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Bales and Balance: A Review of the Methods Used to Assess the Economic Impact of Bt Cotton on Farmers in Developing Economies

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We assess 47 peer-reviewed articles that have applied stated economics methods to measure the farm-level impacts of Bt cotton in developing agriculture from 1996. We focus on methods, although findings are also contrasted and compared in qualitative terms. The central research question assessed by the articles reviewed is: what are the current and potential advantages of transgenic cotton with respect to yield, pesticide use, input cost, revenue and/or profits at the farm-level, by farm type, and geographical region? We find that, while the evidence is promising, the balance sheet remains inconclusive—in part because of some methodological limitations and in part because institutional and political context, which is mutable and often ignored, shapes economic impacts, especially over the longer-term. Most often, the contextual factors that influence whether a new variety succeeds or fails are more critical than whether yield advantages can be demonstrated in on-farm trials.

Key words: Bt cotton, developing economies, economic impact, literature review.

Objective

Immense literature has accumulated since the first genetically modified (GM) crops were released to farmers in 1996. A comparatively minor segment of this literature consists of studies conducted by agricultural economists to measure the farm-level impact of GM crops in developing economies. Numerous reviews of this literature have surveyed the findings for both industrialized and non-industrialized agriculture at various points in time, but surveys of methods are less frequent and have typically examined only one overall question or approach (Table 1). The objectives of this article are to a) identify and compare, across studies, the methods used to assess economic impact at the farm-level and b) revisit the evidence for Bt cotton by taking methods into account.[1]

Search Summary

The boundaries of the domain we searched were carefully delineated. Studies were included only if they explicitly stated an economics method and presented data in order to omit theoretical studies and critical essays. Only literature reviewed by peers has been included (reports, discussion papers, presented papers, and journal articles), although the peer review is sometimes minimal (discussion papers). Research conducted in industrialized countries has been consulted only for purposes of identifying specific methodologies.

The search 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 January 12, 2005, CAB Direct had 3,477 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.

After reviewing the contents of each of roughly 300 papers, we found that 106 peer-reviewed articles published from 1996 through mid-2006 met our criteria. Of these, Bt cotton is the subject of more than half (56). As shown in Table 2, the majority of the Bt cotton studies (47) were conducted with information from farm-level surveys, with most of them (42) coming from just three countries (India, China, and South Africa.) Two studies in Mexico included both a farm-level and industry-level analysis. Several other studies are based on trade models. Given the dominance of Bt cotton in the literature, much can be learned about methods from consulting these studies.

Few documents found in the French language literature met our criteria. Three peer-reviewed articles were

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[1] *Bt cotton is the name used for cotton that has been genetically modified by the insertion of genes of a soil bacterium known as Bacillus thuringiensis. The inserted genes produce toxins that confer protection to plants from bollworms.*

Table 1. Review of findings or methods used to analyze the impact of genetically-engineered crop varieties in industrialized and non-industrialized agriculture.

First author	Year	Publication	Crops	Period	Focus	Review type
a. Global						
Brookes, G.	2005	AgBioForum	multiple	1996-2005		findings
Fernandez-Cornejo, J.	2006	ERS Electronic report	multiple	1996-2006	USA	findings
Marra, M.	2002	AgBioForum	multiple	1996-2002	USA	findings
Purcell, J.	2004	AgBioForum	cotton	1996-2003		findings
Wu, F, Butz,W	2004	Rand	multiple	1996-2003		findings
FAO	2004	State of Food and Agriculture	multiple	1996-2003		findings
Babu, S. C.	2003	Asian Biotech. & Dev. R.	multiple	-		methods
Scatasta, S.	2006	Mansholt Diss. Paper				methods
Shoemaker, R.	2001	ERS	multiple	1996-1999	USA	
b. Industrialized countries						
Demont, M.	1999	KU Leuven	multiple	-	EU	methods
Carpenter, J.	2001	Nat. Center for Food and Ag. Policy	maize, cotton, potatoes, soybeans	1996-2000	USA	findings
Caswell.M.F.	1994	ERS Ag Econ Report		up to 1994	USA	findings
Price, G.	2003	USDA/ERS	soybean, cotton	1997	USA	methods findings
c. Non-industrialized countries						
Falck-Zepeda, J.	2003	OECD	multiple			findings
Heusing,J.	2004	AgBioForum	multiple	1996-2003		findings
Qaim, M.	2005	Quarterly Journal of International Ag.	multiple	1996-2005		findings
Raney, T.	2006	Current Opinion in Biotechnology	cotton, maize, soybeans	1996-2005		findings
Schaper, M.	2001	Grupo Zapallar	multiple	1996-2001	LAC	findings
da Silveira, J-M.	2005	Bellagio	soybean	1996-2004	Brazil	findings
Toenniessen, G.	2003	Current Opinion in Plant Biology	multiple	1996-2001		findings
Nuffield Council on Bioethics	2004	Nuffield	multiple			findings
Trigo	2002	IDB	multiple	-	LAC	findings
ISNAR	2002	ISNAR		-		methods
OECD	2003	OECD		-		methods
Qaim, M.	1998	ZEF	multiple	-		methods

Table 2. Count of peer-reviewed, English, French, and Spanish language articles about the economic impact of Bt cotton.

