The economic impact of transgenic crops in developing countries: a note on the methods

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Abstract: A vast literature has accumulated since crop varieties with transgenic resistance to insects and herbicide tolerance were released to farmers in 1996 and 1997. A comparatively minor segment of this literature consists of studies conducted by agricultural economists to measure the farm-level impact of transgenic crop varieties, the size and distribution of the economic benefits from adopting them and the implications for international trade. This paper focuses only on the applied economics literature about the impact of transgenic crop varieties in non-industrialised agricultural systems, with a focus on the methods. A number of studies have surveyed the findings for both industrialised and non-industrialised agriculture at various points in time, but surveys of methods are less common and most treat one aspect of economic impact. Clearly, the methods used in research influence the findings that are presented and what they mean. Three levels of impact analysis are considered: farm, industry and trade. We conclude that because the methods used present challenges and limitations, the few transgenic crop-trait combinations released in developing economies and the relatively brief time frame of most analyses, the results are promising but the balance sheet is mixed. Thus, the findings of current case studies should not be generalised to other locations, crops and traits.

Keywords: genetically engineered crops; economic impacts; technology adoption; developing economies; economics methods.

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1 Objective and scope

A vast literature has accumulated since crop varieties with transgenic resistance to insects and herbicide tolerance were released to farmers in 1996 and 1997. A comparatively minor segment of this literature consists of studies conducted by agricultural economists to measure the farm-level impact of transgenic crop varieties, the size and distribution of the economic benefits from adopting them, and implications for international trade. An even smaller subset treats the impacts of transgenic crops in developing economies with non-industrialised agriculture. This paper reviews the applied economics literature about the impact of transgenic crop varieties in non-industrialised agricultural systems, with an emphasis on methods.

A number of studies have surveyed the findings for both industrialised and non-industrialised agriculture, at various points in time, but surveys of methods are less frequent and have typically examined only one overall question or approach. The methods used in research influence the findings that are presented. Understanding the methods, their strengths and weaknesses, enhances the understanding of the scope of research findings.

The review has been organised according to three scales or levels of economic impact (farm, industry and international trade). Summary information from the search is presented next. Then, the methods applied by authors, research findings and limitations are grouped by level of analysis.

2 Search summary

To facilitate direct comparisons of methods, the boundaries of the literature reviewed were narrowly delineated. A statement of method and presentation of data were two criteria for including a study in our review. Only literature reviewed by peers, for which the focus of analysis is a developing agriculture economy, has been included. The review concentrates on observed or estimated impacts on farms, industries, or trade. French and English language literature has been searched exhaustively and a web-based review of Spanish language literature has been conducted.

The search approach used for this compilation included four principal sources: CAB Direct, ISI Web of Knowledge, other published bibliographies, and references from published articles. CAB Direct and ISI are both searchable databases, which have millions of references in various fields. As of 12 January 2006, CAB Direct had 3477 references under agricultural economics and biotechnology. The vast majority of these references did not meet our criteria, and our first cut of this literature included less than one-tenth of them.

The count of articles by research question that applied a stated economics method to an empirical dataset is shown in Table 1. After reviewing the contents of each of over 300 of these, 90 peer-reviewed articles published from 1996 through mid-2006 met our criteria. Of these, over half (58) address farm level impacts, 13 analyse industry impacts, and 19 assess impacts on international trade. The remainder investigates consumer attitudes. Thus, as indicated by counts of peer-reviewed publications, evaluating technology impacts on farmers represents the foremost research concern during the first decade of growing genetically engineered crops.

Table 1 Count of peer-reviewed English, Spanish and French language articles about the economic impact of genetically engineered crops in developing economies, by research question, 1996–2006

Research question	*Number of publications*
Farmers	52
Farmers, industry	6
Industry	13
Trade	19
Total	90

Note: Some articles address both farm-level and industry impact.

Table 2 shows the count of articles by scale of analysis and crop-trait combination. By far the most researched crop-trait combination is insect-resistant cotton (56 articles). Articles analysing impacts of genetically engineered maize, rice and soybeans follow. A residual category includes other crops: bananas, potatoes, sweet potatoes, cassava, wheat, oilseeds, eggplant, mustard and coarse grains. Categories total to more than the total number of articles because some articles treat more than one crop-trait combination.

Table 2 Count of articles assessing the economic impact of genetically engineered crops in developing economies, by research question and crop (and trait)

Crop-trait	*Farm*	*Farm/Industry*	*Industry*	*Trade*	*Total*
Cotton – insect resistant	44	3	5	4	56
Maize – insect resistant	4	1	3	6	14
Rice – herbicide tolerant/ insect resistant	2	1	1	5	9
Soybeans – herbicide tolerant	3	1	1	6	11
All other crops[a]	1	1	4	2	8
GM – general			1	3	4
Total	54	7	15	26	102

Note: [a] Other crops include bananas, potatoes, sweet potatoes, cassava, wheat, oilseeds, eggplant, mustard and coarse grains.

Table 3 reports the distribution of articles by scale of analysis and country. Again, categories total to more than the total number of articles because some articles treat more than one country. The overall distribution is very much affected by the distribution among articles treating Bt cotton. China, India and South Africa figure heavily.

The higher proportion of studies that have been conducted at the farm-level lead us to devote more space to these analyses, considered next.

Table 3 Count of articles assessing the economic impact of genetically engineered crops in developing economies, by research question and country

Country	*Farm*	*Farm/Industry*	*Industry*	*Trade*	*Total*
China	13	1	1	4	19
India	16		2		18
South Africa	16				16
Argentina	5	1	1	2	9
Philippines	1	1	1	1	4
Mexico		2	1		3
Colombia			2		2
Kenya		1	2		3
Brazil	1			1	2
West Africa			1	1	2
Other countries	1		1	2	4
Global			1	11	12
Total	53	6	12	22	93

Note: Some studies are counted more than once when the analysis covered more than one country.

