Review

Benefits of genetically modified crops for the poor: household income, nutrition, and health

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The potential impacts of genetically modified (GM) crops on income, poverty and nutrition in developing countries continue to be the subject of public controversy. Here, a review of the evidence is given. As an example of a first-generation GM technology, the effects of insect-resistant Bt cotton are analysed. Bt cotton has already been adopted by millions of small-scale farmers, in India, China, and South Africa among others. On average, farmers benefit from insecticide savings, higher effective yields and sizeable income gains. Insights from India suggest that Bt cotton is employment generating and poverty reducing. As an example of a second-generation technology, the likely impacts of beta-carotene-rich Golden Rice are analysed from an *ex ante* perspective. Vitamin A deficiency is a serious nutritional problem, causing multiple adverse health outcomes. Simulations for India show that Golden Rice could reduce related health problems significantly, preventing up to 40,000 child deaths every year. These examples clearly demonstrate that GM crops can contribute to poverty reduction and food security in developing countries. To realise such social benefits on a larger scale requires more public support for research targeted to the poor, as well as more efficient regulatory and technology delivery systems.

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Introduction

The global area under genetically modified (GM) crops grew from 1.7 million hectares in 1996 to 134 million hectares in 2009. Today, 14 million farmers worldwide grow GM crops in 25 countries, including 16 developing countries [1]. So far, most of the commercial applications involve herbicide tolerance and insect resistance, but other GM traits are in the research pipeline and are likely to be commercialised in the short-term to medium-term future. The rapid global spread of GM crops has been accompanied by an intense public debate. Supporters see great potential in the technology to raise agricultural productivity and reduce seasonal variations in food supply due to biotic and abiotic stresses. Against

the background of increasing demand for agricultural products, natural resource scarcities and additional challenges posed by climate change, productivity increases are a necessary precondition for achieving long-term food security. Second-generation GM crops, such as crops with higher micronutrient contents, could also help reduce specific nutritional deficiencies among the poor. Furthermore, GM crops could contribute to rural income increases, which is particularly relevant for poverty reduction in developing countries. And finally, supporters argue that reductions in the use of chemical pesticides through GM crops could alleviate environmental and health problems associated with intensive agricultural production systems.

By contrast, biotechnology opponents emphasise the environmental and health risks associated with GM crops. Moreover, doubts have been raised with respect to the socioeconomic implications in developing countries. Some consider high-tech applications *per se* as inappropriate for smallholder farmers and disruptive for traditional cultivation systems. Also, it is feared that the dominance of multinational companies in biotechnology and the international proliferation of intellectual property rights (IPRs) would lead to the exploitation of agricultural producers. In this view, GM crops are rather counterproductive for food security and development.

Although public controversies continue, there is a growing body of literature providing empirical evidence on impacts of GM crops. This article reviews the pertinent literature, focusing especially on GM crop effects for poor agricultural producers and consumers in developing countries. Two concrete examples are chosen. The first example is insect-resistant *Bacillus thuringiensis* (Bt) cotton. Bt cotton is currently the first-generation GM technology with the widest distribution among smallholder farmers. Hence, solid data about the socioeconomic effects are available for different countries. The second example is Golden Rice. This is a second-generation GM technology that promises to reduce nutritional deficiencies and health problems among the poor through improving the vitamin A status of rice consumers. Golden Rice

is not yet available in the market, so that related impact studies are *ex ante* in nature. Although Bt cotton and Golden Rice certainly do not cover the whole range of current and future GM crop applications, they can nonetheless provide some useful insights into the type of effects to be expected from the first-generation and second-generation technologies.

