转基因作物应用(1996—2012)对全球社会经济与环境的主要影响

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摘　要　本文概述了作物生物技术对全球农业产生的经济和环境影响。分析结果表明,在农场水平上生物技术的应用产生了非常显著的净经济收益,2012 年总计达到 188 亿美元,从 1996 年到 2012 年的 17 年间共计达到 1 166 亿美元,这些经济收益为发展中国家和发达国家的农民的经济收入增长各贡献了大约 50%。转基因技术也对全球四大农作物的生产水平提高作出了重要的贡献。自从 1990 年中期采用这种技术之后,大豆和玉米的世界产量分别增加了 1.22 亿 t 和 2.3 亿 t。在关键的环境影响因素方面,这种技术的应用减少了 5.03 亿 kg 杀虫剂的用量(降低了 8.8%),将使用除草剂和杀虫剂对环境的影响(基于环境影响指数 EIQ 衡量)降低了 18.7%。这种技术也显著降低了农业地区温室气体的排放,在 2012 年减少的排放量相当于马路上的汽车减少了 1 188 万辆。

关键词　产量;成本;收入;生产;转基因作物;杀虫剂;碳固存;免耕;环境影响指数

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本文深入分析了作物生物技术自 20 世纪 90 年代中期第一次商业化推广之后,世界上越来越多的农民采用这种技术并将继续应用于农业生产中的原因。本文的结论主要依据一些经过同行评议的文献,并着重分析这种技术在农场水平上产生的经济效益、生产效益以及由于杀虫剂和除草剂使用量改变而产生的环境影响以及对温室气体排放减少的贡献。

本报告基于转基因作物对现存农场水平上的影响的大量数据的分析。由于并不是每一种作物、每一个年份和每一个国家的原始数据都能获得,这里的分析主要是以大量能够获得的具有代表性的研究和分析数据为主体,并通过作者自己的数据收集和分析进行增补。在分析有关杀虫剂使用时也考虑到了除草剂使用模式上的变化,以反映近年来一些种植者因担心耐除草剂作物的应用而产生抗除草剂(如草甘膦)杂草的问题而采取的一些措施。如需获得更多关于研究方法、原始数据和参考文献(注释 1)等信息,读者可以查阅这 2 篇文章(www. landes-bioscience. com):“Global income and production effects of GM crops 1996－2012,GM Crops and Food:Biotechnology in Agriculture and the Food Chain,5.1,1-11”和“Key environmental impacts of global GM crop use 1996－2012,GM Crops and Food Biotechnology in Agriculture and the Food Chain,5.2,149-160.”

1　经济影响

转基因技术对农业收入产生了显著的积极影响,这得益于生产力和生产效率的提高(表 1)。2012 年,全球直接受益于转基因作物的农业收入有 188 亿美元,这相当于全球四大农作物——大豆、玉米、油菜和棉花的产值增加了 5.6%。自 1996 年以来,农业收入增加了 1 166 亿美元。

2012 年农业收入的增长主要得益于玉米产量的提高。这一年由转基因抗虫玉米产生的 67 亿美元的额外收入相当于使种植了转基因作物的国家的作物产值增加了 6.6%,或者使 2012 年全球玉米产值(2 260 亿美元)增加了 3%。自 1996 年以来,转基因抗虫技术已累计使全球种植玉米的农民收入增加了 323 亿美元。

棉花也因为产量提高而成本降低获得了可观的产值增幅。2012 年,应用转基因技术的国家的棉花产值增加了 55 亿美元;自 1996 年以来,棉花的产值

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表 1　1996 年至 2012 年间全球种植转基因作物获得的农业收入(百万美元)[1)]

Table 1　Global farm income benefits from growing GM crops 1996－2012 (million US $)

性状 Trait	2012 年农业收入增长 Increase in farm income 2012	1996 年至 2012 年农业收入增长 Increase in farm income 1996－2012	2012 年转基因作物额外收益占采用转基因作物国家该作物总产值的比列/% Farm income benefit in 2012 as % of total value of production of these crops in GM adopting countries	2012 年转基因作物额外收益占全球该作物总产值的比例/% Farm income benefit in 2012 as % of total value of global production of crop
转基因抗除草剂大豆 GM herbicide tolerant soybeans	4 797.9	37 008.6	4.4	4.0
转基因抗除草剂玉米 GM herbicide tolerant maize	1 197.9	5 414.7	1.2	0.5
转基因抗除草剂棉花 GM herbicide tolerant cotton	147.2	1 371.6	0.4	0.3
转基因抗除草剂油菜 GM herbicide tolerant canola	481.0	3 664.4	4.9	1.3
转基因抗虫玉米 GM insect resistant maize	6 727.8	32 317.2	6.6	3.0
转基因抗虫棉花 GM insect resistant cotton	5 331.3	36 317.2	13.1	11.2
其他 Others	86.3	496.7	N/a	
总计 Totals	18 769.4	116 590.4	6.8	5.6

1)其他指抗病毒木瓜和西葫芦以及抗除草剂甜菜。总计不包括“其他作物”(即 4 种主要作物——大豆、玉米、油菜以及棉花以外的其他作物)。农业收入计算是指考虑了对产量、作物质量以及生产成本的主要变量影响之后的农业净收入变化(如种子的支付溢价和农作物保护支出的影响)。All values are nominal. Others＝Virus resistant papaya and squash and herbicide tolerant sugar beet. Totals for the value shares exclude ‘other crops’ (ie,relate to the 4 main crops of soybeans,maize,canola and cotton). N/a: Not applicable. Farm income calculations are net farm income changes after inclusion of impacts on yield,crop quality and key variable costs of production (eg,payment of seed premia,impact on crop protection expenditure).

共计增加了 377 亿美元。2012 年增加的收入相当于使这些国家的棉花产值增长了 13.5%，对全球 470 亿美元的棉花收入而言增长了 11.5%。2 种新的棉花种子技术对农业收入所带来的大幅度提高是很可观的。

转基因技术也使大豆和油菜的农业收入有显著的提高。2012 年，转基因抗除草剂技术在大豆中的应用使农业收入增加了 48 亿美元，自 1996 年以来累计增加了 370 亿美元。油菜行业(主要是北美)在 1996 至 2012 年间的产值增加了 36.6 亿美元。

表 2 总结了转基因作物对主要种植国家的农业收入影响，其中最为显著的是南美洲(包括阿根廷、玻利维亚、巴西、巴拉圭和乌拉圭)的转基因抗除草剂大豆、中国和印度的转基因抗虫棉花以及美国的一系列转基因品种所带来的重要收益。表 2 中数据显示了南非、菲律宾、墨西哥和哥伦比亚的农业收益也在逐渐提高。

发展中国家与发达国家农民收益的比例比较表明，在 2012 年 46.2%的收益是由发展中国家的农民获得的(表 3)。发展中国家的农民收入增长绝大部分得益于转基因抗虫棉花和转基因抗除草剂大豆的种植。自 1996 年到 2012 年的 17 年间，发展中国家的农民收入增长了 49.9%(581.5 亿美元)。