Level of analysis	India	China	South Africa	Argentina	Mexico	West Africa	Global	All
Farm	15	12	14	3	0	0	0	44
Farm, Industry	0	1	0	0	2	0	0	3
Industry*	2	1	0	1	0	1	0	5
Trade	0	2	0	0	0	1	1	4
All	17	16	14	4	2	2	1	56

** Two articles about regulatory costs in India and one article about regulatory costs in China are included in the industry row.*

identified, two of which were written by the same author. Among the major French journals of agricultural economics, several articles discuss themes related to genetically-engineered crops in *developed* economies, but not their economic impact on *developing* economies. The lack of documents in the databases of the main French research centres such as INRA (National Research Institute of Agronomy), CIRAD (Research Centre for Agronomic Development), IRD (Research and Development Institute), and CNRS (National Centre of Scientific Research), surprised us. One explanation for this result is that given popular opinion in France concerning genetically-engineered crops, the audience most interested in research of this type tends to publish in English-language journals. It may also be that web-based information is less extensive. Similarly, we found no studies meeting our criteria written in the Spanish language. Either authors published in English, or articles were more focused on findings than on methods.

Research Approach

The central question posed in the farm-level studies is: what are the (potential, actual) advantages of transgenic crop varieties with respect to yield, pesticide use, input cost, revenue and/or profits at the farm-level, by farm type, and geographical region? Two main approaches are used in this literature: 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 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 data based on a theoretical economics model. Building on the farm survey analysis, gradually more sophisticated econometric analyses were used to test hypotheses about productivity, efficiency, and trade-offs in yield and pesticide effects. Both are based on the farm survey data, 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, as well as biocide or inequality indices.

Table 3 summarizes the methods applied in the 47 articles about the farm-level impact of Bt cotton in developing economies. The count of unique studies is fewer than the apparent count because the same findings are often reported in more than one article. Often, slightly different analytical models were applied to the same (relatively small) data sets in multiple studies. Generally, the same groups of authors contributed, although the authorship on the studies in India is more broad.

Methods and Findings

South Africa

Thirtle et al. (2003, p. 731) describe Makhathini Flats as “a low potential area for cotton production,” and “atypical in that the biotech companies are locally present, and support services are unusually good, which affects the wider applicability of this study.” Over 31,500 ha were planted with cotton in South Africa in 2001/02, with 22,000 in the drylands, of which Makhathini Flats represented only 31% (6800 ha) (Gouse, Kirsten, & Jenkins, 2003). At least from 2002 to 2004, insecticide prices were substantially higher in Makhathini Flats than in other parts of the province (Hofs, Fok, & Vaissayre, 2006). Thus, research in Mahkhathini Flats is purposive in placement, and findings can be generalized to other locations only to the extent that other locations bear the same characteristics. Thus, research in Mahkhathini Flats is purposive in placement, and findings can be generalized to other locations only to the extent that these locations bear the same characteristics. Otherwise stated, there may be statistical bias associated with study placement.

Of the 14 articles published on Bt cotton in South Africa, 7 are based on the same sample of only 100 farmers. Authors have been careful to cite some concerns with sampling methodology. For example, "there was some potential for bias in the 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). Though the survey spanned two seasons (1998/99 and 1999/2000), neither year was normal; there was drought in the first season and late heavy rains in the second (Kirsten & Gouse, 2003).

Partial budgets tend to indicate some advantages from growing Bt cotton in terms of either yield or pesticide costs. Ismael et al. (2002b, 2002c) found that farmers who grew Bt cotton had both higher yields and lower pesticide costs than those who did not, outweighing the higher seed costs. They estimated the difference in gross margins at 11% in 1998/99 and 77% in 1999/2000, however. Based on data from Vunisa (the cotton gin in Makhathini Flats), Gouse et al. (2005a) found no clear yield advantage to the Bt variety in either year, though pesticide costs were lower.

Whether growing Bt cotton is associated with reduced pesticide use has since been questioned by researchers. Reduced pesticide use can lead not only to lower production costs and labor savings, but also to lower exposure of farmers and the environment to hazardous chemicals. Hofs et al. (2006) compared near-isogenic lines and monitoring agrononomic practices daily, using a different sample of 20 farmers in Makhathini Flats. They observed a decrease in pyrethroid use during the 2002/03 and 2003/04 seasons, though farmers did not abandon it altogether. At the same time, farmers applied substantial amounts of organophosphates to control pests not affected by the Bt toxin. The extent of the labor savings was not as great as expected. Surprisingly, "more money was invested in insect management for Bt cotton than for non-Bt cotton crops, probably because farmers…upgraded their seed-cotton yield objectives and adjusted their investment" (Hofs et al., 2006, p. 5). Note also that while concern with identifying the correct counterfactual was the reason why the authors used isogenic lines, rigor with respect to analyzing agronomic practices in this study was not matched by the rigor in sampling farmers. Only 20 farmers were studied in close proximity, raising potential for placement bias.

Similar to Hofs et al. (2006), Bennett et al. (2004b) concluded that while financial returns were good during the time period studied (higher yields, lower insecticide spray costs, and higher gross margins), overall levels of Biocide indices rose in Makhathini Flats with the introduction of Bt cotton. These authors based their analysis on large samples of farm records drawn from Vunisa cotton data, over three seasons (1998/99 to 2000/01). In contrast to Hofs et al. (2006), they found that although Bt growers applied lower amounts of pesticides and had lower Biocide indices than growers of non-Bt cotton, some of this advantage was due to a reduction in non-bollworm insecticide, due to an apparent misunderstanding.