Impacts of Bt cotton

Bt cotton, which is resistant to different lepidopteran and coleopteran insect pests, was among the first GM crops to be commercialised in the mid-1990s. In the US, Bt cotton was commercially approved in 1995. One year later, cotton farmers in Australia started using the technology and in subsequent years it was commercialised in China, Mexico, Argentina, South Africa and India and to a limited extent also in Indonesia. Very recently, Burkina Faso has approved Bt cotton as the first low-income country in Sub-Saharan Africa. In 2009, Bt cotton was grown on 16 million hectares (ha), which is over 45% of the total worldwide cotton area. India is now the country with the biggest Bt cotton area (8.4 million ha in 2009), followed by China (3.7 million ha), and the US (2 million ha) [1]. Most of these areas are cultivated with Monsanto's Bollgard I technology, involving the Cry1Ac Bt gene, but Bollgard II – with stacked Cry1Ac and Cry2Ab genes and a broader spectrum of target pests – has also been released in several countries. In addition to the Monsanto technology, in China – and recently also in India – the public sector has developed and commercialised Bt cotton varieties. The widespread and rapid adoption of Bt cotton over the last 15 years suggests that farmers are satisfied with this technology from an economic point of view. Indeed, numerous studies that have been carried out in different countries confirm that the socioeconomic benefits are sizeable [2].

Profit gains in India

In India, over 5 million farmers have already adopted Bt cotton, which is now grown on almost 90% of the country's total cotton

TABLE 1

Crop enterprise budgets for Bt and conventional cotton in India.

	2002		2004		2006	
	Bt	**Conventional**	**Bt**	**Conventional**	**Bt**	**Conventional**
Number of insecticide sprays	4.2[***]	6.8	4.6[***]	7.2	3.3[*]	3.8
Insecticide use (kg/ha)	5.1[***]	10.3	5.2[***]	10.4	3.0[*]	3.8
Yield of raw cotton (kg/ha)	1,628[***]	1,213	1,836[***]	1,362	2,080[***]	1,458
Production cost (US$/ha)						
Seed	81.0[***]	25.2	83.6[***]	27.1	41.3[***]	24.7
Insecticides	64.8[***]	109.5	81.0[***]	124.2	60.4	58.6
Fertilizer	96.9[***]	85.4	96.9[**]	85.7	100.5	75.5
Labour	150.3[***]	116.0	178.1	151.2	236.9	209.4
Other cost	41.5	35.7	19.6	19.6	58.1[**]	34.5
Total cost (US$/ha)	434.5[***]	371.9	459.2[***]	407.8	497.2[***]	402.7
Revenue (US$/ha)	707.1[***]	533.2	712.5[***]	518.8	864.0[***]	617.9
Profit (US$/ha)	272.5[***]	161.3	253.3[***]	111.0	366.7[***]	215.2

Sources: [3,5].

[*] Mean values are significantly different from those on conventional plots at the 10% level.

[**] Mean values are significantly different from those on conventional plots at the 5% level.

[***] Mean values are significantly different from those on conventional plots at the 1% level.

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TABLE 2

Comparative advantage of Bt over conventional cotton in India.

	2002	2004	2006	Average
Insecticide use	−50%	−51%	−21%	−41%
Yield	+34%	+35%	+43%	+37%
Seed cost	+221%	+208%	+68%	+166%
Total cost	+17%	+11%	+24%	+17%
Gross revenue	+33%	+37%	+40%	+37%
Profit	+69%	+129%	+70%	+89%
Profit gain in US$/ha	+111$	+142$	+152$	+135$

Source: [5].

area. Most of the cotton farms are small-scale, especially in central and southern India. The average size of Bt-adopting farms is less than 5 ha, with an average cotton area of about 1.5 ha. Therefore, a closer look at the impacts in India is particularly interesting.

Table 1 shows cotton enterprise budgets in India with and without Bt technology for three growing seasons between 2002 and 2006. The data were collected from randomly sampled farms in four states and are representative of India's smallholder-dominated cotton production systems [3]. The results are summarised in Table 2. In all three seasons, the number of insecticide sprays and insecticide amounts used were significantly lower on Bt than on conventional plots. The exact reductions vary from year to year, which is partly due to seasonal variations in pest pressure. Moreover, owing to increasing adoption of Bt over time, target pest populations declined, so that even conventional cotton growers could reduce their insecticide sprays considerably in recent years. Average reductions in insecticide use through Bt technology were 41% over the three growing seasons. These reductions occur mostly in highly toxic chemicals, so that Bt cotton is also associated with significant benefits for the environment and farmers' health.