转基因技术应用的成本分析(表 4)显示，2012 年 4 种主要转基因作物的总成本相当于总收益(包括农业收入增长加上支付给种子供应链的技术成本，注释 2)的 23%。对发展中国家的农民而言，总成本相当于总技术收益的 21%；对发达国家的农民而言，总成本相当于总技术收益的 25%。尽管不同国家的具体情况不同，但总体上发展中国家的技术收益比发达国家更高，仍然可以反映出一些问题，比如发展中国家对知识产权保护和强制执行力相对较弱，以及相对于发达国家来讲每公顷农业收入平均水平更高等。

表2 1996—2012年各国转基因作物农业收益(百万美元)[1)]

Table 2 GM crop farm income benefits 1996－2012 **selected countries (million US $)**

国家(地区) Country	转基因抗除草剂大豆 GM HT soybeans	转基因抗除草剂玉米 GM HT maize	转基因抗除草剂棉花 GM HT cotton	转基因抗除草剂油菜 GM HT canola	转基因抗虫玉米 GM IR maize	转基因抗虫棉花 GM IR cotton	总计 Total
美国 US	16 668.7	3 752.3	975.8	268.3	26 375.9	4 046.7	52 087.7
阿根廷 Argentina	13 738.5	766.7	107.0	N/a	495.2	456.4	15 563.8
巴西 Brazil	4 825.6	703.4	92.5	N/a	2 761.7	13.3	8 396.5
巴拉圭 Paraguay	828	N/a	N/a	N/a	N/a	N/a	828.0
加拿大 Canada	358	81.3	N/a	3 368.8	1 042.9	N/a	4 851.0
南非 South Africa	9.1	4.1	3.2	N/a	1 100.6	34.2	1 151.2
中国 China	N/a	N/a	N/a	N/a	N/a	15 270.4	15 270.4
印度 India	N/a	N/a	N/a	N/a	N/a	14 557.1	14 557.1
澳大利亚 Australia	N/a	N/a	78.6	27.3	N/a	659.6	765.5
墨西哥 Mexico	5.0	N/a	96.4	N/a	N/a	136.6	238.0
菲律宾 Philippines	N/a	104.7	N/a	N/a	273.6	N/a	378.3
罗马尼亚 Romania	44.6	N/a	N/a	N/a	N/a	N/a	44.6
乌拉圭 Uruguay	103.8	N/a	N/a	N/a	17.6	N/a	121.4
西班牙 Spain	N/a	N/a	N/a	N/a	176.3	N/a	176.3
其他欧盟国家 Other EU	N/a	N/a	N/a	N/a	18.8	N/a	18.8
哥伦比亚 Colombia	N/a	1.7	18.1	N/a	47.4	15.4	826.6
玻利维亚 Bolivia	432.2	N/a	N/a	N/a	N/a	N/a	432.2
缅甸 Burma	N/a	N/a	N/a	N/a	N/a	215.4	215.4
巴基斯坦 Pakistan	N/a	N/a	N/a	N/a	N/a	725.1	725.1
布基纳法索 Burkina Faso	N/a	N/a	N/a	N/a	N/a	186.9	186.9
洪都拉斯 Honduras	N/a	N/a	N/a	N/a	6.9	N/a	6.9

1)农业收入计算是指考虑了对产量、作物质量以及生产成本的主要变量影响之后的农业净收入变化(如种子的支付溢价和农作物保护支出的影响)。N/a 表示该国没有种植此作物。美国的总额还包括其他作物或性状的4.91亿美元(不包含在表格中)。表中没有显示的还有来自加拿大转基因抗虫甜菜的550万美元的额外农业收入。All values are nominal. Farm income calculations are net farm income changes after inclusion of impacts on yield, crop quality and key variable costs of production (eg, payment of seed premia, impact on crop protection expenditure). N/a: Not applicable. US total figure also includes $491 million for other crops/traits (not included in the table). Also not included in the table is $5.5 million extra farm income from GM HT sugar beet in Canada.

表 3　2012 年发展中国家和发达国家转基因作物农业收益比较(百万美元)[1)]

Table 3　GM crop farm income benefits 2012：developing versus developed countries(million US ＄)

性状 Phenotypic trait	发达国家 Developed	发展中国家 Developing
转基因抗除草剂大豆 GM HT soybeans	2 955.4	1 842.5
转基因抗除草剂玉米 GM HT maize	654.0	543.9
转基因抗除草剂棉花 GM HT cotton	71.4	75.8
转基因抗除草剂油菜 GM HT canola	481.0	0
转基因抗虫玉米 GM IR maize	5 327.5	1 400.3
转基因抗虫棉花 GM IR cotton	530.7	4 800.7
转基因抗病毒木瓜和西葫芦以及转基因抗除草剂甜菜 GM virus resistant papaya and squash and GM HT sugar beet	86.3	0
总计 Total	10 106.3	8 663.2

1)发展中国家指所有南美的国家、墨西哥、洪都拉斯、布基纳法索、印度、中国、菲律宾以及南非。Developing countries＝All countries in South America，Mexico，Honduras，Burkina Faso，India，China，the Philippines and South Africa.

表 4　2012 年转基因成本与获益总额比较(百万美元)[1)]

Table 4　Cost of accessing GM technology relative to the total farm income benefits 2012 (million ＄)

性状 Phenotypic trait	技术成本：所有农民 Cost of technology：all farmers	农业收入增加：所有农民 Farm income gain：all farmers	技术给农民和种子供应链的总收益 Total benefit of technology to farmers and seed supply chain	技术成本：发展中国家 Cost of technology：developing countries	农业收入增加：发展中国家 Farm income gain：developing countries	技术给农民和种子供应链的总收益：发展中国家 Total benefit of technology to farmers and seed supply chain：developing countries
转基因抗除草剂大豆 GM HT soybeans	1 528.1	4 797.9	6 326.0	998.7	1 842.5	2 841.2
转基因抗除草剂玉米 GM HT maize	1 059.4	1 197.9	2 257.3	364.5	543.9	908.4
转基因抗除草剂棉花 GM HT cotton	295.0	147.2	442.2	22.2	75.8	98.0
转基因抗除草剂油菜 GM HT canola	161.2	481.0	642.2	N/a	N/a	N/a
转基因抗虫玉米 GM IR maize	1 800.8	6 727.8	8 528.6	512.3	1 400.3	1 912.6
转基因抗虫棉花 GM IR cotton	720.7	5 331.3	6 052.0	422.7	4 800.7	5 223.4
其他 Others	76.2	86.3	162.5	N/a	N/a	N/a
总计 Total	5 641.4	18 769.4	24 410.8	2 320.4	8 663.2	10 983.6

1)N/a 表示没有种植此作物。转基因技术应用成本是指与传统种子相比，农民为转基因种子支付的保险费。N/a：Not applicable. Cost of accessing technology based on the seed premia paid by farmers for using GM technology relative to its conventional equivalents.