Analyses that compare economic returns per ha between smallholder and larger-scale producers in South Africa conclude that smallholders are major beneficiaries of the Bt cotton (Ismael et al., 2002b; Gouse et al., 2003). Despite the differential in technology fee between large-scale and small-scale farmers, Gouse et al. (2004) presented data indicating that the large-scale farmers in irrigated areas earn the greatest amount of yield benefits per hectare, as well as the greatest reduction in pesticides, and the greatest income advantage. The greatest percentage benefit for small-scale farmers is due to yield advantages rather than decreased pesticide use, and large-scale farmers in the drylands gain the least at the margin. Gouse et al. (2003, 2004) report that larger-scale farmers save in terms of lower diesel and tractor costs, and "managerial freedom." While there is some evidence that Bt cotton reduced inequality in Makhathini Flats, Ismael et al. (2002b) concluded that "the per capita distribution of income from cotton in this area is about as unequal as the distribution of per capita incomes in the Western European countries" (p. 346).

In their latest publication, Bennett et al. (2006b) carefully assembled all available farm record and survey data, reviewing gross margin advantages by year and farm size. They conclude that while adoption is linked to slightly *larger* farm sizes in years 1 and 3, adoption is linked to *smaller* farm sizes in year 2. In all three seasons, adopters had gross margin advantages over non-adopters, but this was particularly the case in the wetter year, when the smallest producers growing less than one hectare of cotton fared the worst. They report data suggesting that the number of accidental pesticide poisoning cases has declined. While acknowledging that no

Table 3. Summary of methods applied in English/French language peer-reviewed articles about the economic impact of Bt cotton on farmers.

Country	Authors	Year published	Data type	Sample size	Sample unit	Survey year	Methods
Argentina	Qaim, M., and A. de Janvry	2003	statistical survey	299	farms	1999/2000-2000/01	farm survey analysis, contingent valuation and contingent behavior, data enrichment, combined stated and preferences, adoption model and WTP model
Argentina	Qaim, M., E. J. Cap, and A. de Janvry	2003	statistical survey, entomological and agroecological data for physiological model	299	farms	1999/2000-2000/01	farm survey analysis, other (insecticide use and insecticide reduction functions), damage control production function (IV insecticide use model), simulation of physiological model of resistance, brief
Argentina	Qaim, M., and A. de Janvry	2005	statistical survey, entomological and agroecological data for physiological model	299	farms	1999/2000-2000/01	farm survey analysis, other (insecticide use and insecticide reduction functions), damage control production function (IV insecticide use model), simulation of physiological model of resistance, benefits by farm size
China	Fan, C., J. Li, R. Hu, and C. Zhang	2002	statistical survey	1055	farmer	1999-2001	farm survey analysis
China	Fok, M., W. Liang, G. Wang, and Y. Wu	2005	statistical survey, key informant, government data	207	farmer	2003	farm survey analysis, review, institutional analysis
China	Huang, J., R. Hu, C. Fan, C. Pray, and S. Rozelle	2002	statistical survey, key informant	282; 407; 366	farmer	1999-2001	farm survey analysis, yield model, pesticide use model, IV estimation, 2SLS, Cobb-Douglas function, damage control function
China	Huang, J., R. Hu, Q. Wang, J. Keeley, and J. Falck-Zepeda	2002	statistical survey, key informant, trial data	282	farmer	2000	laboratory survey, farm survey analysis

China	Huang, J., R. Hu, S. Rozelle, F. Qiao, and C. Pray	2002	statistical survey, key informant, government data	282	farmer	1999	farm survey analysis, pesticide use model, IV estimation, damage control production function
China	Huang, J., R. Hu, C. Pray, F. Qiao, and S. Rozelle	2003	statistical survey	282	farmer	2000	farm survey analysis, multivariate pesticide use model (OLS)
China	Huang, J., R. Hu, C. Pray, and S. Rozelle	2005	statistical survey, field trials (rice)	337/45; 494/122; 542/179; 123/224	bt/non-bt plots per year, cotton; rice	1999-2001	farm survey analysis, yield pesticide use model, IV estimation, 2SLS, Cobb-Douglas function, damage control function
China	Kuosmanen, T., D. Pemsl, and J. Wesseler	2006	statistical survey, leaf tissue	150	farmer	2002	damage control production function (two-stage, semiparametric), interaction between pest exposure and damage control, plot monitoring, leaf tissue analysis
China	Pemsl, D., H. Waibell, and A. P. Gutierrez	2006	statistical survey, leaf tissue	150	farmer	2002	damage control production function, plot monitoring, leaf tissue analysis
China	Pray, C., D. Ma, J. Huang, and F. Qiao	2001	statistical survey, key informant	283	farmer	1999	farm survey analysis, economic surplus
China	Pray, C., J. Huang, R. Hu, and S. Rozelle	2002	statistical survey, key informant	282	farmer	1996-2001	farm survey analysis, institutional analysis, brief
China	Yang, P. Y., M. Iles, S. Yan, and F. Jolliffe	2005	statistical survey	92	farmer	2002	farm survey analysis
China, India	Russsell, D., and J.P. Deguine	2006	unknown	n/a	n/a	n/a	n/a
India	Bennett, R., Y. Ismael, U. Kambhampati, and S. Morse	2004	statistical survey	7751; 1580	plot	2002-2003	farm survey analysis
India	Bennett, R., Y. Ismael, S. Morse, and B. Shankar	2005	statistical survey	622	farmer	2003	farm survey analysis, multiple regression analysis
India	Bennett, R., U. Kambhampati, S. Morse, and Y. Ismael	2006	statistical survey	7751; 1580	plot	2002-2003	farm survey analysis, production function
India	Morse, S., R. Bennett, and Y. Ismael	2005	statistical survey	622	farmer	2003	farm survey analysis