In addition to insecticide reductions, a major effect of Bt cotton in India is a sizeable yield advantage due to lower crop losses, as previously predicted by Qaim and Zilberman [4]. Over the years, average yields were 30–40% higher on Bt than on conventional plots, which is due to more effective pest control and thus a reduction in crop damage. Again, differences over the years are largely due to variability in pest pressure. Regression analyses confirm the gains in effective yields through Bt even after controlling for differences in input use and other factors [3,5]. Higher yields and crop revenues are also the main reasons for the significant gains in cotton profits, in spite of higher seed prices. Profit differences between Bt and conventional cotton even increased over time, which is partly due to seed price caps that state governments have introduced since 2006. Over the three seasons observed, mean profit gains were in a magnitude of 89%, or 135 US$ per ha. These are large benefits for cotton-producing households in India, many of whom live near or below the poverty line. Extrapolating these profit gains to the total area under Bt cotton in India (8.4 million ha) implies an additional 1.13 billion US$ per year in the hands of smallholder farmers.

In spite of this evidence, which is also confirmed in other studies [6,7], there are widespread public concerns that smallholder farmers would not benefit from Bt and that the technology would rather cause economic and social problems among the poor [8]. What the mean values discussed above (Tables 1 and 2) mask is that there was considerable impact variability in the early years of Bt cotton adoption. Especially in 2002, there were some farmers in certain regions who did not profit, due to insufficient information on how to use the technology successfully. Moreover, only a small number of Bt varieties were available, which were not suitable for all agroecological conditions [3,9]. These initial problems were overcome, however, as is reflected in the rapid and widespread aggregate adoption.

Income distribution and poverty in India

Beyond the direct effects on crop profits for adopting farmers, new technologies such as Bt cotton also entail indirect effects through backward and forward linkages to other markets. For instance, higher cotton yields through Bt provide more employment opportunities for agricultural labourers and a boost to rural transport and trading businesses. Income gains among farmers and farm workers entail higher demand for food and non-food items, inducing growth and household income increases also in other local sectors. Such indirect effects were positive and large for Green Revolution technologies in the 1970s and 1980s [10]. Related studies for GM crops have hardly been carried out. One exception is Bt cotton in India, for which wider rural development effects have been analyzed by Qaim et al. [11] and Subramanian and Qaim [12]. The results of this research are summarised in the following.

Using detailed census data from a typical cotton-growing village in central India and building on a social accounting matrix (SAM) multiplier model, the total income effects of Bt cotton were estimated. These effects not only incorporate the direct benefits for cotton farmers in terms of higher profits, but also include the indirect effects that occur in other markets and sectors. Overall, each ha of Bt cotton creates aggregate incomes that are 246 US$ higher than those of conventional cotton (Figure 1). For the total Bt cotton area in India, this translates into an annual rural income
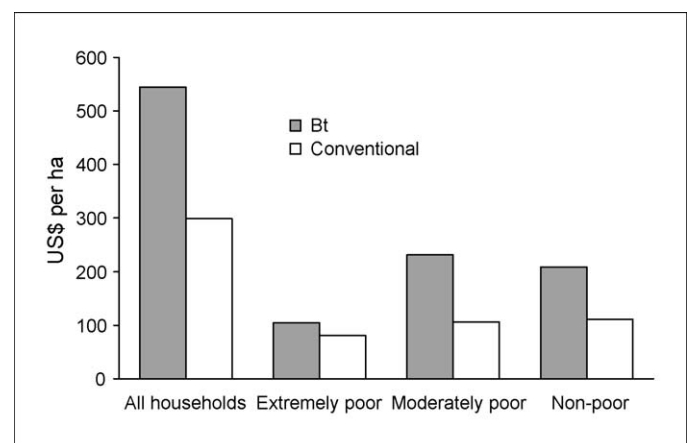

FIGURE 1

Income effects of Bt cotton in comparison to conventional cotton in rural India.