2　转基因技术的生产效益

自 1996 年以来，转基因作物的应用已经使全球玉米、棉花、油菜和大豆的产量大幅增加(表 5)。转基因抗虫技术的应用对玉米和棉花产量的额外增长分别贡献了 97.1％和 99.3％。与传统技术(如使用杀虫剂和种子处理)相比，转基因抗虫技术为所有采用这种技术的国家(除了澳大利亚的转基因抗虫棉花，注释 3)的作物产量都带来了积极的作用。自 1996 年以来的 17 年间，所有种植抗虫作物地区的玉米和棉花的平均产量分别增加了 10.4％和 16.1％。

表 5　由转基因导致的作物额外产量(百万 t)[1)]

Table 5　Additional crop production arising from positive yield effects of GM crops (million tonnes)

作物 Crops	1996 年至 2012 年额外产量 1996－2012 additional production	2012 年额外产量 2012 additional production
大豆 Soybeans	122.3	12.0
玉米 Maize	231.4	34.1
棉花 Cotton	18.2	2.4
油菜 Canola	6.6	0.4
甜菜 Sugar beet	0.6	0.15

1)转基因抗除草剂甜菜只有美国和加拿大的数据(自 2008 年)。GM HT sugar beet only in the US and Canada since 2008.

转基因抗除草剂技术并不是直接提高作物产量，而是降低除草的成本和提供更便利的除草方法。然而这种优化后的除草技术也的确能够使一些国家的作物产量增加。这种技术的优势在于免耕的便利性、缩短生产周期，并能使南美洲的大量农民能够在一个生长季收获完小麦之后马上种上大豆，因此，间接地提高作物产量。相比传统的大豆生产，这种第二茬种植的大豆使阿根廷和巴拉圭在1996至2012年间的大豆产量增加了1.143亿t（占所有与转基因相关的大豆产量增加值的93.5%）。

3 杀虫剂与除草剂用量改变对环境的影响

为了研究杀虫剂与除草剂用量改变对环境的影响，研究者分析了这两种有效成分的使用，并利用环境影响指数（EIQ）来评估更广泛的环境影响（包括对动物和人类健康的影响）。EIQ是将不同转基因作物与传统生产中的各种杀虫剂对环境和健康的不同影响提炼为一个“每公顷阈值”以描述各种产品的主要毒性和环境暴露的数值。采用这种衡量方式比仅仅衡量活性成分的用量能够更直观地比较各种杀虫剂对环境和人类健康的影响。不过，也请读者们注意，EIQ只是一种指标（主要是针对毒性），并不能包括所有的环境问题和影响。在分析转基因抗除草剂技术时，我们假设传统的替代方法与转基因抗除草剂技术具有同等水平的除草能力。

杀虫剂和除草剂对环境的影响在转基因作物种植地区有显著的下降，这种下降与相应的转基因特性相关（表6）。自1996年以来，转基因作物种植地区的杀虫剂使用量减少了5.03亿kg活性成分（下降了8.8%）。如果用EIQ衡量，用于转基因作物上的杀虫剂和除草剂对环境造成的影响下降了18.7%。

表6 1996—2012年全球因种植转基因作物对除草剂与杀虫剂使用量变化的影响

Table 6 Impact of changes in the use of herbicides and insecticides from growing GM crops globally 1996—2012

性状 Trait	活性成分使用量的变化/(10^6 kg) Change in volume of active ingredient used	田间环境影响指数的变化/(10^6 EIQ/hm^2) Change in field EIQ impact (in terms of million field EIQ)	用于转基因作物的活性成分的变化/% Change in ai use on GM crops	与转基因作物使用的除草剂与杀虫剂相关的环境影响变化/% Change in environmental impact associated with herbicide & insecticide use on GM crops	2012年种植面积/(10^6 hm^2) Area GM trait 2012
转基因抗除草剂大豆 GM herbicide tolerant soybeans	−4.7	−6 654	−0.2	−15.0	79.1
转基因抗除草剂玉米 GM herbicide tolerant maize	−203.2	−6 025	−9.8	−13.3	38.5
转基因抗除草剂油菜 GM herbicide tolerant canola	−15.0	−509	−16.7	−26.6	8.6
转基因抗除草剂棉花 GM herbicide tolerant cotton	−18.3	−460	−6.6	−9.0	4.4
转基因抗虫玉米 GM insect resistant maize	−57.6	−2 215	−47.9	−45.1	42.3
转基因抗虫棉花 GM insect resistant cotton	−205.4	−9 256	−25.6	−28.2	22.1
转基因抗除草剂甜菜 GM herbicide tolerant sugar beet	+1.3	−2.0	+29.3	−2.0	0.51
总计 Totals	−503.1	−25 121	−8.8	−18.7	

从绝对数字来看，最大的环境效益与转基因抗虫技术的应用有关。传统的棉花一直是杀虫剂使用的大户，转基因抗虫棉花的应用使杀虫剂活性成分的用量减少了25.6%，并使EIQ降低了28.2%（1996年至2012年）。类似的，转基因抗虫技术在玉米中的应用也大大减少了杀虫剂的使用，带来了显著的环境效益。

转基因玉米中除草剂的使用量也减少了2.03亿kg（1996年至2012年），降低了9.8%，由此对环境造成的影响也降低了13.3%。这些数据清楚地表明了转基因抗除草剂作物所使用的除草剂活性成分比传统作物所使用的对环境更为友好。

大豆和油菜行业也取得了可观的环境效益。1996年至2012年大豆中除草剂的使用量减少了470万kg，并且由于使用了对环境更为友好的除草剂类型，转基因大豆种植地区除草剂的使用对环境

造成的影响降低了 15%。油菜中除草剂的使用也减少了 1 500 万 kg(降低了 16.7%)，由于使用对环境更为友好的除草剂类型对环境的影响降低了 26.6%。

在 1996 年至 2012 年间杀虫剂和除草剂用量减少所获得的环境效益方面，发达国家与发展中国家各占 54%和 46%。发展中国家中大约 3/4(73%)的环境效益得益于转基因抗虫棉花的应用。

表 7　1996－2012 年杀虫剂与除草剂用量减少的环境获益：发展中国家与发达国家(百万指数每公顷)

Table 7　GM crop environmental benefits from lower insecticide and herbicide use 1996－2012：developing versus developed countries

性状 Trait	田间环境影响指数变化：发达国家 Change in field EIQ impact：developed countries	田间环境影响指数变化：发展中国家 Change in field EIQ impact：developing countries
转基因抗除草剂大豆 GM HT soybeans	－4 773.9	－1 880.2
转基因抗除草剂玉米 GM HT maize	－5 585.9	－438.8
转基因抗除草剂棉花 GM HT cotton	－351.0	－109.3
转基因抗除草剂油菜 GM HT canola	－509.1	0
转基因抗虫玉米 GM IR maize	－1 574.4	－640.8
转基因抗虫棉花 GM IR cotton	－805.5	－8 451.0
转基因抗除草剂甜菜 GM HT sugar beet	－2.0	0
总计 Totals	－13 601.8	－11 520.1

值得注意的是，在一些转基因抗除草剂作物广泛种植的地区，一些农民过于依赖使用单一的除草剂如草甘膦来管理田间杂草，这种做法已经造成杂草抗性的产生。目前全球范围内确认的抗草甘膦的杂草有 28 种，其中有一些与转基因抗草甘膦作物并无关系(www.weedscience.org)。例如，在美国目前发现了 14 种杂草对草甘膦有抗性，其中 2 种与转基因抗草甘膦作物无关。目前美国受影响的面积占玉米、棉花、油菜、大豆和甜菜(转基因抗除草剂作物)总种植面积的 20%～40%。