3 Farmers

Two main approaches are used in assessing farm-level impacts: (1) farm accounting, or partial budgets, and (2) econometric analysis to test hypotheses about factors affecting variation in output per hectare (partial productivity), input use per hectare (cost savings), and output per unit of input (efficiency). The first main approach involves calculation of marginal returns based on comparisons of per unit changes in variable costs and benefits. The second involves the application of a statistical model to continuous database on a theoretical economics model. Both are based on the farm survey data (often the same sample of farmers or plots), or in some instances, trial data. Combined with the first type of analysis, some survey analyses present information about pesticide use, farmer perceptions of effects on health and biocide or inequality indices.

More than half of farm-level studies have examined IR cotton. Four major country case studies have been published as of 2006: South Africa, China, India and Argentina. These are reviewed next, highlighting methods.

3.1 Insect resistant cotton

3.1.1 South Africa

Of the 14 articles published on Bt cotton in South Africa, seven are based on the same sample of only 100 farmers in Makhathini Flats, a low potential area for cotton production that is "atypical in that the biotech companies are locally present and support services are unusually good" (Thirtle *et al*., 2003, p.731). Over 31 500 ha were planted to cotton in South Africa in 2001–2002, with 22 000 in the drylands, of which Makhathini Flats represented only 31% (6800 ha) (Gouse *et al*., 2003). Thus, it is important to remember that there are other areas that are more representative of cotton production in South Africa, and that findings for Makhathini Flats should not be broadly generalised.

Authors have also been careful to express concerns about "the bias of the sample selection process, as Vunisa agents purposely targeted farmers with larger areas of cotton during the first year of Bt cotton release, and to a lesser extent also in the second year" (Ismael *et al*., 2002a, p.3). As in any cross-sectional study of agriculture, estimates can differ significantly from one year to the next. Though the survey spanned two seasons (1998–1999 and 1999–2000), neither year was normal; there was drought in the first season and late heavy rains in the second (Kirsten and Gouse, 2003).

In early years of study, partial budgets indicated that on average, adopting farmers benefited in terms of either higher yields or lower expenditures on pesticides (Ismael *et al*., 2002b–c; Gouse *et al*., 2005). Whether or not growing Bt cotton is associated with reduced pesticide use in Makhathini Flats has since been questioned by researchers. Reduced pesticide use can lead not only to lower production costs and labour savings, but lower exposure of farmers and the environment to hazardous chemicals. Based on a comparison of near-isogenic lines and daily monitoring of agronomic practices, Hofs *et al.* (2006) observed a decrease in pyrethroid use during two growing seasons, although farmers applied substantial amounts of organophosphates to control pests not affected by the Bt toxin. Using larger samples of farm records made available by Vunisa Cotton for three seasons, Bennett *et al*. (2005) also concluded that overall levels of Biocide indices rose in Makhathini Flats with the introduction of Bt cotton.

Initially, researchers hypothesised that reductions in labour costs were a major reason why farmers chose to grow Bt cotton, given the duress of backspraying, and collecting water for spraying (often accomplished by women and children). In their most recent published work, Shankar and Thirtle (2005) conclude that Bt is not labour-saving in the case of smallholder farmers in South Africa.

Analysts of the situation in Makhathini Flats have tested more subtle hypotheses over time with increasingly sophisticated econometric approaches (Ismael *et al*., 2002c; Thirtle *et al*., 2003; Ismael *et al*., 2002b; Gouse *et al*., 2003; 2005). The article by Shankar and Thirtle (2005) is perhaps the most exhaustive in terms of advanced methods, also testing for sample selection bias. An important conclusion drawn by these authors is that adoption in Makhathini Flats is driven by supply rather than by demand.

Given supply-driven adoption, whether a new variety fails or succeeds is particularly sensitive to the organisation of the marketing channel, a point underscored by Gouse *et al*., 2005). Over 90% of cotton farmers in Makhathini Flats grew Bt cotton in 2001–2002. Gouse *et al*. (2003) proposed that, contrary to expectations, it may have been the vertical integration in the cotton industry, with the monopsony of the local ginnery that also supplied seed and credit, which enabled success to occur in Makhathini Flats.

In a later publication, Bennett *et al.* (2006) carefully assemble all available farm record and survey data, reviewing gross margin advantages by year and farm size. While acknowledging that no data or method is above criticism, they argue that the evidence is broadly consistent with the conclusion that the Bt cotton varieties have generally benefited farmers in Makhathini Flats.

However, given farmer dependence on external market arrangements, combined with a harsh production environment, year-to-year swings in farmer benefits from Bt cotton can be wide. For this reason, Hofs *et al.* (2006) caution that, given current management practices, the level of expected income generated is not sufficient to generate tangible and sustainable improvement in farmer well-being, and may in fact increase financial risk of smallholder cotton farmers such as those of Makhathini Flats.

3.1.2 China

Huang *et al*. have implemented continuous, in-depth survey research since 1999 (Huang *et al*., 2002a–c; 2003; 2004; Pray *et al*., 2001; 2002). As in the case of Makhathini Flats, they have applied increasingly sophisticated statistical and econometric methods; unlike the Makhathini Flats case, they are able to base their analyses on larger samples.

The first year of survey data in China (1999) included 282 farmers in Hebei and Shandong provinces. Multivariate analysis of the first-year survey data, published in 2003 (Huang *et al*., 2003), confirmed the initial findings that Bt use reduced the use of pesticides, and particularly organophosphates, contributing to labour savings and more efficient production. Initially, the authors found that the main benefit came from savings in pesticide expenditures and labour, since the yields of major Bt and non-Bt varieties were statistically "indistinguishable" (p.61). Since some farmers saved seed, and seed use was lower per hectare for Bt seed, overall seed costs were not much lower for non-Bt seed. Furthermore, they found that all Bt cotton varieties – including those introduced by foreign life science companies and those bred by China's research system – were 'equally effective'.