Note: The results shown include direct benefits among cotton farmers as well as indirect effects through backward and forward linkages with other rural markets and sectors. For the evaluation of income distribution effects, households were disaggregated using local poverty lines, which are very near to the World Bank's thresholds of 1 and 2 US$ a day (purchasing power parity) for extreme and moderate poverty, respectively. *Source*: [11].

gain of 2.07 billion US$. Considering that the direct profit gains for Bt cotton farmers are in a magnitude of 1.13 billion US$ (see previous subsection), it can be concluded that each dollar of direct benefits is associated with about 83 cents of additional indirect benefits in the local economy.

In terms of income distribution, all types of households benefit, including those below the poverty line (Figure 1). 60% of the gains accrue to the extremely and moderately poor. Bt cotton is also net employment generating, with interesting gender implications: compared to conventional cotton, Bt increases aggregate returns to labour by 42%, while the returns for hired female agricultural workers increase by 55%. This is largely due to additional labour employed for picking cotton, which is primarily a female activity in India [12]. As is known, women's income has a particularly positive effect for child nutrition and welfare [13].

These results on income distribution cannot be simply extrapolated to other regions and other GM technologies, as impacts always depend on the conditions in a particular setting. Nonetheless, the fact that a first-generation GM crop such as Bt cotton already contributes to poverty reduction and rural welfare growth has not been widely recognised up till now. Income gains among the rural poor can also have positive food security effects, as 50% of the worldwide hungry are smallholder farmers and another 20% are landless rural workers [14]. For these people, rising incomes mean better access to food, even when the income gain itself is due to a new technology in a non-food crop such as cotton. Needless to say, positive food security effects could be higher still when GM food crops – adapted to smallholder conditions – become available in the future.

Evidence from other countries
As mentioned above, Bt cotton has also been widely adopted in several other countries, for most of which studies on the direct impacts are available in the literature. Table 3 gives an international overview. Although the concrete effects vary, the overall trends observed in India – namely that the technology reduces insecticides, increases effective yields, and allows significant gains in cotton profits – are confirmed in the other countries as well. Strikingly, the gains are predominantly higher in developing countries than they are in the US or Australia. This is partly due to more pronounced yield effects of Bt as a result of higher uncontrolled crop losses among smallholder farmers in the tropics

[4,15]. Moreover, Bt seeds are mostly cheaper in developing countries due to weaker IPR protection. An exception is Argentina, where Bt cotton is patented and seed prices are relatively high [16].

As in India, cotton is often also cultivated by small-scale farmers in other developing countries. Especially in China and South Africa, Bt cotton is often grown by farms with less than 3 ha of land. Several studies show that small-scale farmers benefit to a similar extent from Bt adoption as larger-scale producers. In some cases, the advantages for smallholders are even significantly greater [17,18]. However, distributional effects do depend not only on the characteristics of a technology, but also on the institutional setting at national and local levels. For instance, information, credit, and infrastructure constraints can hinder proper access of poor farmers to GM seeds, especially in countries where rural markets do not function well. Therefore, beyond introducing new technologies, policies that strengthen institutions and reduce market failures are required, to achieve pro-poor outcomes on a larger scale. This is particularly important when GM crops are commercialised in the least-developed countries.

Expected impacts of Golden Rice
Golden Rice (GR), which has been genetically modified to produce β-carotene in the grain, has been proposed as a possible intervention to control vitamin A deficiency (VAD) [19,20]. VAD is a considerable public health problem in many developing countries: it affects 140 million pre-school children and 7 million pregnant women world wide. Of these, up to 3 million children die every year [21]. Apart from increasing child mortality, VAD can lead to visual problems, including blindness, and also increases the incidence of infectious diseases. The deficiency is most widespread in poverty households, where diets are dominated by staple foods with relatively low nutritional value. Food supplementation and industrial fortification programs can be effective in reducing VAD, but they often do not reach the target populations in rural areas [22]. Widespread consumption of Golden Rice promises to improve the situation in rice-eating populations. However, this technology is not yet available in the market, so that concrete outcomes can only be predicted. Golden Rice will probably be commercialised in selected Asian countries starting from 2012.

Nutrition and health benefits
Stein et al. [23] developed a methodology for comprehensive *ex ante* evaluation of Golden Rice, focusing on nutrition and health effects as well as on socioeconomic aspects. This methodology was used for an empirical study in India [24]. India is one of the target countries for Golden Rice, because mean levels of rice consumption are relatively high, and VAD is widespread. Of the 140 million pre-school children suffering from VAD worldwide, more than 35 million live in India [21].