India	Morse, S., R. Bennett, and Y. Ismael	2005	statistical survey	7751; 1580	plot	2002-2003	farm survey analysis
India	Naik, G.	2001	unknown	n/a	n/a	n/a	n/a
India	Naik, G., M. Qaim, A. Subramanian, and D. Zilberman	2005	statistical survey	341	farmer	2003	farm survey analysis, production function
India	Narayanamoorthy, A., and S. S. Kalamkar	2006	statistical survey	150, include 50 non-bt	farmer	2003	farm survey analysis
India	Orphal, J.	2005	sample from list of list of a Bt-seed sales list of Mahyco/ Monsanto Company	100	farmer	2002-2003	farm survey analysis
India	Pemsl, D., H. Waibel, and J. Orphal	2004	statistical survey, literature	100	farmer	2002	stochastic partial-budget
India	Qaim, M.	2003	sample from on-farm trials	157	farmer	2001	trial data analysis
India	Qaim, M., and D. Zilberman	2003	on-farm trials	157	farmer	2001	trial data analysis, yield-density function, logistic damage control function
India	Qaim, M., A. Subramanian, G. Naik, and D. Zilberman	2006	statistical survey	341	farmer	2003	farm survey analysis, production function
India	Sahai, S., and S. Rehman	2003	statistical survey	100	farmer	2002-2003	farm survey analysis
India	Sahai, S., and S. Rehman	2004	survey (possibly statistical)	136	farmer	2003-2004	farm survey analysis, key informant
Mexico	Traxler, G., S. Godoy-Avila, J. Falck-Zepeda, and J. J. Espinoza-Arellano	2003	statistical survey, key informant	152; 242	farmer	1997-1998	farm survey analysis, economic surplus, brief
Mexico	Traxler, G., and S. Godoy-Avila	2004	statistical survey, key informant	152; 242	farmer	1997-1998	farm survey analysis, economic surplus, small open economy, brief
South Africa	Bennett, R., T. Buthelezi, Y. Ismael, and S. Morse	2003	unclear	32	farmer	1997/98-2000/01	case study interview
South Africa	Bennett, R., Y. Ismael, S. Morse, and B. Shankar	2004	company data	1283; 441; 499	yearly farm records	1998/99-2000/01	farm record analysis, production function, Gini coefficient, Biocide index

South Africa	Bennett, R., S. Morse, and Y. Ismael	2006	unknown	1283; 441; 499; 32; 100	yearly farm records; farmer	unknown	farm record analysis, farm survey analysis, Gini coefficient
South Africa	Gouse, M., J. Kirsten, and L. Jenkins	2003	statistical survey	unclear	farmer	1999-2001	farm survey analysis, data envelope analysis, VMP curve
South Africa	Gouse, M., C. Pray, and D. Schimmelpfennig	2004	statistical survey, key informant	143 (100 smallholders; 43 large-scale)	farmer	1999/2000	farm survey analysis
South Africa	Gouse, M., J. Kirsten, B. Shankar, and C. Thirtle	2005	statistical survey, key informant	100	farmer	1998/99 - 2000-2004	farm survey analysis, stochastic production frontier, damage control production function, value of marginal product analysis, institutional analysis
South Africa	Hofs, J.-L., M. Fok, and M. Vaissayre	2006	statistical survey	20	farmer	2002-2004	farm survey analysis, plot monitoring
South Africa	Ismael, Y., L. Beyers, C. Thirtle, and J. Piesse	2002	statistical survey, key informant	100	farmer	1998/99-1999/2000	farm survey analysis, adoption model, stochastic production frontier, deterministic frontier programming model, Gini coefficient
South Africa	Ismael, Y., R. Bennett, and S. Morse	2002	statistical survey	100	farmer	1998/99-1999/2000	farm survey analysis
South Africa	Ismael, Y., R. Bennett, and S. Morse	2002	statistical survey	100	farmer	1998/99-1999/2000	farm survey analysis
South Africa	Kirsten, J., and M. Gouse	2003	key informant, field trials	not a sample	n/a	n/a	review, findings, institutional analysis
South Africa	Morse, S., R. Bennett, and Y. Ismael	2005	company data	1283; 441; 499	yearly farm records	1998/99-2000/01	farm record analysis
South Africa	Shankar, B., and C. Thirtle	2005	statistical survey	100	farmer	1999/2000	farm survey analysis, damage control production function, tests for endogeneity of pesticide use and Bt choice, model tests, value of marginal product analysis
South Africa	Thirtle, C., L. Beyers, Y. Ismael, and J. Piesse	2003	statistical survey, key informant	100	farmer	1998/99-1999/2000	farm survey analysis, adoption model, stochastic efficiency frontier

data or method is above criticism, they argue that the evidence is broadly consistent that the Bt cotton varieties have benefited the farmers of Makhathini Flats.