近年来，研究杂草的专家们越来越多地意识到需要改变转基因抗除草剂作物的杂草管理方式，因为这些杂草正在朝着抗草甘膦的方向进化，应该鼓励转基因抗除草剂作物的种植户更有前瞻性，采用不同类型的除草剂(具有不同或互补的作用)联合草甘膦进行杂草控制，而不是单一使用一种除草剂，即使在尚未发现除草剂抗性杂草的地区也应该如此。

具有前瞻性的、多样化的杂草管理方式是避免抗除草剂作物中产生抗性杂草的主要策略，也是处理传统作物中杂草抗性的主要方法。一个具有前瞻性的杂草控制方式通常要求更少的除草剂用量、更好的环境效益，并且要比被动性的杂草控制更为经济。

不管是采用被动性还是前瞻性的杂草控制方式，在宏观的层面上都已经开始影响转基因抗除草剂大豆、棉花、玉米以及油菜中除草剂使用的混合量、总量以及整体的环境效益，这些结果也体现在这篇报告的数据中。

4　对温室气体(GHG)排放的影响

转基因作物在减少温室气体排放中的作用主要体现在两个方面：第一，由于杀虫剂和除草剂的用量减少，降低了生产杀虫剂和除草剂产生的燃料消耗，也减少了土壤培养的能量消耗。相对于传统作物，种植转基因作物时喷洒杀虫剂或除草剂的次数减少，以及向保护型耕作、少耕或者免耕的农业生产方式的转变减少了二氧化碳的排放。2012 年，二氧化碳的排放量减少了 21.11 亿 kg(燃料的使用量减少了 7.91 亿 L)。在 1996 年至 2012 年间，累计减少的燃料使用量估计可产生 167.36 亿 kg 二氧化碳(源于燃料使用量减少了 62.68 亿 L)。第二，免耕和少耕(注释 4)农业的应用。这些生产方式的普及速度随着转基因抗除草剂作物的推广而大大提高，因为转基因抗除草剂技术能够有力地帮助种植者控制杂草，而不再需要依赖土壤培养或者准备发芽床来控制杂草。因此，用于耕作的拖拉机燃料使用量减少，土壤质量提高，水土流失也减少。更多的二氧化碳留在土壤中，使得温室气体的排放量减少。由于北美和南美洲迅速采用免耕和少耕农业生产方式所减少的燃料使用，估计 2012 年土壤中碳储存量增加了 67.06 亿 kg(相当于排放到大气中的二氧化碳减少了 246.13 亿 kg)。土壤中累积的碳储存量可能比估计的值更高，因为土质一年比一年更好。不过，也有可能总的碳储存量会更低，因为只有部分种植地区会继续使用免耕和少耕的耕作方式。由于缺乏数据，难以确切地估算传统耕作改变之后土壤的

碳固存量，因此，我们应该谨慎对待减少了 2 035.6 亿 kg 二氧化碳排放量的估计。

如果把这些固碳的效益转换为汽车碳排放的概念，从表 8 的数据可以看出：2012 年，由燃料减少而引起的二氧化碳排放减少量相当于马路上的汽车减少了 94 万辆；2012 年，土壤中可能的碳固存量增加值相当于马路上的汽车减少了 1 094 万辆；2012 年，由燃料减少而引起的二氧化碳排放减少量和土壤中可能的碳固存量增加值总共相当于马路上的汽车减少了 1 188 万辆，相当于英国注册汽车总数的 41.38%；不可能确切估算出自 1996 年以来的土壤碳的固存量。如果过去 17 年一直用免耕或少耕的方式种植转基因抗除草剂作物，那么会使二氧化碳排放量减少 2 035.6 亿 kg，相当于马路上的汽车减少了 9 050 万辆。当然，这只是可能的最大值，实际的二氧化碳减少量可能会少一些。

表 8 2012 年固碳的影响：与之对应的汽车减少数量[1)]

Table 8 Context of carbon sequestration impact 2012: car equivalents

作物/性状/国家 Crop/Trait/Country	由于燃料使用量减少导致的永久 CO_2 减少量/(10^6 kg) Permanent carbon dioxide savings arising from reduced fuel use	永久燃料减少量：相当于1年内从道路上减少的普通家庭汽车数量/10^3 Permanent fuel savings: as average family car equivalents removed from the road for a year	潜在额外土壤固碳水平/(10^6 kg) Potential additional soil carbon equestration savings	潜在固碳效益：相当于1年内从道路上减少的普通家庭汽车的数量/10^3 Soil carbon sequestration savings: as average family car equivalents removed from the road for a year
美国：转基因抗除草剂大豆 US: GM HT soybeans	210	93	1 070	475
阿根廷：转基因抗除草剂大豆 Argentina: GM HT soybeans	736	327	11 186	4 972
巴西：转基因抗除草剂大豆 Brazil GM HT soybeans	394	175	5 985	2 660
玻利维亚、巴拉圭、乌拉圭：转基因抗除草剂大豆 Bolivia, Paraguay, Uruguay: GM HT soybeans	156	69	2 365	1 051
加拿大：转基因抗除草剂油菜 Canada: GM HT canola	203	90	1 024	455
美国：转基因抗除草剂玉米 US: GM HT corn	210	93	2 983	1 326
全球转基因抗虫棉花 Global GM IR cotton	45	20	0	0
巴西：抗虫玉米 Brazil IR corn	157	69	0	0
总计 Total	2 111	936	24 613	10 939

1)假设一辆普通家用汽车每公里产生 150 g CO_2，平均 1 年行驶 15 000 km，则每年排放 2 250 kg CO_2。Assumption: an average family car produces 150 grams of carbon dioxide per km. A car does an average of 15 000 km/year and therefore produces 2 250 kg of carbon dioxide/year.

5 小 结

迄今为止，作物生物技术已经为农民提供了很多特定的农艺性状去克服许多生产制约因素。这使得 2012 年 1.6 亿 hm^2 土地上的农业产量和收益大幅上涨，也让应用这一技术的 1 700 万农民增加了收入。

过去 17 年里，尽管这项技术只用于有限的农艺性状改良而且只有小范围的转基因作物实现了商业化，但它对社会经济和环境都产生了重大的积极影响。

作物生物技术通过本身的技术优势及其在农耕方式改革中扮演的重要角色，尤其是加快农耕方式的效率化和环保化方面，给经济和环境带来了双赢。具体来说：(1)转基因抗虫性状的益处大部分直接来源于这种技术(产量增加、生产风险降低和农药使用量减少)。因此，农民(大部分是发展中国家)在增加作物产量和经济效益的同时也在实践更为环境友好型的种植方式。(2)转基因抗除草剂性状的益处来源于直接的收益(大部分是因为种植成本的减少)和