Adverse health outcomes of VAD include increased mortality, night blindness, corneal scarring, blindness and measles among children, as well as night blindness among pregnant and lactating women. Stein et al. [24] calculated the disease burden associated with VAD-attributable fractions of these outcomes, building on a disability-adjusted life year (DALY) approach. The combined annual mortality and morbidity burden is expressed in terms of the number of DALYs lost. The present burden, calculated based on available health statistics, is the situation without Golden Rice.

TABLE 3

Effects of Bt cotton in different countries.

Country	Insecticide reduction (%)	Increase in effective yield (%)	Increase in profit (US$/ha)
Argentina	47	33	23
Australia	48	0	66
China	65	24	470
India	41	37	135
Mexico	77	9	295
South Africa	33	22	91
USA	36	10	58

Source: [2].

In a next step, present β-carotene intakes from nationally representative food consumption data were derived and the likely shift in the intake distribution through future consumption of Golden Rice was established. This required assumptions which were based on experimental data and expert estimates about the technology's efficacy and future coverage. Higher β-carotene intakes will improve the vitamin A status of individuals, thus reducing the incidence of adverse health outcomes. These new incidence rates were derived and used to re-calculate the expected remaining burden with Golden Rice. The difference in the disease burden with and without Golden Rice is the expected impact of the technology expressed in terms of the number of DALYs saved.

According to these calculations, the current annual disease burden of VAD in India amounts to a loss of 2.3 million DALYs, of which 2.0 million is lost due to child mortality alone. In terms of incidence numbers, more than 70,000 Indian children under the age of six die each year due to VAD. In this context, widespread consumption of Golden Rice could reduce the burden of VAD by 59%, which includes the saving of almost 40,000 lives each year (Table 4). Because the severity of VAD is negatively correlated with income, the positive effects are most pronounced in the poorest income groups.

While these results suggest that Golden Rice alone is unlikely to eliminate the problems of VAD, the projected improvements in public health and nutrition are huge. Similar effects can also be expected in other rice-eating countries with a high prevalence of VAD. Beyond the reduction in health costs and individual suffering, nutritional improvements are associated with positive impacts on labour productivity. Anderson et al. [25] used a macro-economic model to simulate the benefits of Golden Rice at the global level. Modelling consumer nutrition and health effects among the poor as an increase in the productivity of unskilled labourers, they estimated worldwide welfare gains of over 15 billion US$ per year, with most of the benefits accruing in Asia.

TABLE 4

Burden of vitamin A deficiency in India and potential impact of Golden Rice.

Current burden of vitamin A deficiency	
Number of DALYs lost each year (thousands)	2,328
Number of lives lost each year (thousands)	71.6
Potential impact of Golden Rice	
Number of DALYs saved each year (thousands)	1382
Reduction of the DALYs burden (%)	59.4
Number of lives saved each year (thousands)	39.7
Cost-effectiveness of Golden Rice and other vitamin A interventions	
Cost per DALY saved through Golden Rice (US$)	3.1
World Bank cost-effectiveness standard for DALYs saved (US$)	200
Cost per DALY saved through supplementation (US$)	134
Cost per DALY saved through industrial fortification (US$)	84

Note: The impact estimates reported here build on the 'high impact scenario' in [24]. Given recent evidence about the high efficacy of Golden Rice [27] the assumptions in that scenario appear realistic when the technology receives public support for social marketing efforts.
Source: [24].

In China, for instance, Golden Rice is projected to entail a 2% growth in national income [25].

Cost-effectiveness
The high expected effectiveness of Golden Rice in reducing the problems of VAD was shown in the previous subsection. This certainly is a cause for optimism. However, from an economic perspective it needs to be asked at what cost a certain effect is achieved. The major costs of Golden Rice are the investments in research as well as in developing, testing and disseminating the GM technology. Dividing these costs by the number of DALYs saved, and taking into account the time when costs and benefits occur through discounting, results in the average cost per DALY saved, which is a common measure for the cost-effectiveness of health interventions. This was done by Stein et al. [24] in their analysis for Golden Rice in India. According to their projections, the cost per DALY saved through Golden Rice is in a magnitude of 3 US$ (Table 4), which is very low. A sensitivity analysis showed that, even with much more pessimistic assumptions, the cost would not rise to more than 20 US$ per DALY saved.