Although labor costs were not recorded in the data, authors hypothesized that the cost saving in labor was a major reason why farmers chose to grow Bt cotton. The duress of backspraying and collecting water for spraying, often accomplished by women and children, cannot be understated. This area is also hard-hit by HIV/AIDS. Kirsten and Gouse (2003) note that labor saved because of fewer pesticide applications could have been canceled out by the need for more harvesting labor with higher yields. In their most recent published work, Shankar and Thirtle (2005) conclude that Bt is not labor-saving in the case of smallholder farmers in South Africa.

Though the seven articles based on the same sample of 100 farmers represent a single case study, researchers have tested more subtle hypotheses over time with increasingly sophisticated econometric approaches. The initial approaches included deterministic frontier models (Ismael et al., 2002c), stochastic frontier models (Thirtle et al., 2003; Ismael et al., 2002b), and data envelope analysis (Gouse et al., 2003). Gouse et al. (2003) and Thirtle et al. (2003) found that Bt cotton growers, whether smallholders or large-scale farmers, were more technically efficient than growers of non-Bt cotton. Gouse et al. (2005) subsequently estimated a damage control model, which explicitly treats the fact that pesticides are not *output-enhancing* inputs but *damage-abating*, adding nothing to output if there are no pests.

In the most thorough analysis based on this same sample, Shankar and Thirtle (2005) estimated a damage control production function and explored the efficiency of pesticide use with the estimated value of the marginal product, also testing for sample selection bias and for the endogeneity of pesticide use[2]. They conclude that farmers do not apply pesticides in response to pests but in a pre-determined, prophylactic way.

An important conclusion drawn by Shankar and Thirtle (2005) is that adoption in Makhathini Flats is driven by supply rather than by demand. Shankar and Thirtle begin to assemble other pieces of the jigsaw puzzle in Makhathini Flats in a systematic way. Contrary to evidence from China and Argentina, where pesticides are over-used and the principal benefit to farmers is reduced pesticide use, pesticides are not heavily used. Yields are 600 kg/ha, as compared to 3,000 kg/ha in China. The damage control framework, unlike the approaches they previously applied (data envelope analysis, stochastic frontier), does reveal the productivity of pesticide use and that smallholders under-use pesticide with both Bt and non-Bt cotton relative to the economic optimum. Nonetheless, the yield effect is more important than damage abatement for smallholders in Makhathini Flats. The authors report the limitations they notice in their own work, mentioning the need for a household economics framework and analysis of the insurance function of Bt cotton.

Given supply-driven adoption, whether a new variety fails or succeeds is particularly sensitive to the organization of the marketing channel, a point underscored by Gouse et al. (2005). More than 90% of cotton farmers in Makhathini Flats grew Bt cotton in the 2001/02 growing season. The Vunisa Cotton Company supplied growers with inputs and credit, and bought the cotton they produced, also providing some extension advice. After a few seasons, farmers defaulted on loans from Vunisa by selling to a new gin, and in the following year, no seed or credit was supplied. Production declined in subsequent seasons. 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.

Given farmer vulnerability to 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) cautioned 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.

China

So far, the peer-reviewed, published literature suggests that China is the most successful case for Bt cotton in terms of sustained, positive effects on reduced pesticide use, crop income, health and environmental benefits, regional coverage, and sustainability since 1999 (Huang et al., 2002a, 2002b, 2002c, 2003, 2005; Pray et al., 2001, 2002). Still, other points of view add some complexity to the case regarding Bt effectiveness and regional variation in the benefits to farmers (Yang et al., 2005; Pemsl et al., 2006; Fok et al., 2005).

Huang and colleagues have implemented continuous, in-depth survey research. As in the case of Makhathini Flats, they have applied increasingly sophisticated statistical and econometric methods. Unlike the

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[2] *A problem of endogeneity would mean that the same factors that influence yield also influence whether or not the farmer chooses to apply pesticides, leading to biased regression coefficients.*

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 the Hebei and Shandong provinces, cultivating an average of 0.78 ha per household, of which 39% was planted with cotton. While Bt and non-Bt growers shared similar sociodemographic and farm characteristics, and yields did not differ significantly between the two groups, the difference in pesticide use was marked: five times higher in quantity and seven times the costs for non-Bt growers. The cost of production for Bt varieties was only 77-80% that of growing non-Bt varieties due to reduced pesticide and labor use. Returns to labor were more than twice as high for Bt growers, and net income was *positive*, while it was *negative* for non-Bt growers. The authors also reported some initial evidence that farmers perceived positive health effects from reduced pesticide use. The survey data suggested that pesticide use declined by an average of 47 kg/ha, which would imply a reduction of 15,000 tons in the regions studied.

Multivariate analysis of the first-year survey data, published in 2003 (Huang et al.), confirmed that Bt use reduced the use of pesticides, and particularly organophosphates, contributing to labor savings and more efficient production. The main benefit came from savings in pesticide expenditures and labor, since the yields of major Bt and non-Bt varieties were statistically "indistinguishable" (2003: 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 all Bt cotton varieties, including those introduced by foreign life science companies and those bred by China's research system, to be "equally effective."

Huang et al. (2002c) then estimated a damage-control production function, also recognizing that farmers chose pesticide levels in response to pest pressures by implementing an instrumental-variables model, specifying interactions between use of Bt and use of pesticides. Findings regarding effects of Bt cotton use on efficiency and reduced use of pesticides were substantiated in this article. Still, they were based on only one year of survey data. Next, they expanded the sample coverage. Huang et al. (2002b) developed their most complete analysis, with three years of survey data and expanded sample coverage, a damage control production function, and an attempt to correct for the potential bias from endogeneity of pesticide use and farmers' decision to grow Bt cotton varieties. Applying more advanced methods, they conclude that growing Bt cotton varieties 1) has a positive effect on crop yield and not just damage abatement; 2) reduces yield losses through abated damage; 3) abates *only* damage with pesticide use on non-Bt cotton varieties 4) has benefits that vary across provinces, and are lowest in Henan and Jiangsu; and 5) does not lessen farmers' overuse of pesticides.

