Peer-reviewed surveys indicate positive impact of commercialized GM crops

To the Editor:

The benefits of genetically modified (GM) crops continue to be disputed, despite rapid and widespread adoption since their commercial introduction in the United States and Canada in 1995. Last year, 14 million farmers in 25 countries grew GM crops commercially, over 90% of them small farmers in developing countries[1]. Farmer surveys are a valuable measure of the impact of GM crops. These surveys estimate the technology's performance as it is incorporated into farmer practices, given constraints on time, access to information, differing levels of risk aversion and other factors. This analysis summarizes results from 49 peer-reviewed publications reporting on farmer surveys that compare yields and other indicators of economic performance for adopters and non-adopters of currently commercialized GM crops. The surveys cover GM insect-resistant and herbicide-tolerant crops, which account for >99% of global GM crop area[1]. Results from 12 countries indicate, with few exceptions, that GM crops have benefitted farmers. The benefits, especially in terms of increased yields, are greatest for the mostly small farmers in developing countries, who have benefitted from the spillover of technologies originally targeted at farmers in industrialized countries.

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. By far the largest numbers of results comparing yields of adopters and non-adopters come from India and the United States, which account for 26% and 23% of the results, respectively (**Table 1**). An annotated bibliography of results for yield, costs and economic performance, and a description of the methodology used in this analysis, can be found in **Supplementary Tables 1** and **3**.

The results for yields indicate that farmers in developing countries are achieving greater yield increases than farmers in developed countries (**Table 2**). 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. 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. The first wave of GM crops to be commercialized has embodied traits intended to improve pest management and therefore reduce or eliminate losses from insect damage or weed competition. These technologies do not raise yield potential, but they can improve yields substantially owing to improved pest management. Where conventional weed- and insect-control technologies were lacking because of inherent limits to the effectiveness of available conventional pest-management options or limited access to conventional control methods, yields would be expected to increase. These conditions may be more common in developing countries.

As the most frequently studied case, GM insect-resistant cotton (*Bacillus thuringiensis* (*Bt*) cotton) in India provides examples of both the highest yield increases observed as well as several of the negative results. The largest yield increases found in this review are reported for *Bt* cotton in India, where surveys show yield increases of up to 150%. Of the negative results, six are for the first year of commercialization of *Bt* cotton in India, and the rest of the negative results are from developed countries in the first few years of commercialization.

The results show the variability of benefits from region to region and year to year. A survey of Indian cotton farmers in crop harvest years 2005–2006 through 2007–2008 showed that *Bt* cotton growers in Gujarat had larger yield improvements than their counterparts in Maharashtra, with the former obtaining 82–150% greater yields, whereas the latter obtained only 24–40% higher yields. Smallholders in KwaZulu Natal, South Africa, who were surveyed from harvest years 1998–1999 to 2000–2001 reported a yield benefit associated with *Bt* cotton between 56% and 85%, which is attributed to variable weather conditions and pest pressure from year to year. It is important to note that the analysis of yield differences is complicated by differences in yield potential and other characteristics of background germplasm that may differ between the varieties that are available with and without the engineered trait. For example, the first *Bt* cotton varieties to be approved for commercialization in India had been in the regulatory pipeline for several years, during which time conventional breeding had continued to produce varieties with superior yields and disease resistance. These earliest official varieties were known to be susceptible to wilt when subjected to early moisture stress, which may have driven the negative results observed

Table 1 Number and direction of results comparing yields of GM adopters to those of non-adopters, by country

Country	Positive	Neutral	Negative	Total
Developed countries	36	18	7	61
Australia	0	2	2	4
Canada	7	0	1	8
Spain	3	6	0	9
United States	26	10	4	40
Developing countries	88	13	6	107
Argentina	5	1	0	6
China	15	0	0	15
Colombia	4	1	0	5
India	35	2	6	43
Mexico	2	0	0	2
Philippines	5	2	0	7
Romania	2	0	0	2
South Africa	20	7	0	27
Total	124	32	13	168

Positive and negative directions refer to a comparison of GM to conventional crops.

in Andhra Pradesh in the first year of commercialization[2,3]. In the early years of commercialization, it is likely that the technology would not be available in the highest-yielding background varieties or in varieties that are most suited to the growing conditions in all areas.

Profitability is an important measure that complements data on yields, as even a technology that does not necessarily increase yields can improve a farmer's bottom line if it reduces costs. In addition to yields, many of the surveys reviewed here also look at changes in costs and various measures of farm economic performance. In all but one case reviewed, the cost of seeds (including any technology fees) rose. However, this was offset by decreases in pesticide costs, which were found in all but 12 cases.