农业耕作方式升级的便利。因此，转基因抗除草剂技术(尤其是在大豆中)促使农民使用低成本的广谱除草剂(草甘膦)，在北美和南美促进农业生产方式由传统形式转变为免耕或少耕的方式。这种农耕系统的改变对农民的经济收入有积极的贡献，而且有重要的环境效益，主要是显著降低了温室气体的排放(主要源于拖拉机燃料的减少和土壤碳固存量的增加)。(3)抗虫性状和抗除草剂性状对全世界大豆、玉米、棉花、油菜的产量也有相当重要的贡献。然而，在转基因抗除草剂作物的应用中，有些地区的农民过度依赖草甘膦的使用而导致了杂草抗性的产生。因此，越来越多的农民采取了混合多种除草剂进行预防式和应对式相结合的杂草控制方案。尽管如此，转基因作物的总体环境效益和经济效益还是相当可观的，而且还会继续发挥积极的作用。

总之，在经过同行评议的文献中有相当多的证据定量分析了作物生物技术对经济和环境的积极影响，本文只是对其作了一个概括。希望本文能够激起读者的兴趣去阅读这里引用的这些文献，以及其他更多关于这一主题所发表的文章，并得到读者的认识和结论。

注　释

① 本文的参考文献总数约为 150 篇，绝大部分都是来自经同行评审的杂志。

② 种子供应链的技术成本包括零售商、繁种、育种家、经销商和转基因技术支持。

③ 这反映了之前通过大量地使用杀虫剂很好地控制了棉铃虫的危害。在澳大利亚采用转基因技术的主要好处在于节约了大量的成本(在杀虫剂上)以及减少杀虫剂使用所带来的环境收益。

④ 免耕意味着不再需要耕地，少耕则意味着与传统耕作方式相比对土地的干扰更少。例如，采用免耕的方式，可以将大豆种子直接播种在之前种植的作物如玉米、棉花或小麦遗留下来的有机物质上。

Key global economic and environmental impacts of genetically modified (GM) crop use 1996－2012

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Abstract　This paper summarises the economic and key environmental impacts that crop biotechnology has had on global agriculture. The analysis shows that there have been very significant net economic benefits at the farm level amounting to ＄18.8 billion in 2012 and ＄116.6 billion for the seventeen year period 1996－2012 (in nominal terms). These economic gains have been divided roughly 50％ each to farmers in developed and developing countries. GM technology have also made important contributions to increasing global production levels of the four main crops, having added 122 million tonnes and 230 million tonnes respectively, to the global production of soybeans and maize since the introduction of the technology in the mid 1990s. In terms of key environmental impacts, the adoption of the technology has reduced pesticide spraying by 503 million kg (－8.8％) and, as a result, decreased the environmental impact associated with herbicide and insecticide use on these crops (as measured by the indicator the Environmental Impact Quotient (EIQ)) by 18.7％. The technology has also facilitated a significant reduction in the release of greenhouse gas emissions from this cropping area, which, in 2012, was equivalent to removing 11.88 million cars from the roads.

Key words　yield; cost; income; production; genetically modified crops; pesticide; carbon sequestration; no tillage; environmental impact quotient

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Abstract This paper summarises the economic and key environmental impacts that crop biotechnology has had on global agriculture. The analysis shows that there have been very significant net economic benefits at the farm level amounting to $18. 8 billion in 2012 and $116. 6 billion for the seventeen year period 1996-2012 (in nominal terms). These economic gains have been divided roughly 50% each to farmers in developed and developing countries. GM technology have also made important contributions to increasing global production levels of the four main crops, having added 122 million tonnes and 230 million tonnes respectively, to the global production of soybeans and maize since the introduction of the technology in the mid 1990s. In terms of key environmental impacts, the adoption of the technology has reduced pesticide spraying by 503 million kg (−8. 8%) and, as a result, decreased the environmental impact associated with herbicide and insecticide use on these crops (as measured by the indicator the Environmental Impact Quotient (EIQ)) by 18. 7%. The technology has also facilitated a significant reduction in the release of greenhouse gas emissions from this cropping area, which, in 2012, was equivalent to removing 11. 88 million cars from the roads.
Keywords yield; cost; income; production; genetically modified crops; pesticide; carbon sequestration; no tillage; environmental impact quotient

1 Introduction

This paper provides insights into the reasons why so many farmers around the world have adopted crop biotechnology and continue to use it in their production systems since the technology first became available on a widespread commercial basis in the mid 1990s. The paper draws, and is largely based on, the considerable body of peer reviewed literature available that has examined these issues. It specifically focuses on the farm level economic effects, the production effects, the environmental impact resulting from changes in the use of insecticides and herbicides, and the contribution towards reducing greenhouse gas (GHG) emissions.

The report is based on extensive analysis of existing farm level impact data for biotech crops. Whilst primary data for impacts of commercial cultivation were not available for every crop, in every year and for each country, a substantial body of representative research and analysis is available and this has been used as the basis for the analysis presented. This has been supplemented by the authors' own data collection and analysis. The analysis of pesticide usage also takes into consideration changes in the pattern of herbicide use in recent years that reflect measures taken by some farmers to address issues of weed resistance to the main herbicide (glyphosate) used with herbicide tolerant biotech crops. For additional information on the methodology, data sources and references[①], readers should consult a detailed examination of these issues in the two papers in the journal GM Crops, www.landesbioscience.com-Global income and production effects of GM crops 1996-2012, GM Crops and Food:Biotechnology in Agriculture and the Food Chain, 5.1, 1-11 and key environmental impacts of global GM crop use 1996-2012, GM Crops and Food Biotechnology in Agriculture and the Food Chain, 5.2, 149-160. These papers follow on from 15 previous peer reviewed papers by the authors on the subject of crop biotechnology impact.

2 Economic impacts

GM technology has had a significant positive impact on farm income derived from a combination of enhanced productivity and efficiency gains (Table 1). In 2012, the direct global farm income benefit from GM crops was $18.8 billion. This is equivalent to having added 5.6%

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Table 1 Global farm income benefits from growing GM crops 1996-2012 million $

Trait	Increase in farm income 2012	Increase in farm income 1996-2012	Farm income benefit in 2012 as % of total value of production of these crops in GM adopting countries	Farm income benefit in 2012 as % of total value of global production of crop
GM herbicide tolerant soybeans	4 797.9	37 008.6	4.4	4.0
GM herbicide tolerant maize	1 197.9	5 414.7	1.2	0.5
GM herbicide tolerant cotton	147.2	1 371.6	0.4	0.3
GM herbicide tolerant canola	481.0	3 664.4	4.9	1.3
GM insect resistant maize	6 727.8	32 317.2	6.6	3.0
GM insect resistant cotton	5 331.3	36 317.2	13.1	11.2
Others	86.3	496.7	N/a	N/a
Totals	18 769.4	116 590.4	6.8	5.6

Notes:All values are nominal. Others=Virus resistant papaya and squash and herbicide tolerant sugar beet. Totals for the value shares exclude 'other crops' (ie, relate to the 4 main crops of soybeans, maize, canola and cotton). N/a=not applicable. Farm income calculations are net farm income changes after inclusion of impacts on yield, crop quality and key variable costs of production (e.g., payment of seed premia, impact on crop protection expenditure)

to the value of global production of the four main crops of soybeans, maize, canola and cotton. Since 1996, farm incomes have increased by $116.6 billion.