The first conclusion reflects the fact that when comparisons are made without the use of isogenic lines, observed yield advantages are the outcome of the effectiveness of the trait, the genotype, management, environment, and interactions among all of these factors. Trade-offs in yield potential and resistance levels among non-Bt cotton varieties, combined with the variety choices farmers make and their management practices, provide possible explanations for their results. The authors note that farmers generally grow non-Bt varieties that are resistant, but lower in yield. Higher yielding, more susceptible, non-Bt varieties are grown in minor areas. On the other hand, once Bt substitutes for other mechanisms of genetic resistance, it is likely that farmers choose to grow the highest-yielding Bt varieties. Breeders are also likely to have inserted the gene into higher-yielding, susceptible varieties. Finally, farmers who choose to grow Bt varieties may also be those who attain higher average yields.

Which factors have contributed to the success of Bt cotton in China? Some outsiders have argued that China's success reflects heavier government control of production, seed supply, and marketing systems, but Huang and colleagues highlight two other major considerations. First, China is most likely the largest pesticide user in the world and cotton producers have used pesticides most intensively. Estimated damage control functions demonstrate that Chinese farmers tend to over-use pesticides, while observation reveals that they do not protect themselves (Huang et al., 2002c). Thus, the health benefits and reduced costs of Bt cotton are readily observable to farmers. Second, in China, the public research program had the capacity to develop and disseminate transgenic insect-resistant cotton varieties (Pray et al., 2002), so that technology fees were not imposed by Monsanto, dependence on external supplies was lessened, and seed prices were more competitive. The Beijing-based Biotechnology Research Institute of the Chinese Academy of Agricultural Sciences (CAAS) obtained patent, plant variety, and trademark protection in China for its Bt cotton. The original transgenic lines were sub-licensed to provincial seed companies and transgenes were backcrossed into more than 22 locally-adapted varieties (Toenniessen et al., 2003).

Other articles confirm that continued investment in Bt research is necessary, along with efforts to better disseminate information to 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, recommending farmer training in integrated pest management (IPM) and basic ecology to ensure sustainable production. In the Shandong province, for the 2002 cropping season only, Pemsl et al. (2006) employed a damage control framework, estimated simultaneously with an insecticide use function. Bt concentration, measured by sampling leaves, was employed as a much more precise indicator than a zero-one variable for growing a Bt variety. Their results confirmed that Bt growers also overuse pesticides, but they also found that neither insecticide use nor Bt use reduced damage from bollworm. They caution that problems such as measurement errors in recording pesticide use and monitoring response, varying control effectiveness under farmers' conditions, and lack of farmer knowledge, imply that the benefits of Bt cotton in China and in other developing countries could be lower than argued elsewhere.

Fok et al. (2005) combined a detailed review of farm-level profitability in other studies with an in-depth treatment of the institutional and epidemiological context of Bt cotton production in China. They affirm the success of Bt cotton in the Yellow River region of China where resistance to insecticides had evolved and farmers applied 10 to 12 treatments, as compared to 2 to 4 in most countries. However, they cite evidence to the contrary in the Yangtze river valley (Jiangsu) and other provinces, where pest pressures are lower and the germplasm is not as well adapted. They highlight the importance of a number of institutional factors, such as 1) the decentralization of breeding efforts in China, leading to the "enviable wealth of cotton varieties," 2) the low seed costs for both the newly released cotton hybrids and varieties, 3) the competitive nature of the seed market, and 4) despite the elimination of support prices and subsidies, an effective price premium due to import controls in the domestic cotton industry.

The remarkable aspect of Bt cotton commercialization, noted by Fok et al. (2005) in connection with the China case, is not the seed price per se, but rather, the technology fee, as well as the "rules of the game" adopted to protect business interests through contracts with growers. Under the rules that are most conducive to protecting intellectual property rights and a company's market, farmers must pay a technology fee (initially separate, but now embedded in the seed price) and engage in a contractual arrangement that binds them to refrain from planting farm-saved seed and requires them to establish refuges. In China, the seed price (including the technology fee) is lower than in other countries because of competition from public sector breeding programs, an inability to protect intellectual property, and limited capacity to enforce contracts. At the same time, Fok et al. noted that the presence of the US companies stimulated positive change in an anachronistic, state-controlled seed system. When seed was publicly provided by the same organization that bought the product, farmers did not appreciate the difference between seed and grain. Now, they appreciate the guarantee of seed quality, packaging, and instructions that accompanies a more competitive seed market.