These results should be compared with suitable benchmarks. The World Bank classifies health interventions as very cost-effective when their cost is less than 200 US$. This underlines that Golden Rice could be extremely cost-effective. But how does Golden Rice compare with conventional vitamin A interventions? Scaling up food supplementation or industrial fortification programs for vitamin A in India would cost between 84 and 134 US$ per DALY saved (Table 4). The major cost of these conventional interventions is not to produce the vitamin pills or food fortificants, but to reach the target population in remote rural areas, which requires large investments and monitoring on a regular basis. This is different for Golden Rice: even though the initial investment is high, recurrent costs will be low, because Golden Rice seeds will spread through existing formal and informal distribution channels and can be reproduced by farmers themselves. Nonetheless, possible issues of consumer acceptance must be considered, and suitable strategies to convince farmers to adopt Golden Rice varieties have to be developed. A combination of β-carotene with interesting agronomic traits in rice might be a practicable avenue.

In spite of the high projected cost-effectiveness, Golden Rice should not be seen as a substitute for existing vitamin A interventions, but as a complementary strategy. No single approach will eliminate the problem of VAD and all interventions have their strengths and weaknesses in particular situations. While supplementation and industrial fortification might be more suitable for urban areas and feeding programs for well-defined target groups, Golden Rice is likely to achieve a wider coverage, for example in remote rural areas. It is only in the long run that poverty reduction and economic growth may be expected to contribute to dietary diversification, which might then reduce the urgency for more specific micronutrient interventions.

Conclusion
GM crops are not a magic bullet against all problems in developing countries, but they hold significant potential to contribute to poverty reduction, better nutrition and health, and sustainable development. Some of these potentials have already materialised. Yet it should be stressed that GM technologies can be very diverse,

so instead of talking about the impacts of GM crops in general, concrete statements have to be differentiated. For instance, the impacts of herbicide tolerance are different from the impacts of insect resistance or of nutritionally enhanced crops. Moreover, impacts depend on the agronomic and institutional conditions, such as pest pressure, intellectual property rights, and the functioning of seed and other rural markets.

This article has reviewed the outcomes of Bt cotton in different contexts, highlighting that this technology can be very suitable for smallholder farmers. In particular, the example from India showed that Bt cotton not only reduces insecticide use and increases yield, but also contributes to employment generation and income gains among the rural poor. Preliminary evidence suggests that similar effects are also likely for other Bt crops that are already available in some developing countries (like Bt maize and Bt rice) or may be commercialised soon (like Bt eggplant) [26]. The benefits of future GM crop applications, including those that involve tolerance against abiotic stress, could be much greater than the ones already observed [2].

As a promising second-generation GM technology, this article has analysed the expected impacts of Golden Rice, building on available *ex ante* research. It was shown that Golden Rice has the potential to reduce the burden of vitamin A deficiency substantially and at low average costs, even when accounting for sizeable outlays that might be necessary for future social marketing. Therefore, Golden Rice promises to be an effective, efficient and sustainable pro-poor nutrition intervention. Its inclusion into strategies that aim at the elimination of vitamin A deficiency in rice-eating populations should be promoted.

In spite of these encouraging examples, more public support is needed in biotechnology development, to ensure that other promising technologies for the poor are being developed, and in technology delivery, to ensure that they are widely accessible. In this respect, the negative public attitudes towards GM crops, especially in Europe, which are largely the result of biased information, are a fundamental obstacle. Not only do they limit public investments into GM crop research, but they also contribute to an overly complex regulatory framework. Some regulation is necessary to avoid risks, but over-regulation unnecessarily increases the cost of technologies, thus introducing a bias against small crops, small countries and small research organisations, which also implies a bias against the poor. This situation needs to be rectified through better and more science-based information flows.

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