The largest gains in farm income in 2012 have arisen in the maize sector, largely from yield gains. The $6.7 billion additional income generated by GM insect resistant (GM IR) maize in 2012 has been equivalent to adding 6.6% to the value of the crop in the GM crop growing countries, or adding the equivalent of 3% to the $226 billion value of the global maize crop in 2012. Cumulatively since 1996, GM IR technology has added $32.3 billion to the income of global maize farmers.

Substantial gains have also arisen in the cotton sector through a combination of higher yields and lower costs. In 2012, cotton farm income levels in the GM adopting countries increased by $5.5 billion and since 1996, the sector has benefited from an additional $37.7 billion. The 2012 income gains are equivalent to adding 13.5% to the value of the cotton crop in these countries, or 11.5% to the $47 billion value of total global cotton production. This is a substantial increase in value added terms for two new cotton seed technologies.

Table 2 GM crop farm income benefits 1996-2012 selected countries million $

	GM HT soybeans	GM HT maize	GM HT cotton	GM HT canola	GM IR maize	GM IR cotton	Total
US	16 668.7	3 752.3	975.8	268.3	26 375.9	4 046.7	52 087.7
Argentina	13 738.5	766.7	107.0	N/a	495.2	456.4	15 563.8
Brazil	4 825.6	703.4	92.5	N/a	2 761.7	13.3	8 396.5
Paraguay	828	N/a	N/a	N/a	N/a	N/a	828.0
Canada	358	81.3	N/a	3 368.8	1 042.9	N/a	4 851.0
South Africa	9.1	4.1	3.2	N/a	1 100.6	34.2	1 151.2
China	N/a	N/a	N/a	N/a	N/a	15 270.4	15 270.4
India	N/a	N/a	N/a	N/a	N/a	14 557.1	14 557.1
Australia	N/a	N/a	78.6	27.3	N/a	659.6	765.5
Mexico	5.0	N/a	96.4	N/a	N/a	136.6	238.0
Philippines	N/a	104.7	N/a	N/a	273.6	N/a	378.3
Romania	44.6	N/a	N/a	N/a	N/a	N/a	44.6
Uruguay	103.8	N/a	N/a	N/a	17.6	N/a	121.4
Spain	N/a	N/a	N/a	N/a	176.3	N/a	176.3
Other EU	N/a	N/a	N/a	N/a	18.8	N/a	18.8
Colombia	N/a	1.7	18.1	N/a	47.4	15.4	826.6
Bolivia	432.2	N/a	N/a	N/a	N/a	N/a	432.2
Burma	N/a	N/a	N/a	N/a	N/a	215.4	215.4
Pakistan	N/a	N/a	N/a	N/a	N/a	725.1	725.1
Burkina Faso	N/a	N/a	N/a	N/a	N/a	186.9	186.9
Honduras	N/a	N/a	N/a	N/a	6.9	N/a	6.9

Notes:All values are nominal. Farm income calculations are net farm income changes after inclusion of impacts on yield, crop quality and key variable costs of production (eg, payment of seed premia, impact on crop protection expenditure). N/a=not applicable. US total figure also includes $491 million for other crops/traits (not included in the table). Also not included in the table is $5.5 million extra farm income from GM HT sugar beet in Canada

Significant increases to farm incomes have also resulted in the soybean and canola sectors. The GM HT technology in soybeans has boosted farm incomes by $4.8 billion in 2012, and since 1996 has delivered over $37 billion of extra farm income. In the canola sector (largely North American) an additional $3.66 billion has been generated (1996-2012).

Table 2 summarises farm income impacts in key GM crop adopting countries. This highlights the important farm income benefit arising from GM HT soybeans in South America (Argentina, Bolivia, Brazil, Paraguay and Uruguay), GM IR cotton in China and India and a range of GM cultivars in the US. It also illustrates the growing level of farm income benefits being obtained in South Africa, the Philippines, Mexico and Colombia.

In terms of the division of the economic benefits obtained by farmers in developing countries relative to farmers in developed countries, Table 3 shows that in 2012, 46.2% of the farm income benefits have been earned by developing country farmers. The vast majority of these income gains for developing country farmers have been from GM IR cotton and GM HT soybeans. Over the seventeen years, 1996-2012, the cumulative farm income gain derived by developing country farmers was 49.9% ($58.15 billion).

Table 3 GM crop farm income benefits 2012:developing versus developed countries million $

	Developed	Developing
GMHT soybeans	2 955.4	1 842.5
GMHT maize	654.0	543.9
GMHT cotton	71.4	75.8
GMHT canola	481.0	0.0
GMIR maize	5 327.5	1 400.3
GMIR cotton	530.7	4 800.7
GM virus resistant papaya and squash and GM HT sugar beet	86.3	0.0
Total	10 106.3	8 663.2

Notes: Developing countries=all countries in South America, Mexico, Honduras, Burkina Faso, India, China, the Philippines and South Africa

Examining the cost farmers pay for accessing GM technology, Table 4 shows that across the four main GM crops, the total cost in 2012 was equal to 23% of the total technology gains (inclusive of farm income gains plus cost of the technology payable to the seed supply chain[②]).

For farmers in developing countries the total cost was equal to 21% of total technology gains, whilst for farmers in developed countries the cost was 25% of the total technologygains. Whilst circumstances vary between countries, the higher share of total technology gains accounted for by farm income gains in developing countries, relative to the farm income share in developed countries, reflects factors such as weaker provision and enforcement of intellectual property rights in developing countries and the higher average level of farm income gain on a per hectare basis derived by developing country farmers relative to developed country farmers.

3 Production effects of the technology

Based on the yield impacts used in the direct farm income benefit calculationsabove and taking account of the second soybean crop facilitation in South America, GM crops have added important volumes to global production of maize, cotton, canola and soybeans since 1996 (Table 5).

The GM IR traits, used in maize and cotton, have accounted for 97.1% of the additional maize production and 99.3% of the additional cotton production. Positive yield impacts from the use of this technology have occurred in all user countries (except for GM IR cotton in Australia[③]) when compared to average yields derived from crops using conventional technology (such

Table 4 Cost of accessing GM technology relative to the total farm income benefits 2012 million $

	Cost of technology: all farmers	Farm income gain:all farmers	Total benefit of technology to farmers and seed supply chain	Cost of technology: developing countries	Farm income gain:developing countries	Total benefit of technology to farmers and seed supply chain:developing countries
GMHT soybeans	1 528.1	4797.9	6 326.0	998.7	1 842.5	2 841.2
GMHT maize	1 059.4	1 197.9	2 257.3	364.5	543.9	908.4
GMHT cotton	295.0	147.2	442.2	22.2	75.8	98.0
GMHT canola	161.2	481.0	642.2	N/a	N/a	N/a
GMIR maize	1 800.8	6 727.8	8 528.6	512.3	1 400.3	1 912.6
GMIR cotton	720.7	5 331.3	6 052.0	422.7	4 800.7	5 223.4
Others	76.2	86.3	162.5	N/a	N/a	N/a
Total	5 641.4	18 769.4	24 410.8	2 320.4	8 663.2	10 983.6

Notes: N/a= not applicable. Cost of accessing technology based on the seed premia paid by farmers for using GM technology relative to its conventional equivalents.