India

Studies conducted in India illustrate several points of major importance for measuring farm-level impact. The first, as with any new crop variety, is that the more heterogeneous the growing environment, pest pressures, farmer practices, and social context, the more variable the benefits are likely to be. This "truism" holds for any new crop variety, no matter how widely-adapted. Cotton is grown in most of India's agro-ecological zones on approximately 9 million hectares distributed in just over nine states. Sixty percent of this area is rain-fed. 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 point, 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 varieties in both irrigated and non-irrigated cotton in Karnataka. As in their China study, Pemsl et al. (2006) they argue that the high expectations placed on Bt cotton may not be met from an economic point of view: "Bt cotton is not a new green revolution variety but simply another option of bollworm control" (p. 1256). Hence, the economics of Bt cotton are determined by the severity of pressure by lepidopteran insects. Another study in the state of Karnataka found that for 100 farmers sampled, Bt cotton growers used lower numbers of pesticide applications than non-Bt cotton farmers, but the promise of higher yields was only realized for irrigated farms (Orphal, 2005). Local varieties appear to perform better than Bt hybrids under rain-fed conditions.

Narayamamoorthy and Kalamkar (2006) collected data for the 2003 rainy season in two districts in the

Vidarbha region of Maharashtra, targeting their analysis to pairwise yield comparisons of two Bt and non-Bt hybrids (MECH 162 and MECH 184 for Bt; Bunny 145 and Ankur 651 for *non*-Bt) under irrigated conditions. They found that yield advantages differed for the same hybrid by region and within regions, by hybrid.

Bennett et al. (2004) and Morse et al. (2005b) analyzed farm survey data for over 9,000 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. (2006b) 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.

A second point is unique to the India case relative to other cases. Given the context of agro-ecological and social heterogeneity, an active civil society that is vocal *for* and *against* GM seed has polarized perspectives. Polarization is evident even in the peer-reviewed literature. Perhaps more significantly, the debate in civil society is carried into government decision-making fora. Thus, methods limitations, which commonly occur in any applied economics research, take on particular significance.

For example, data from Mahyco-Monsanto Biotech Ltd. 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 80-87% yield advantages (Qaim, 2003; Qaim & Zilberman, 2003). Generally, trial data is not considered to be representative of farmers' conditions, though budgets based on trial data can be adjusted in order to provide greater insights. Qaim (2003) acknowledges these limitations. Aranachalam and Ravi (2003) and Sahai and Rehman (2003) were among the first critics of Qaim's results. Aranachalam and Ravi 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.

Sahai and Rehman (2003) conducted a random sample survey for the first cotton season after the commercial release of the Bt hybrids in 2002, reporting that the only advantage they found for Bt cotton was a shorter growing period and that Bt cotton was more costly to produce. Losses were reported for some farms, and they state that 98% of farmers had no interest in growing Bt cotton again. Sample sizes were small (25 farmers in Maharashtra and 75 in Andhra Pradesh), and details of the sampling method were not presented. In 2004, the same authors implemented another survey in four districts of Andhra Pradesh, reporting economic losses for 60% of farmers growing Monsanto Bt cotton hybrids. To the discredit of the Qaim and Zilberman study, they argued that farmers sought unapproved Bt variants and good local hybrids because these outperformed the Monsanto hybrids.

In contrast, Barwale et al. (2004) reported the advantages of the MMB hybrids over non-Bt cotton, including higher yields, higher profits, and lower application of pesticide. The survey of 1,069 farmers was implemented by Mahyco in the six states where Bt cotton seed was sold in the 2002 season. Methods for selecting farmers were not elaborated in the article. Economic "profits" were based on imputed prices rather than actual survey data

In a three-year study in Andhra Pradesh, Qayum and Sakkhari (2005) found that Mahyco-Monsanto Bt cotton was inferior to non-Bt cotton in terms of yields, pesticide use was negligible for both types of cotton, non-Bt farmers had higher profits and lower costs of cultivation, and suspected Bt cotton of a root rot that affected their soils for subsequent crops. The Deccan Development Society, which implemented the study, used a number of research approaches, but the sampling methods were not detailed and the report was not published in a peer-reviewed journal. We mention the study in our discussion (but not in our search count) because it has been so widely publicized and has generated controversy.

A third theme that recurs in the studies is the importance of host germplasm, given Bt effectiveness. 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 & Ravi, 2003; Sahai & 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) influenced farm level benefits. They also reported circumstantial evidence that black market sales of unapproved cultivars and sales of F2 seed at lower prices explain *some* crop losses.

Two final points concern marketing arrangements, and these arrangements are again unique to the country of study. India's cotton seed industry, like the seed industry in general, is liberalized and dynamic. Today southern India is the only area in the world where cotton production is based on hybrids. India is also the only country that has commercialized hybrid Bt cotton varieties. Both cotton hybrids and improved cotton varieties are grown by farmers; the private sector produces hybrids, and the public sector has bred both. To date, approval for commercialization has been granted to a total of 40 Bt cotton hybrid varieties developed by 13 seed companies (APCoAB, 2006). There are also a large number of non-approved Bt cotton hybrids in the market in western states (Murugkur et al., 2005; Jayaraman, 2004).

The impressive array of materials is accompanied by a proliferation of seed brands at points-of-sale, including "flawed or mislabeled products" or identical seeds sold under different brand names. The number of input shops Stone (in press) counted in Warangal city alone was 190. His survey of 37 shops revealed that they sold 125 different cotton brands from 51 companies in a three-year period. Of the 78 types of seeds sold in the 2005 season, only 24 had been around since 2003. Monitoring at points-of-sale may be a policy consideration in liberalized seed systems.

Related to this asymmetry of information regarding seed is the fact that channels for obtaining information about practices, fertilizers, and pesticides, as well as the credit to finance production, are often separated (as compared to other vertically integrated systems) for Indian farmers. This means that the farmer not only earns the benefits in good years with higher prices, but is also heavily exposed to financial risk.