Huang *et al*. (2002b) develop their most complete analysis based on three years of survey data and expanded sample coverage. Applying more advanced methods than previously, they conclude that growing Bt cotton varieties:

- *does* have a positive effect on crop yield
- Bt cotton also reduces yield losses through abated damage
- pesticide use on non-Bt cotton varieties only abates damage
- benefits from Bt cotton vary across provinces, and are lowest in Henan and Jiangsu
- farmers overuse pesticides, even when they grow Bt cotton.

Still, other points of view do add some complexity to this case, particularly with respect to regional variation in the effectiveness of Bt and the magnitude of benefits earned by farmers. Yang *et al.* (2005) concluded that in Liqing County, Shandong Province, farmers grew more than six varieties of Bt cotton but were still over-using pesticides after adoption. In Shandong province, for the 2002 cropping season only, Pemsl *et al.* (2006) measured Bt concentration by sampling leaves. They found that Bt growers overuse pesticides, and that neither insecticide use nor Bt use reduced damage from bollworm. Fok *et al.* (2005) affirm the success of Bt cotton in the Yellow River region of China where resistance to insecticides had evolved and farmers applied 10–12 treatments, as compared to 2–4 in most countries. However, they cite evidence to the contrary from the Yangtze river valley (Jiangsu) and other provinces, where pest pressures are lower and the Bt varieties were not as well adapted.

3.1.3 India

Studies conducted in India illustrate three points of major importance for measuring farm-level impacts of IR crops. The first is that the more heterogeneous the growing environment, pest pressures, farmer practices, and social context, the more variable the benefits are likely to be. Cotton is grown in most of the India's agro-ecological zones on approximately 9 million hectares distributed in just over nine states. Sixty percent of this area is rainfed. While the most damaging pests are bollworms, hundreds of other pests are widespread and the soil and climatic conditions are difficult.

A number of the published studies demonstrate this fact, using different approaches. For example, by introducing risk and uncertainty into the analysis of per hectare economic returns, Pemsl *et al.* (2004) concluded that a prophylactic chemical control strategy would be superior to the use of Bt hybrids in both irrigated and non-irrigated cotton in Karnataka. Another study of 100 farmers in the state of Karnataka found that Bt cotton growers used lower numbers of pesticides applications than non-Bt cotton farmers, but the promise of higher yields was only realised for irrigated farms (Orphal, 2005). Using pairwise yield comparisons of Bt and non-Bt hybrids, Narayamamoorthy and Kalamkar (2006) found that yield advantages differed for the same hybrid by region and within regions, by hybrid. Bennett *et al*. (2004) and Morse *et al*. (2005) analysed farm survey data for over 9000 cotton plots. Gross margins/ha were higher on Bt plots, but the difference was much greater in 2003 than in 2002, varying spatially among subregions. Bennett *et al*. (2006) estimated a production function that introduces use of Bt hybrids as a shift and interaction variable, with a large sample of pooled cross-sectional and time-series data recorded at the plot level, collected by company extension agents. Their analysis confirmed the spatial and temporal variation in partial productivity of Bt cotton. In some areas, they found that farmers did not benefit at all.

The research in India also shows that active debate in civil society can polarise not only public opinion but peer-reviewed literature. Limitations in methods can thus take on particular significance. For example, data from on-farm trials of the first three approved Bt hybrids in Maharashtra, Madhya Pradesh and Tamil Nadu formed the basis for Qaim and Zilberman's initial, optimistic report of 80% to 87% yield advantages (Qaim, 2003; Qaim and Zilberman, 2003). Generally, trial data is not considered to be representative of farmers' conditions, which was acknowledged by Qaim (2003). Arunachalam and Bala Ravi (2003) and Sahai and Rehman (2003) were among the first critics of Qaim's results. Arunachalam and Bala Ravi (2003) questioned the data, claiming that more reliable data from trials conducted by Punjab Agricultural University in 2002 showed yields were higher for non-Bt materials than for the three MMB hybrids. Based on their own sample surveys in Andhra Pradesh, Sahai and Rehman (2003; 2004) reported economic losses for farmers growing Bt cotton hybrids from Monsanto. They argued that farmers sought unapproved Bt variants and good local hybrids because these outperformed the Monsanto hybrids.

This finding raises a third point concerning the importance of good host germplasm, given that the Bt trait is effective. The first three Bt cotton hybrid seeds (MECH-12 Bt, MECH-162 Bt and MECH-84 Bt) were developed by Mahyco-Monsanto Biotech Ltd. and were approved for commercial release in March 2002. There was some suggestion that the host germplasm was not broadly adapted to Indian growing conditions (*e.g*., Arunachalam and Bala Ravi, 2003; Sahai and Rehman, 2004). Naik *et al.* (2005) and Qaim *et al.* (2006) estimated a production function for farmers in four states in India. They found a high degree of heterogeneity among farmers in terms of agroecological, social and economic conditions, also noting that the better adaptation of local non-Bt hybrids compared to Bt hybrids (germplasm effect) influence farm level benefits. They also report circumstantial evidence that black market sales of unapproved cultivars and sales of F2 seed at lower prices explain some crop losses. Bennett *et al.* (2005) show that official Bt varieties significantly outperform the unofficial varieties but unofficial, locally produced Bt hybrids can also perform better than non-Bt hybrids. They report that second generation F2 Bt seed appears to have no yield advantage compared to non-Bt hybrids but can save on insecticide use.

3.1.4 Argentina

The case of Argentina has limited applicability to other cases in developing economies, but reveals the significance of IPR in determining adoption rates and net returns to farmers. As compared to the smallholder farmers of South Africa, China and India, Bt cotton adopters in Argentina farm an average of over 400 ha of cotton on farms of over 1000 ha – they are representative of the medium-and large-scale farmers running family businesses that typically employ one or more permanent workers (Qaim and de Janvry, 2003).