Table 5 Additional crop production arising from positive yield effects of GM crops

million tonnes

	1996-2012 additional production	2012 additional production
Soybeans	122.3	12.0
Maize	231.4	34.1
Cotton	18.2	2.4
Canola	6.6	0.4
Sugar beet	0.6	0.15

Note: GM HT sugar beet only in the US and Canada since 2008

as application of insecticides and seed treatments). The average yield impact across the total area planted to these traits over the 17 years since 1996 has been +10.4% for maize and +16.1% for cotton.

The primary impact of GM HT technology has been to provide more cost effective (less expensive) and easier weed control, as opposed to improving yields. The improved weed control has, nevertheless, delivered higher yields in some countries. The main source of additional production from this technology has been via the facilitation of no tillage production system, shortening the production cycle and how it has enabled many farmers in South America to plant a crop of soybeans immediately after a wheat crop in the same growing season. This second crop, additional to traditional soybean production, has added 114.3 million tonnes to soybean production in Argentina and Paraguay between 1996 and 2012 (accounting for 93.5% of the total GM-related additional soybean production).

4 Environmental impact from changes in insecticide and herbicide use

To examine this impact, the study has analysed both active ingredient use and utilised the indicator known as the Environmental Impact Quotient (EIQ) to assess the broader impact on the environment (plus impact on animal and human health). The EIQ distils the various environmental and health impacts of individual pesticides in different GM and conventional production systems into a single ‘field value per hectare’ and draws on key toxicity and environmental exposure data related to individual products. It therefore provides a better measure to contrast and compare the impact of various pesticides on the environment and human health than weight of active ingredient alone. Readers should, however, note that the EIQ is an indicator only (primarily of toxicity) and does not take into account all environmental issues and impacts. In the analysis of GM HT technology we have assumed that the conventional alternative delivers the same level of weed control as occurs in the GM HT production system.

GM traits have contributed to a significant reduction in the environmental impact associated with insecticide and herbicide use on the areas devoted to GM crops (Table 6). Since 1996, the use of pesticides on the GM crop area was reduced by 503 million kg of active ingredient (8. 8% reduction), and the environmental impact associated with

Table 6 Impact of changes in the use of herbicides and insecticides from growing GM crops globally 1996-2012

Trait	Change in volume of active ingredient used/(million kg)	Change in field EIQ impact (in terms of million field EIQ/(ha units)	Change in ai use on GM crops/%	Change in environmental impact associated with herbicide & insecticide use on GM crops/%	Area GM trait 2012/(million ha)
GM herbicide tolerant soybeans	−4.7	−6 654	−0.2	−15.0	79.1
GM herbicide tolerant maize	−203.2	−6 025	−9.8	−13.3	38.5
GM herbicide tolerant canola	−15.0	−509	−16.7	−26.6	8.6
GM herbicide tolerant cotton	−18.3	−460	−6.6	−9.0	4.4
GM insect resistant maize	−57.6	−2 215	−47.9	−45.1	42.3
GM insect resistant cotton	−205.4	−9 256	−25.6	−28.2	22.1
GM herbicide tolerant sugar beet	+1. 3	−2	+29.3	−2.0	0.51
Totals	−503.1	−25 121	−8.8	−18.7	

herbicide and insecticide use on these crops, as measured by the EIQ indicator, fell by 18.7%.

In absolute terms, the largest environmental gain has been associated with the adoption of GM insect resistant (IR) technology. GM IR cotton has contributed a 25.6% reduction in the volume of active ingredient used and a 28.2% reduction in the EIQ indicator (1996-2012) due to the significant reduction in insecticide use that the technology has facilitated, in what has traditionally been an intensive user of insecticides. Similarly, the use of GM IR technology in maize has led to important reductions in insecticide use, with associated environmental benefits.

The volume of herbicides used in GM maize crops also decreased by 203 million kg (1996-2012), a 9.8% reduction, whilst the overall environmental impact associated with herbicide use on these crops decreased by a significantly larger 13.3%. This highlights the switch in herbicides used with most GM herbicide tolerant (HT) crops to active ingredients with a more environmentally benign profile than the ones generally used on conventional crops.

Important environmental gains have also arisen in the soybean and canola sectors. In the soybean sector, herbicide use decreased by 4.7 million kg (1996-2012) and the associated environmental impact of herbicide use on this crop area decreased, due to a switch to more environmentally benign herbicides (−15%). In the canola sector, farmers reduced herbicide use by 15 million kg (a 16.7% reduction) and the associated environmental impact of herbicide use on this crop area fell by 26.6% (due to a switch to more environmentally benign herbicides).

In terms of the division of the environmental benefits associated with less insecticide and herbicide use for farmers in developed countries relative to farmers in developing countries, Table 7 shows a 54%:46% split of the environmental benefits (1996-2012) respectively in developed (54%) and developing countries (46%). About three-quarters (73%) of the environmental gains in developing countries have been from the use of GM IR cotton.

Table 7 GM crop environmental benefits from lower insecticide and herbicide use 1996-2012: developing versus developed countries

	Change in field EIQ impact (in terms of million field EIQ/ha units): developed countries	Change in field EIQ impact (in terms of million field EIQ/ha units): developing countries
GM HT soybeans	−4 773.9	−1 880.2
GM HT maize	−5 585.9	−438.8
GM HT cotton	−351.0	−109.3
GM HT canola	−509.1	0.0
GM IR maize	−1 574.4	−640.8
GM IR cotton	−805.5	−8 451.0
GM HT sugar beet	−2.0	0. 0
Total	−13 601.8	−11 520.1

It should, however, be noted that in some regions where GM HT crops have been widely grown, some farmers have relied too much on the use of single herbicides like glyphosate to manage weeds in GM HT crops and this has contributed to the development of weed resistance. There are currently 28 weeds recognised as exhibiting resistance to glyphosate worldwide, of which several are not associated with glyphosate tolerant crops (www.weedscience.org). For example, there are currently 14 weeds recognised in the US as exhibiting resistance to glyphosate, of which two are not associated with glyphosate tolerant crops. In the US, the affected area is currently within a range of 20%−40% of the total area annually devoted to maize, cotton, canola, soybeans and sugar beet (the crops in which GM HT technology is used).

In recent years, there has also been a growing consensus among weed scientists of a need for changes in the weed management programmes in GM HT crops, because of the evolution of these weeds towards populations that are resistant to glyphosate. Growers of GM HT crops are increasingly being advised to be more proactive and include other herbicides (with different and complementary modes of action) in combination with glyphosate in their integrated weed management systems, even where instances of weed resistance to glyphosate have not been found.

This proactive, diversified approach to weed management is the principal strategy for avoiding the emergence of herbicide resistant weeds in GM HT crops. It is also the main way of tackling weed resistance in conventional crops. A proactive weed management programme also generally requires less herbicide, has a better environmental profile and is more economical than a reactive weed management programme.

