 compared to 2006	Kovach's Environmental Impact	reduction of 12% for 2006 compared to 1994–96	149
Canada	HT canola	farmer survey	1995 compared to 2000	Kovach's Environmental Impact	reduction of 36.8%	150
Belgium	HT corn	current herbicide regime compared to possible HT regime	ex ante	pesticide occupational and environmental risk (POCER) indicator	reduction of 1/6 when glyphosate or glufosinate used alone	151
US	HT soybean	expert opinion on common HT and conventional herbicide regimes	2004	Kovach's Environmental Impact	reduction of 59%	152
US	HT canola	expert opinion on common HT and conventional herbicide regimes	2004	Kovach's Environmental Impact	reduction of 42%	152
US	HT cotton	expert opinion on common HT and conventional herbicide regimes	2004	Kovach's Environmental Impact	reduction of 42%	152
US	HT corn	expert opinion on common HT and conventional herbicide regimes	2004	Kovach's Environmental Impact	reduction of 39%	152
Global	HT soybean, HT corn, HT cotton, HT canola, IR corn, IR cotton	several	1996–2007	Kovach's Environmental Impact	aggregate reduction of 15.4%	153
Australia	Bt cotton	farmer survey	2002/03–2003/04	Kovach's Environmental Impact	reduction of 64%	154
US	HT soybean	farmer survey of weed pressure combined with herbicide selector software	not indicated	LD_{50} doses for rats	reduction of 40% of total doses	155

The impact of the introduction of GM crops on crop diversity has not been thoroughly studied. However, the small number of studies that have been done (cotton in the US and India, soybeans in the US) find that the introduction of GM crops has not decreased crop diversity.

The potential impact of Bt crops on soil organisms is well studied. Few or no effects on soil organisms have been reported. Some reported differences, particularly in soil microbial communities, may have been due to differences in geography, temperature, plant variety and soil type.

Changes in weed community composition and abundance have been reported, due to changes in herbicide regimes and tillage practices associated with herbicide tolerant crops.

GM crops have increased yields, and therefore may have already alleviated pressure to convert natural habitat into agricultural use.

Pest populations have declined in some areas with high adoption rates of Bt crops, which benefits growers of other host crops and reduces the need for insecticide use.

The potential non-target impacts of insect resistant Bt crops on above-ground invertebrates have been extensively studied, with several hundred studies comparing effects of Bt and non-Bt crops. Several comprehensive reviews of the literature have been published, concluding that effects on natural enemies were observed only when Bt-susceptible, sublethally damaged herbivores were used as prey or host, with no indication of direct toxic effects. Field studies have confirmed that the abundance and activity of parasitoids and predators are similar in Bt and non-Bt crops.

Potential non-target impacts of herbicide tolerant crops on above-ground invertebrates have been the subject of several studies, mostly notably, the Farm Scale Evaluation in the UK. Changes in abundance of invertebrates and birds followed changes in weed control efficacy.

The introduction of herbicide tolerant crops has facilitated adoption of conservation tillage, which is expected to decrease erosion, increase water infiltration and decrease pesticide-runoff.

Adopters of GM crops have reduced insecticide use and switched to more environmentally friendly herbicides.

GM crops can continue to decrease the pressure on biodiversity as global agricultural systems expand to feed a world population that is expected to continue to increase for the next 30 to 40 years. Due to higher income elasticities of demand and population growth, these pressures will be greater in developing countries.[94] Both current and pipeline technology hold great potential in this regard. The potential of currently commercialized GM crops to increase yields, decrease pesticide use and facilitate the adoption of conservation tillage has yet to be realized, as there continue to be countries where there is a good technological fit, but have not approved these technologies for commercialization.[95-101]

In addition to the potential benefits of expanded adoption of current technology, several pipeline technologies offer additional promise of alleviating the impacts of agriculture on biodiversity. Continued yield improvements in crops such as rice and wheat are expected with insect resistant and herbicide tolerant traits that are already commercialized in other crops.[102-106] Bt eggplant, which is expected to increase yields and decrease insecticide use significantly, is currently under consideration by Indian regulators.[107,108]

Technologies such as drought tolerance and salinity tolerance would alleviate the pressure to convert high biodiversity areas into agricultural use by enabling crop production on suboptimal soils.[1] Drought tolerance technology, which allows crops to withstand prolonged periods of low soil moisture, are anticipated to be commercialized within 5 years.[109] The technology has particular relevance for areas like sub-Saharan Africa, where drought is a common occurrence and access to irrigation is limited.[110] Salt tolerance addresses the increasing problem of saltwater encroachment on freshwater resources.[111]

Nitrogen use efficiency technology is also under development, which can reduce run-off of nitrogen fertilizer into surface waters. The technology promises to decrease the use of fertilizers while maintaining yields or increase yields achievable with reduced fertilizer rates where access to fertilizer inputs is limited.[112] The technology is slated to be commercialized within the next 10 years.[109]

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