In Argentina, Monsanto strictly enforced intellectual property rights on Bt cotton contributing to low net returns and low rates of adoption in cotton (Trigo and Cap, 2004; Qaim and de Janvry, 2003). Technology fees were imposed, and seed was sold at US$103/ha by a sole supplier. The authors point out that this price is equivalent to a technology premium of US$78, approximately the same as what US farmers have to pay for Bt cotton. In addition, while Argentine seed law allows farmers to reproduce their cotton seed for one season before buying new, certified material, the seed supplier prohibited the use of farm-saved seed (Trigo and Cap, 2004; Qaim and de Janvry, 2003).

Methods applied in the Argentina case are exemplary from the standpoint of disciplinary excellence. Using revealed and stated preferences, Qaim and de Janvry showed that both farmers and monopoly supplier would have been better off at a lower seed price, contributing also to incentives to cheat through illegal seed sales. In one of the most comprehensive approaches applied in the literature, the authors (Qaim *et al*., 2003; Qaim and de Janvry, 2005) estimate the effectiveness of Bt use and predict the impact of the technology by farm size. They concluded that while large family businesses benefit primarily through reduced pesticide use (pesticide use is positively correlated with farm size), smallholders, who use few pesticides, would attain the highest gross benefits per hectare because of substantial yield advantages (of up to 42%). They included a physiological model of the Bt cotton-test system calibrated with entomological data from Argentina, drawing implications for the size of Bt refuge areas need to ensure the durability of farm level benefits.

3.2 Herbicide-tolerant soybeans

Despite the fact that RR soybeans dominate the area of genetically modified crops worldwide, there are few peer-reviewed studies that analysed their socio-economic impact in either developed or developing countries, including the USA, Argentina and some preliminary studies in Brazil.

Based on a survey of 59 farmers in three soybean growing regions of Argentina, Qaim and Traxler (2005) used partial budgeting methods to analyse the impact of RR soybeans on yields, production costs and gross margins. By considering farmers' experiences with and without RR soybeans (over a three year average), the authors established that there were no significant differences in soybean yields. While herbicide applications in RR cultivations were higher, herbicide costs per hectare were significantly lower for RR than for conventional soybeans. Similar to experiences in the USA, they found that while glyphosate applications had increased, the number of herbicides from other herbicide families had decreased. One of the main reasons for higher glyphosate applications was the increase in no-till farming practices in Argentina. Seed costs were higher for RR soybeans, but seed price differentials were considerably lower compared to the USA. This is attributable to the fact that Monsanto does not have patent rights on RR soybeans in Argentina (Trigo and Cap, 2004). Considering gross margins, Qaim and Traxler (2005) found that on average RR soybeans had an income advantage of about US$23 per hectare; and these margins were not biased toward large-scale farmers.

Using partial budgeting applied to data from the Institute of Agricultural Technology in Argentina over the period 1998 to 2000, Penna and Lema (2003) also found that RR soybeans and no-till farming led to the highest gross margin in all three years. Similar to conditions in the USA, they showed that yield differences between RR soybeans and conventional soybeans are on average small. To account for uncertainties in the calculation of gross margins, Penna and Lema (2003) used Monte Carlo estimation techniques to simulate gross margins under different cultivation scenarios and to establish the cumulative distribution function for each of these scenarios. Parameters for yields and prices used in the simulations were obtained through expert interviews. The authors demonstrated that the gross margin of HT soybeans cultivated in the major growing seasons under no-till practices is likely to be higher at every level of gross margin than for other cultivation practices, even when variability is taken into account. This means that regardless of attitudes toward risk, considering only gross margins, growers would be better off with HT soybeans. They also showed that HT-soybeans and no-till practices are strongly complementary.

3.3 Insect-resistant maize

Cabanilla (2004) has estimated the potential impact of Bt maize on farms in the Philippines using a mixed integer programming procedure, based on representative technologies and farms. Yorobe and Quicoy (2004) estimated the partial productivity impact of Bt maize in the Philippines with sample data from 470 farmers in four provinces of the country, for a single cropping season. Yield and income were higher among Bt growers, and insecticide expenditure was lower. The converse was also true: income, as well as education, were factors that significantly influenced the adoption of Bt maize.

Gouse *et al.* (2004; 2006) present the first few years of evidence about Bt (white) maize adoption and impact among large- and small-scale farmers in South Africa, beginning in 1998. Using farm survey analysis alone, they find that yields are higher for both groups and pesticide applications are reduced particularly for large commercial farmers. In the later article, they recognise the consumption characteristics of white maize, noting that the yield benefits with the highest value were among those farmers who grind maize for home consumption. South Africa is the first developing economy to release a genetically engineered food crop, and this point has implications for other countries.

3.4 Methodological limitations

Methodological limitations impede the extent to which the findings published so far can be generalised. There are at least five limitations associated with these studies.

1 Use of partial budgets:

- Partial budgets are deceptively simple, when in fact, considerable care must be used to construct them. In many of the studies, only gross margins are reported. Gross margins include the costs of intermediate inputs but ignore the use of labour and land. Net margins include these costs.
- Partial budgets are 'partial' because they treat only one farm activity at a time. Even where farmers are fully commercialised, the net impact on whole-farm production, factors of production, income or well-being cannot be deduced.
- Partial budgets are typically presented as averages. While these are useful as a starting point, the statistical distribution of economic returns carries other important information about variability and risk.

2 Household farm decision-making: Even if the whole-farm is considered, when farmers are not fully commercialised, and operate in situations with market imperfections, the input and output prices that influence their decisions are endogenously determined and household-specific.

3 Institutional context: Findings clearly point to the hypothesis that marketing arrangements, the extent of vertical coordination, monopsony as compared to competition, affect the farm-level impact and adoption. Yet this aspect has received less systematic attention that is due.