At the macro level, the adoption of both reactive and proactive weed management programmes in GM HT crops has already begun to influence the mix, total amount and overall environmental profile of herbicides applied to GM HT soybeans, cotton, maize and canola and this is reflected in the data presented in this paper.

5 Impact on greenhouse gas (GHG) emissions

The scope for GM crops contributing to lower levels of GHG emissions comes from two principal sources: Reduced fuel use from less frequent herbicide or insecticide applications and a reduction in the energy use in soil cultivation. The fuel savings associated with making fewer spray runs (relative to conventional crops) and the switch to conservation, reduced and no-till farming systems, have resulted in permanent savings in carbon dioxide emissions. In 2012 this amounted to about 2 111 million kg (arising from reduced fuel use of 791 million litres). Over the period 1996 to 2012 the cumulative permanent reduction in fuel use is estimated at 16 736 million kg of carbon dioxide (arising from reduced fuel use of 6 268 million litres);The use of ‘no-till’ and ‘reduced-till’ (4) farming systems. These production systems have increased significantly with the adoption of GM HT crops because the GM HT technology has improved growers ability to control competing weeds, reducing the need to rely on soil cultivation and seed-bed preparation as means to getting good levels of weed control. As a result, tractor fuel use for tillage is reduced, soil quality is enhanced and levels of soil erosion cut. In turn more carbon remains in the soil and this leads to lower GHG emissions. Based on savings arising from the rapid adoption of no till/reduced tillage farming systems in North and South America, an extra 6 706 million kg of soil carbon is estimated to have been sequestered in 2012 (equivalent to 24 613 million kg of carbon dioxide that has not been released into the global atmosphere). Cumulatively, the amount of carbon sequestered may be higher than these estimates due to year-on-year benefits to soil quality;however it is equally likely that the total cumulative soil sequestration gains have been lower because only a proportion of the crop area will have remained in no-till and reduced tillage. It is, nevertheless, not possible to confidently estimate cumulative soil sequestration gains that take into account reversions to conventional tillage because of a lack of data. Consequently, our estimate of 203 560 million kg of carbon dioxide not released into the atmosphere should be treated with caution.

Placing these carbon sequestration benefits within the context of the carbon emissions from cars, Table 8 shows that: In 2012, the permanent carbon dioxide savings from reduced fuel use were the equivalent of removing 0.94 million cars from the road;The additional probable soil carbon sequestration gains in 2012 were equivalent to removing 10.94 million cars from the roads;In total, in 2012, the combined GM crop-related carbon dioxide emission savings from reduced fuel use and additional soil carbon sequestration were equal to the removal from the roads of 11.88 million cars, equivalent to 41.38% of all registered cars in the UK;It is not possible to confidently estimate the probable soil carbon sequestration gains since 1996. If the entire GM HT crop in reduced or no tillage agriculture during the last

Table 8 Context of carbon sequestration impact 2012: car equivalents

Crop/trait/country	Permanent carbon dioxide savings arising from reduced fuel use (million kg of carbon dioxide)	Permanent fuel savings: as average family car equivalents removed from the road for a year ('000s)	Potential additional soil carbon sequestration savings (million kg of carbon dioxide)	Soil carbon sequestration savings:as average family car equivalents removed from the road for a year ('000s)
US:GM HT soybeans	210	93	1 070	475
Argentina:GM HT soybeans	736	327	11 186	4 972
Brazil GM HT soybeans	394	175	5 985	2 660
Bolivia, Paraguay, Uruguay: GM HT soybeans	156	69	2 365	1 051
Canada:GM HT canola	203	90	1 024	455
US:GM HT corn	210	93	2 983	1 326
Global GM IR cotton	45	20	0	0
Brazil IR corn	157	69	0	0
Total	2 111	936	24 613	10 939

Notes: Assumption: an average family car produces 150 grams of carbon dioxideper km. A car does an average of 15 000 km/year and therefore produces 2 250 kg of carbon dioxide/year seventeen years had remained in permanent reduced/no tillage then this would have resulted in a carbon dioxide saving of 203 560 million kg, equivalent to taking 90.5 million cars off the road. This is, however, a maximum possibility and the actual levels of carbon dioxide reduction are likely to be lower.

6 Concluding comments

Crop biotechnology has, to date, delivered several specific agronomic traits that have overcome a number of production constraints for many farmers. This has resulted in improved productivity and profitability for the 17.3 million adopting farmers who have applied the technology to 160 million hectares in 2012.

During the last seventeen years, this technology has made important positive socio-economic and environmental contributions. These have arisen even though only a limited range of GM agronomic traits have so far been commercialised, in a small range of crops.

The crop biotechnology has delivered economic and environmental gains through a combination of their inherent technical advances and the role of the technology in the facilitation and evolution of more cost effective and environmentally friendly farming practices. More specifically: the gains from the GM IR traits have mostly been delivered directly from the technology (yield improvements, reduced production risk and decreased use of insecticides). Thus farmers (mostly in developing countries) have been able to both improve their productivity and economic returns, whilst also practising more environmentally-friendly farming methods; the gains from GM HT traits have come from a combination of direct benefits (mostly cost reductions to the farmer) and the facilitation of changes in farming systems. Thus, GM HT technology (especially in soybeans) has played an important role in enabling farmers to capitalise on the availability of a low cost, broad-spectrum herbicide (glyphosate) and, in turn, facilitated the move away from conventional to low/no-tillage production systems in both North and South America. This change in production system has made additional positive economic contributions to farmers (and the wider economy) and delivered important environmental benefits, notably reduced levels of GHG emissions (from reduced tractor fuel use and additional soil carbon sequestration); Both IR and HT traits have made important contributions to increasing world production levels of soybeans, corn, cotton and canola.

In relation to GM HT crops, however, over reliance on the use of glyphosate by some farmers, in some regions, has contributed to the development of weed resistance. As a result, farmers are increasingly adopting a mix of reactive and proactive weed management strategies incorporating a mix of herbicides. Despite this, the overall environmental and economic gain from the use of GM crops has been, and continues to be, substantial.

Overall, there is a considerable body of evidence, in peer reviewed literature, and summarised in this paper, that quantifies the positive economic and environmental impacts of crop biotechnology. Readers are encouraged to read the peer reviewed papers cited in the references section of the main report this summary is taken from, and the many others who have published on this subject, and to draw their own conclusions.

Notes

① The total number of reference sources used totals about 150, most of which are from peer reviewed journals

② The cost of the technology accrues to the seed supply chain including sellers of seed to farmers, seed multipliers, plant breeders, distributors and the GM technology providers

③ This reflects the very good levels of *Heliothis/Helicoverpa* (boll and bud worm pests) pest control previously obtained with intensive insecticide use. The main benefit and reason for adoption of this technology in Australia has arisen from significant cost savings (on insecticides) and the associated environmental gains from reduced insecticide use

④ No-till farming means that the ground is not ploughed at all,While reduced tillage means that the ground is disturbed less than it would be with traditional tillage systems. For example, under a no-till farming system, soybean seeds are planted through the organic material that is left over from a previous crop such as corn, cotton or wheat