Looking across all measures of economic performance, the results are also overwhelmingly positive. Gross margins are most commonly reported, but the variable costs that are included in these calculations vary greatly from study to study. Of the 98 results in our survey of the peer-reviewed literature that compare the economic performance of GM crops to their conventional counterparts, 71 indicate a positive impact, 11 neutral and 16 negative (**Fig. 1**).

For GM herbicide-tolerant crops, 12 of 17 results show a positive impact on economic performance, whereas 4 results show no difference and 1 result shows a negative impact. One might expect more results showing positive impacts of GM herbicide-tolerant crops on economic performance, particularly as GM herbicide-tolerant crops have been more widely adopted (on 62% of global GM crop acreage in 2009) than GM insect-resistant crops around the world[1]. This may be due to cost savings associated with GM herbicide-tolerant crops that are not included in a traditional accounting of costs. In a study of glyphosate-tolerant soybean in the United States, nonmarket valuation techniques were used to estimate 'non-pecuniary' convenience benefits, such as management-time savings and flexibility, at \$12 ha^{-1} (ref. 4).

For GM insect-resistant crops, 59 of 80 results indicate improved economic performance, 7 results are neutral and 14 results are negative. On the positive side, some of the most striking results come from *Bt* cotton growers in South Africa and China. Negative results are in *Bt* corn in the United States and *Bt* cotton in Australia, China, Colombia, India and South Africa (though positive results are reported in each of these cases as well). Some of the negative results may be explained by year-to-year variation in pest pressure and technology pricing. Furthermore, similar to GM herbicide-tolerant crops, farmers may value intangible benefits of GM insect-tolerant crops. A survey of US corn farmers found that non-pecuniary benefits (handling and labor-time savings, human and environmental safety, reduced yield risk, equipment cost savings and better standability) of GM insect-resistant corn were valued at \$10.32 ha^{-1} (ref. 5).

Table 2 Average impact on yield, by technology, for developed and developing countries

Technology	Difference in yield (%)	Number of results	Minimum (%)	Maximum (%)	Standard error of the mean (%)
Developed countries	6	59	–12	26	1.0
Herbicide-tolerant cotton	0	6	–12	17	3.8
Herbicide-tolerant soybean	7	14	0	20	1.7
Herbicide-tolerant and insect-resistant cotton	3	2	–3	9	5.8
Insect-resistant corn	4	13	–3	13	1.6
Insect-resistant cotton	7	24	–8	26	1.9
Developing countries	29	107	–25	150	2.9
Herbicide-tolerant corn	85	1			
Herbicide-tolerant soybean	21	3	0	35	11
Insect-resistant corn	16	12	0	38	4
Insect-resistant corn (white)	22	9	0	62	6.9
Insect-resistant cotton	30	82	–25	150	3.5

Yield difference for adopters was calculated as (GM yield – conventional yield)/conventional yield, averaging yields across surveys, geographies, years and methodologies. The difference in the number of results reported in **Tables 1** and **2** is due to two results reported as 'positive' with no numerical value. A two-tailed *t*-test shows a significant difference between the average yields of developed and developing countries ($t = 7.48$, df = 134, $P < 0.0005$).

In addition to economic indicators of performance, many surveys also look at indicators of the environmental impact of GM crops, specifically changes in tillage practices for GM herbicide-tolerant crops and changes in pesticide use for GM insect-resistant and herbicide-tolerant crops (**Supplementary Tables 2** and **3**). For GM herbicide-tolerant crops, two surveys, for soybeans in Argentina and the United States, report decreases of 25–58% in the number of tillage operations[6,7]. There are no results indicating an increase in tillage for adopters of GM herbicide-tolerant crops. These results reinforce observations of wider adoption of conservation tillage practices since the introduction of GM herbicide-tolerant crops[8–10].

For insect-resistant crops, 45 results show decreases in the amount of insecticide or number of insecticide applications, or both, used on *Bt* crops compared with conventional crops in Argentina, Australia, China, India and the United States. The reductions range from 14% to 75% in terms of amount of active ingredient and from 14% to 76% for the number of insecticide applications. A small sample survey in South Africa found 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.