4 Sampling methods

- Identifying the counterfactual (which variety the farmer would have grown in the absence of the GM variety, and which practices the farmer would have used) is necessary in order to have an unbiased assessment of the net benefits of adoption – yet this information is generally missing. There are factors influencing whether a farmer grows a Bt cotton variety that may also affect marginal returns to that variety, and these have not, in general, been taken into account. Some are observed and some are unobserved, but there are ways to take account of them. Whether they are observable or not, such factors create a bias due to programme placement as well as programme participation (often referred to as 'selection bias').

- When sample sizes are small, sampling errors are great.
- When they are large, as in the case of farm records, non-sampling (measurement) errors are expected to be substantial.

5 Environmental and health externalities. These have been addressed in very simplified forms in the literature, with biocide indices or farmer perceptions. More advanced methods may warrant consideration.

6 Temporal use patterns and smallholder vulnerability. In the second decade of use of transgenic crops, it may be advisable to examine the durability of impact.

The number of crops and traits addressed are few. Although estimated adoption rates are encouraging (as shown in Appendix Table 1 for the case of Bt cotton), measurement and selection biases, supply side policies, and the need to observe rates over a number of years and in a range of contexts should be borne in mind.

4 Industry

Most analyses of the size and distribution of economic benefits from adopting transgenic crop varieties in an industry (sector) are conducted with adaptations or versions of the economic surplus approach detailed in Alston *et al.* (1999). This approach is also termed a partial equilibrium displacement model because it considers only the effects of the technology change in the market where the technical change occurs. Effects in other markets, such as the input market, are disregarded. In the standard model, the estimated magnitude and distribution of the economic benefits depends on many factors. These include: the price elasticities of supply and demand for the crop, whether the country is a large or small producer (price setter or price taker), whether the country trades the crop internationally, the nature of the innovative change induced by the technology, the crop itself, and for genetic enhancement of agronomic traits, weather and pest infestations. Data are typically drawn from some combination of sample surveys of farmers, (field and greenhouse) trial data, and/or secondary data. The analysis may be conducted at the regional, national, or global level.

A particular aspect of biotechnology provision is the possibility of temporary monopoly conferred through intellectual property rights. Applying the Alston *et al.* (1999) and Moschini and Lapan (1997) theoretical framework to the case of Bt cotton in the US from 1996–1999, Falck-Zepeda *et al.* (1999; 2000a–b) laid out a model that has since provided the foundation for economic surplus applications in developing economies. Most studies reviewed have used this framework, applied in an *ex-ante* assessment. *Ex-post* studies, which examine actual impacts, are discussed next. A summary of study descriptors is provided in Table 4.

The first *ex-post* study reviewed was conducted by Pray *et al.* (2001) on Bt cotton in China. Based on the Falck-Zepeda *et al*. (2000b) approach, for a single year of data, Pray *et al.* found substantial economic benefits for smallholder farmers and no consumer benefits because the government bought almost all of the cotton at a fixed price. Because of weak IPR, farmers obtained the major share of the benefits, with very little accruing to Monsanto or the public research institutions that developed local Bt varieties.

Table 4 Study descriptors, industry (sector) impact of genetically engineered crops

Author	*Year published*	*Crops*	*Data type*	*Scale*	*Country*	*Methods*
Avila *et al.*	2002	GM				*Ex-ante*
Cabanilla *et al.*	2004	Cotton		Country	Mali focus, also Burkina Faso, Bening, Cote d'Ivoire, Senegal	Linear programming, sensitivity. *Ex-ante*
De Groote *et al.*	2005	Maize	On farm trial data	Country	Kenya	Farm survey analysis, consumer survey analysis, direct crop loss estimation, consumer surplus, closed economy, participatory rural appraisal, brief. Ex-ante
De Groote *et al.*	2003	Maize	On farm trial data	Country	Kenya	Direct crop loss estimation, economic surplus, closed economy. *Ex-ante*
Falck-Zepeda *et al.*	2006	Potato	On farm data, focus groups	Sub-country	Colombia	Economic surplus. *Ex-ante*
Hareau *et al.*	2006	Rice	Trade	Country	Uruguay	Economic surplus, small country, open economy, stochastic simulation, endogenous adoption. *Ex-ante*
Kambhampati *et al*	2005	Cotton	Key informant	Sub-country	India	Supply chain analysis
Pray *et al.*	2006	Cotton	Key informant, government data	Sub-country	China	Cost analysis
Pray *et al.*	2005	Cotton, also hybrid mustarnd and Bt eggplant	Key informant	Country	India	Regulatory costs, social benefits, simulation

Table 4 Study descriptors, industry (sector) impact of genetically engineered crops (continued)

Author	*Year published*	*Crops*	*Data type*	*Scale*	*Country*	*Methods*
Pray *et al*.	2001	Cotton	Statistical survey, key informant	Sub-country	China	Farm survey analysis, economic surplus. *Ex-post*
Qaim	2001	Sweetpotato	Pilot survey, key informant	Country	Kenya	Farm survey analysis, economic surplus, closed economy, cost-benefit analysis, sensitivity. *Ex-ante*
Qaim	1999	Potato	Pilot survey, key informant	Country	Mexico	Economic surplus, small country, closed economy, benefit-cost, sensitivity. *Ex-ante*
Qaim and Traxler	2005	Soybeans	Pilot survey, key informant	Sub-country	Argentina	Farm survey analysis, economic surplus, large open economy, three regions, institutional analysis. *Ex-post*
Traxler and Godoy-Avila	2004	Cotton	Statistical survey, key informant	Sub-country	Mexico	Farm survey analysis, economic surplus, small open economy, brief. *Ex-post*
Traxler *et al*.	2003	Cotton	Statistical survey, key informant	Sub-country	Mexico	Farm survey analysis, economic surplus, brief. *Ex-post*
Trigo *et al*.	2002	Soybeans, maize, cotton	Government data	Country	Argentina	Adoption model, simulation model. *Ex-ante*
Yorobe and Quicoy	2004	Maize	Statistical survey	Sub-country	Philippines	Economic surplus
Zimmermann and Qaim	2004	Rice	Statistical survey, key informant, government data	Country	Philippines	DALYs, cost-benefit, simulation. *Ex-ante*

The remaining *ex-post* studies have been conducted for cotton in Mexico and soybeans in Argentina by Traxler and colleagues. Based on survey data for a 1997–1998, Traxler *et al.* (2003) and Traxler and Godoy-Avila (2004) find that Bt cotton reduced costs and raised revenues for farmers in the Comarca Lagunera in North-Central Mexico, such that "cotton has become a low pesticide crop, benefiting both farmers and residents of the region" (p.61). They estimated that seed suppliers and innovators earned an average over the two years of the study of only 15% of the benefits from adoption, while farmers earned the remainder. The authors assert that the risk of crop failure has declined with the use of the Bt cotton technology.

In Argentina, Qaim and Traxler (2005) combined farm survey data from three regions (but a small sample), institutional information, and secondary data for 1996–2001 to examine the impacts of HT soybeans. The USA and Argentina gained economic benefits while the non-HR producing countries of the world lost them. Farmers in Argentina gained more than US farmers as a share of the total benefits because of weaker IPR protection. An interesting detail is that some of the model parameters they employ are those estimated for the USA, reinforcing the perception that soybean producers in Argentina are relatively large-scale, fully commercialised growers. They attribute the success of the technology in Argentina to: (a) a suitable agro-ecology; (b) a strong seed sector that sold a lot of seed even though IPR was weak and there were black market sales, (c) adaptive research capability, and (d) a functioning regulatory framework. These are key factors that govern how benefits derived from gene events produced in one country spillover to other potential adopting countries.

4.1 Methodological limitations

The major advantages of the economic surplus approach are that the methods are parsimonious with respect to data and can be used to portray the distributional effects of various institutional and market structures. The principal disadvantages are:

- The surplus calculated is Marshallian, accounting for price effects but not for changes in the income of farmers.
- The approach ignores transactions costs, assuming that markets clear and function perfectly.
- As with any partial equilibrium model, they fix prices and quantities of other commodities produced by farmers.
- Effects on input markets are unclear, and in particular, they do not account explicitly for returns to land and labour, which are important factors for measuring the impact of new technologies.
- Furthermore, farmers are considered to be risk-neutral, price-takers who either maximise profits or minimising costs.
- As in farm-level studies (Question 1), year-specific effects on productivity can be large but are not accounted for in single-year, *ex-post* studies. Location-specific effects on the farm budget data that serve as the basis for some parameters can also be large. These aspects are salient for production systems in developing countries where crop management practices and conditions are so heterogeneous.

In other words, the assumptions best depict an industry with commercially oriented farmers who buy and sell in well-organised markets and grow their crop under relatively homogeneous conditions.

The quality of the underlying data is crucial to the validity of the results. In general, reliable cross-sectional time-series data are not yet available for these technologies in developing economies because they are too costly. In contrast, in the USA, extensive surveys have been conducted continually (*e.g.*, the ARMS survey on which many of the detailed analyses are based), and cheaper methods are feasible (mail and phone interviews). 'Pure' ex-ante analyses (with no field observations) are even more limited, since all model parameters must be projected based on expert interviews and existing secondary data. Nonetheless, it should be remembered that adaptations are feasible to treat some of these challenges, and this type of estimation provides the type of information that most national policy-makers require. For example, one of the studies augmented the framework with sensitivity analysis based on stochastic simulation, which facilitates the treatment of risk and uncertainty.

5 Trade

Aside from purely theoretical treatments, or more cursory forms of forecasting (Brookes and Barfoot, 2003; Paarlberg, 2006), there are two major categories of applied trade models. The first category use partial equilibrium models that model one or several sectors of the economy in a few countries, focusing on particular vertical or horizontal linkages. They have the advantage of being more flexible, which enables the representation of a more complex set of institutional and market policies but they do not take into account the linkages with non-agricultural sectors and specific regulations affecting bilateral trade relationship with sensitive importing countries. The second type uses multi-country computable general equilibrium models. These models provide a consistent and comprehensive structural representation of the economy and of international trade linkages, but because they are highly aggregated and based on important assumptions about the market, they are less conducive to representing specific policies and institutional arrangements. Study descriptors are shown in Table 5.

The partial equilibrium approach is applied in several articles. Moschini *et al.* (2000) study the adoption of HR soybeans in a four-region model composed of the USA, Brazil and Argentina, and the ROW (rest of the world) under various IPR scenarios in these four regions. Their results suggest that the USA gains most, with the innovator capturing the largest share of the gains. On the same regions and crop, Sobolevsky *et al.* (2005) use a partial equilibrium trade model that includes product differentiation and the costs of identity preservation in segregating markets. Consumers in the importing region view GE soybeans and products as weakly inferior substitutes. They find that in a world where no segregation is feasible, the long run equilibrium is worldwide adoption. When segregation technology is available at a cost, the US emerges as the only region with partial adoption, and all other regions specialise in HT soybeans. Berwald *et al.* (2006) use another five regions partial equilibrium model of trade with heterogeneous consumers, two types of labeling policies, and segregation on the adoption of HR wheat to compute the opportunity cost of non adoption for the USA and Canada when other regions adopt the GE wheat.