The above measures of changes in insecticide use are imperfect, in that they do not indicate the relative toxicity of insecticides used and therefore the human health and environmental impacts associated with the different insecticides that might be used on *Bt* and conventional crops. Researchers have used various approaches to give further insight into the implications of these reductions in insecticide use. In Argentina, a survey showed that the amount of insecticide in all toxicity classes was reduced in *Bt* compared with conventional cotton plots[11]. Three years of survey data for *Bt* cotton in South Africa were combined with ratings of relative toxicity and persistence to calculate a biocide index, which showed substantially lower values for insecticides used on *Bt* compared with conventional cotton[12]. Survey results in China indicate a reduction in the percentage of farmers reporting headaches, nausea, skin pain or digestive problems after applying pesticides associated with adoption of *Bt* cotton[13], though some of the health benefits observed in the early years of adoption may have been eroded by increased spraying for secondary pests[14]. Researchers in South Africa have shown an inverse relationship between the number of local hospital admissions classified as related to cotton growing and the adoption of *Bt* cotton[15].

Few surveys have captured changes in herbicide use with GM herbicide-tolerant crops, perhaps because the impact of GM herbicide-tolerant crops has largely been a switch between herbicides that are applied at different rates, and therefore change in the amount of herbicide used is a poor indicator of environmental impact. Three surveys report changes in herbicide use, showing changes that range from a decrease of 38% to an increase of 108% in the total amount of herbicide used, and an insignificant change in the number of herbicide applications[6,16,17]. The environmental impact of these shifts is better understood by looking at the environmental characteristics of the herbicides. Two of the studies above extend their analysis by applying environmental indicators to observed changes in herbicide use. The aggregate pesticide leaching potential for GM herbicide-tolerant cotton in North Carolina was 25% lower than that of conventional cotton[16]. Reductions of 83% and 100% in the use of herbicides in toxicity classes II and III, respectively, were found in GM herbicide-tolerant soybeans in Argentina, with a corresponding increase of 248% in the use of less toxic class IV herbicides[6]. Some of the environmental benefits that have come with the use of more environmentally benign herbicides may be eroded with the development of glyphosate-resistant weeds, although few data now exist upon which to draw any conclusions.

Several surveys address the question of whether GM crops are benefitting small farmers in developing countries through direct comparisons of outcomes for farmers with different-sized land holdings or by documenting the impacts on small farms. Four surveys from China, Colombia and South Africa make direct comparisons of yields, gross margins or both for farmers with different-sized operations. The surveys indicate that the smallest farmers benefitted most in South Africa and China[15,18,19]. Results from Colombia were mixed[20]. Five studies have shown improvements in economic performance for farmers with <10 ha in China, Colombia, Mexico, India and South Africa[13,20–23]. One explanation of the favorable outcomes for smallholders is the risk-reducing nature of the technology,

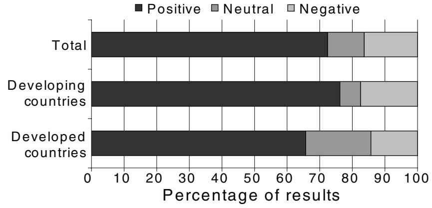

Figure 1 Results by direction of change in economic performance (GM – conventional). A χ^2 test shows a significant difference in the proportion of positive results for developed and developing countries ($\chi^2 = 0.68$, df = 1, $P = 0.41$).

whereas non-adopters with comparably sized land holdings are particularly vulnerable as yields fluctuate from year to year[15].

The accumulated evidence from farmer surveys on the performance of GM crops helps to explain the widespread popularity of the technology in several regions of the world. The surveys reviewed here reflect a wide variety of conditions in terms of environment, pest pressure, farmer practices, social context, intellectual property rights and institutional arrangements. Given this diversity of conditions, it is striking that the results are so consistently positive. Even so, these results cover less than half of the countries currently growing GM crops and are sparse for some already widely adopted technologies, such as GM herbicide-tolerant corn and canola. Furthermore, GM crops have been grown for only 14 years—fewer for those countries that were not among the first adopters—a relatively short period for assessing the long-term impact of any technology. In some cases, results reflect a single growing season, which may not be an adequate basis for judging the sustainability of the technology's impact. Nevertheless, the window of opportunity for directly comparing the outcomes of adopters and non-adopters has closed where adoption rates are very high, and different methods of impact assessment will now be required.

Of interest in the future will be the assessment of the impacts of stacked traits, incorporating a combination of traits, which already represent over 28% of total global GM crop acreage[1] but have been studied by only two surveys. Also of interest will be the assessment of farmers' experiences with GM crop technologies created specifically to address the most pressing constraints of developing-country farmers, such as technologies being developed in cassava, cowpea and rice, as those reach the commercialization stage.

Note: Supplementary information is available on the Nature Biotechnology website.

COMPETING FINANCIAL INTERESTS
The author declares competing financial interests: details accompany the full-text HTML version of the paper at http://www.nature.com/naturebiotechnology/.

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