Table 5 Study descriptors, impact of genetically engineered crops on international trade

Author	*Year published*	*Crops*	*Data type*	*Scale*	*Country*	*Methods*
Anderson *et al.*	2004	Rice	Trade	Global, focus on Asia	Na	Applied general equilibrium model
Anderson and Jackson	2005	Rice, coarse grains, oilseeds, wheat	Trade	Global, focus on SSA	Na	Applied general equilibrium model
Anderson and Yao	2003	Rice, maize, cotton, soybeans	Trade	Global, focus on China	China	Applied general equilibrium model
Anderson *et al.*	2001	GM	Trade		Trade	Applied general equilibrium model
Anderson *et al.*	2006	Cotton	Trade	Global, emphasis on SSA	Global	Applied general equilibrium model
Annou *et al.*	2005	Rice	Trade	Global	Na	Arkansas Global Rice Model
Berwald *et al.*	2006	Wheat	Trade	Global, Focus on USA and Canada	USA, Canada, Argentina	Partial equilibrium world trade model, segregation, voluntary and mandatory labelling
Diaz Osorio *et al.*	2004	Maize	Company data	Country	Chile	Partial equilibrium
Elbehri and Macdonald	2004	Cotton	Trade	Global, focus on WCA	Benin, Burkina Faso, Chad, Mali, Togo, Cote d'Ivoire, Cameroon, CAR	Applied general equilibrium model

Table 5 Study descriptors, impact of genetically engineered crops on international trade (continued)

Author	*Year published*	*Crops*	*Data type*	*Scale*	*Country*	*Methods*
Felloni *et al.*	2003	Grain	Trade	Global, focus on China	China	Applied general equilibrium model, recursive dynamic
Hareau *et al.*	2005	Rice	Trade	Global, focus on Asia	China, India, Indonesia, Bangladesh, Vietnam, Thailand, Philippines, Japan	Applied general equilibrium model
Huang *et al.*	2004	Cotton	Statistical survey, field trials, trade	Global, focus on China	China	Applied general equilibrium model, modified GTAP
Moschini	2001	Multiple	Trade	Global	Na	Review, findings, world trade model, brief
Nielsen and Anderson	2001	Maize, soybeans	Trade	Global, selected countries	Na	Applied general equilibrium model
Nielsen *et al.*	2003	Maize, soybeans	Trade	Global	Na	Multi-region computable general equilibrium model
Nielsen and Anderson	2001	Maize, soybeans	Trade	Global	Na	Applied general equilibrium model
Nielsen *et al.*	2001	Maize, soybeans	Trade	Global	Na	Applied general equilibrium model
Paarlberg	2006	GM	Trade	Multi-country	Na	Review, calculations with secondary data
Sobolevsky *et al.*	2005	Soybeans	Trade	Global, focus on US, Argentina, Brazil	Argentina, Brazil	Partial equilibrium world trade model, segregation, import bans

Fourteen distinct published articles apply computable general equilibrium models based on the GTAP database (Hertel, 1997) to examine the effects of GE technology adoption on multiple sectors and regions. They differ by their assumptions about the productivity effects of the technology, the rate of adoption, and according to the scenarios they depict concerning trade policies, consumer perceptions, and the structure of the non-GE/GE market chain. Overall, these papers can be divided into four groups according to their successive contribution to the improvement in the evolution of the modelling methodology.

First, Nielsen *et al.* (2001) and Nielsen and Anderson (2001) led the way in evaluating the economy-wide international effects of GE soybeans and maize introduction. They modelled the technology with simple Hicks-neutral productivity shift of primary factors or intermediate consumptions and two different approaches to model consumer acceptance in sensitive countries.

A second group of papers (Stone *et al.*, 2002; Nielsen *et al.*, 2003; Anderson and Yao, 2003; Anderson and Jackson, 2005) provided slight refinements to the methodology both in terms of productivity effects and the modelling of trade policies. For example, Stone *et al.* (2002) focused on Australia within a multiregion world, and modelled the introduction of GE maize and soybeans based on updated data, using more accurate productivity shifts, more realistic national adoption rates, and consumer demand changes, as well as regulatory costs. Anderson and Yao (2003) focused on China and applied the same method to cotton, maize and soybeans, with an additional a scenario that eliminates the Chinese voluntary export restraint on textile.

Third, van Meijl and van Tongeren (2004) provided a study of GE introduction in the EU and USA with a change of methodology driven by a criticism of Nielsen and Anderson (2001). They replaced Hicks-neutral shifts by factor-biased productivity shifts for cereals, include technology spillover effects, and provide a more realistic representation of the EU's Common Agricultural Policy by including the isolation of EU countries from world prices. Their results for Europe differ significantly with Nielsen and Anderson (2001).

The fourth group of published studies (Elbehri and Macdonald, 2004; Huang *et al.*, 2004; Anderson *et al.*, 2004; Anderson and Jackson, 2005; Hareau *et al.*, 2005; Anderson *et al.*, 2006) focused on specific regions and commodities. Authors employ more realistic assumptions with mixed, Hicks-neutral/factor-biased productivity shifts and additional layers of complexity. For example, Huang *et al.* (2004) analysed the effects of GE cotton and rice introduction in China, based on regional farm-level survey data, adding labelling costs, loss of demand in export markets, and dynamic adoption, but without adoption of these crops in any other country. Elbehri and Macdonald (2004) evaluated the potential effects of Bt cotton in West and Central Africa based on a careful analysis of productivity effects in the region (using farm and national budgets).

5.1 Methodological limitations

Only a few published articles used partial equilibrium simulation models to evaluate GE crop introduction, and even less focus on developing countries. One of the main challenges of modellers is to make realistic assumptions about the parameters that determine the effect of national and international regulations. Simulations in partial equilibrium also rely on relatively simplistic assumptions on the adoption and the productivity effects of the technology. Overall, this field of studies will be strengthened with better representation of the technology effects and improved calibration on the effects of competitive structures and trade related regulations.

As noted above, applied general equilibrium modelling has progressively improved in the published literature. More realistic assumptions concerning productivity shifts, adoption rates, the updated GTAP database on the one hand, and segregation, demand and trade-related regulations on the other, have improved the accuracy of the results. Yet, several key methodological issues remain:

- None of the published studies make an effort to adjust for the aggregated sectors of the GTAP database. For instance, to model the introduction of GE maize, they induced technology shifts on the cereal sector of GTAP, which excludes wheat and rice, but that includes other significant crops, such as barley, sorghum and millets.
- None of the papers model a realistic situation with pure non-GE as opposed to GE and non-GE mixed commodity trade.
- Trade regulations on GE food are represented by moratoria in the EU, Japan or South Korea, when in fact these countries do import large volumes of undifferentiated soybeans and/or maize from GE producing countries for animal feed and non-food uses.
- The productivity modelling should be improved to account for regional differences, labour effects, land types, and seed prices, linked to improved sector models.
- Consumer acceptance and labeling effects may need some refinements.
- There is no effort to model market imperfection in the input sector.
- Adoption rates are exogenous and somewhat arbitrary. Modelling adoption in as endogenously determined in a dynamic framework would improve the utility of these models.
- The role of trade-related regulations for genetically-engineered products, particularly labeling and import approval regulations, needs to be better depicted.

These limitations call for as many improvements in the methodology. For example, in the context of a standard trade model, it is difficult to estimate the impacts of a technology that is more productive yet is also stigmatised from the perspective of many consumers and regulators. While applied general equilibrium evaluations can be improved through use of more realistic data, some of the issues of policy interest may be difficult if not impossible to model within already complex macroeconomic models of international trade.

6 Conclusions

An exhaustive review of peer-reviewed, applied economic literature about the impacts of genetically-engineered crops in non-industrialised agriculture leads us to several general conclusions. As expressed in publication counts, agricultural economists have focused relatively more attention on assessing impacts at the farm level. Among crops, case studies of IR cotton in China, South Africa and India have dominated the literature. Other than IR cotton, only IR maize and HT soybeans have been analysed *ex-post*, since these are the technologies that have been widely diffused so far.

We have mentioned a number of methodological limitations that are apparent in the literature, many of which are recognised by authors, and most of which are common to any impact analysis. Clearly, economists have applied increasingly sophisticated analytical methods. In general, the initial enthusiasm for the technology has been superseded by a more careful measurement of farm profitability by crop and trait, among regions, and among farmers. Although averages tend to show positive returns for the crops studied, averages mask considerable variation, and for some farmers, costs outweigh benefits.

On the one hand, the balance sheet of this literature is fairly consistent with the broader literature about the impacts of new crop varieties in agriculture. First, any particular variety, even if widely adapted, will perform with considerable variation across location and time. Second, the net economic impact of new crop varieties on society is not easily measured. No single method is in and of itself sufficient to analyse the impacts of seed technical change. Third, the length of the time period of observation of adoption and use matters for assessment of impact, since discontinuities in adoption are common where markets function poorly, production environments are variable, or economic policies shift dramatically from one year to the next. Fourth, the institutional and social context of technology introduction is often of greater significance for determining the direction and magnitude of impacts than the effectiveness of any particular trait (Raney, 2006). In fact, the necessary institutional changes and investments required for nations and their farmers to benefit from genetically engineered crops have been put in place by very few countries (FAO, 2004). Given this fact, there are marked gaps in this first phase of literature with respect to analysis of institutions and market function. Finally, the next wave of economics studies will need to look more critically at impacts on labour, health, environment, equity and poverty – which have not yet received rigorous treatment in the peer-reviewed, applied economics methods.

On the other hand, some aspects of impact analysis for genetically-engineered crops are unique, though much of what is unique is unrelated to the technology itself. For example, the technology is knowledge-intensive in the development phase and in mounting the regulatory framework needed to release it to farmers. Embodying the pesticide or insecticide in the seed removes much of the uncertainty or risk in timing and intensity of chemical applications, particularly for less literate or poorly informed farmers. For agronomic traits such as pest and disease resistance, however, the chances of sustained, high returns improve with the adoption of the resistant variety if farmers' management practices are fine-tuned to account for secondary pests and resistance evolution. Integrated pest management is knowledge-intensive, whether or not it is associated with a genetically engineered crop variety.

The active involvement of civil society, and the heightened concern of civil society about potential health and environmental impacts, distinguish genetically engineered crop varieties from other modern varieties. Thus, risk assessment and analysis of regulatory frameworks play a much larger role than would otherwise be the case. The significance of consumer attitudes against GM technology in general (as compared to more common questions of product quality, tastes and preferences) leads to the need for more advanced consumer analysis as part of the technology assessment. We do not consider these here. The structure of the industry entails the need to develop models that account for transfer fees and rents from non-competitive market structures. Trade models must take segregated markets and other policies into account for genetically engineered crops that are sold on world markets. Thus, at present, the overall complexity of the impact analysis is much greater with GE varieties as compared to other modern varieties.

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Appendix

Table 1 Adoption rates for genetically engineered cotton

	GM cotton areas					*Adoption rates*				
	2002/3	*2003/4*	*2004/5*	*2005/6*	*2006/7*	*2002/3*	*2003/4*	*2004/5*	*2005/6*	*2006/7*
Country	*Thousand has*					*Percentage*				
Argentina	7.31	15.29	37.46	61.02	100.00	5	6	10	20	25
Australia	66.15	117.9	188.4	301.5	127.80	30	60	60	90	90
Brazil					5.48					1
China	2,133.84	2,962.93	3,700.45	3,985.8	4,402.00	51	58	65	70	71
Colombia		5.49	11.33	20.07	21.49		10	14	35	43
India	38.34	97.88	465.66	1,223.46	3,727.31	0.5	1.3	5.3	14	41
Indonesia	0.09	0.1	0.12			1	1	1		
Mexico	20.75	23.71	64.26	72.64	67.15	50	38	61	57	59
SouthAfrica	22.11	32.51	26.62	17.78	12.86	74	75	95	90	90
USA	3,869.20	3,740.44	4,121.59	4,524.53	4,400.12	77	77	78	81	85
World	6,157.79	6,996.25	8,615.89	10,241.04	12,864.21	20.6	21.8	24.4	29.8	37.0

Source: International Cotton Advisory Committee (ICAC), personal communication