Mexico

Mexico provides an example of "farming by formula," or a form of contract farming for Bt cotton. There, the strength of the institutional arrangements for delivering Bt technology and marketing cotton, combined with Bt effectiveness, solved a major production problem for farmers in the Comarca Lagunera region of the Durango and Coahuila states. Bt is effective against the major pest threats, pink bollworm and tobacco budworm, a spectrum of the pest population that is not economically significant in other Mexican states (Traxler & Godoy-Avila, 2004; Traxler et al., 2003). Given this situation, a moderate-sized sample served as the representative basis of the authors' analysis of industry impact using an economic surplus model.

Intellectual property rights (IPR) were strictly enforced, as in the US. To protect their revenue, Monsanto established contracts with farmers and gin owners. Farmers who desired access to the Bt cotton technology were obligated to forfeit the right to save seed and to have cotton ginned only where "authorized." In their contracts, farmers specify the total area to be planted and Monsanto spot checked cotton fields for compliance. Gins are given the opportunity to be authorized (and hence, become monopsonists) by agreeing to refrain from selling Bt seed obtained in the ginning process. Contracts with the innovators Monsanto/Deltapine where drawn to protect IPR, but also with private sector credit agencies, banks, and large cooperatives to gain access to credit. These contracts delineated the terms for technical assistance to be provided by the credit agencies themselves, production processes, as product marketing.

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. In contrast with the smallholder farmers of South Africa, China, and India, Bt cotton adopters in Argentina farm an average of more than 400 ha of cotton on farms greater than 1000 ha; they are representative of the medium and large-scale farmers running family businesses that typically employ one or more permanent workers (Qaim & 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 & Cap, 2004; Qaim & de Janvry, 2003). Technology fees were imposed and seed was sold at \$103/ha by a sole supplier. The authors point out that this price was equivalent to a technology premium of \$78, approximately the same as what US farmers had 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 (ibid).

Methods applied in the Argentina case are exemplary from the standpoint of disciplinary excellence. Qaim and de Janvry used a combined stated and revealed preference approach to estimate farmers' willingness-to-pay for Bt seed. By constructing farmer demand functions for seed and profit functions for the supplier, they showed that both farmers and monopoly suppliers 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 & de Janvry 2005) use a damage control framework to estimate the effectiveness of Bt use and to 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 pest system calibrated with entomological data from Argentina, drawing implications for the size of Bt refuge areas needed to ensure the durability of farm level benefits.

Conclusions

The most obvious limitation with the evidence so far is simply the brevity of the time period considered. The effects of seed technical change in farming communities is difficult to establish both because of the direction of causality and subsequent, indirect effects that occur with the passage of time.[3] A second is the small number of different authors publishing case studies in peer-reviewed, international journals. A third is related to methodological problems, although it is important to recognize that no method is perfect, and typically, multiple methods will be needed to generate a fuller analysis of impact.

Partial budgets are deceptively simple, when in fact, considerable care must be used to construct them (CIMMYT, 1988; Murugkar et al., 2005). There are at least six major limitations associated with their use in these studies. First, in many of the studies, only gross margins are reported. Gross margins include the costs of intermediate inputs but ignore the use of labor and land. Net margins include these costs.

Second, when farmers are not fully commercialized and operate in situations with market imperfections, the price of labor that influences their decisions is endogenously determined and household-specific. Hence, though cotton markets may function well where labor markets are imperfect, as in most developing economies, the relevant price of labor is not the market price.

Third, partial budgets are “partial” because they treat only one farm activity at a time. Even where farmers are fully commercialized, the net impact on whole-farm production, factors of production, income, or well-being cannot be deduced. No studies have yet been published about the impacts of Bt cotton on wider dimensions of farmer income-generation and vulnerability.

Fourth, 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, such factors create a bias due to program placement and program participation (often referred to as “selection bias”).

Fifth, 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. In all of the cases analyzed, one, the other, or both problems are apparent.

Recognizing the temporal limitations of survey data, and the inherent uncertainty of yields and prices in agriculture at the time that farmers make seed choices, some researchers have used stochastic simulation to generate a statistical distribution of crop incomes. Concern for the limitations of partial budget analysis led a number of authors to apply more sophisticated econometric methods; yet, generally speaking, the econometric analyses are only as good as the survey data that underpins them.

To overcome the limitations of small sample sizes and selection bias, some authors have used farm records for different plots cultivated by the same farmers. This approach is not feasible where farmers adopt completely, and plot-wise analysis gives a very incomplete picture of whole-farm or farm family effects. Later arti-

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[3] *For example, a first round of studies on the effects of the Green Revolution in Asia found increasing inequality of assets and income distributions (Griffin, 1974). Second-generation studies of the effects of the Green Revolution in Asia concluded that, at least in the more favorable production areas, absolute poverty declined when food price effects and indirect linkages to the rural non-farm economy were taken into account (Mellor & Johnston, 1989; Hazell & Ramaswamy, 1991; Lipton & Longhurst, 1989; Pinstrup-Andersen, 1979). One stylized fact of the Green Revolution that it is most often the underlying social structure that predetermines much of the social impact of technology adoption.*

cles tend to address the representativeness of findings, and the study by Shankar and Thirtle (2005) is the most thorough we have seen in its consideration of selection bias. Econometric analysis of this topic presents statistical challenges because of the possible endogeneity of both pesticide use and Bt choice.

Use of damage control production functions in later analyses is a major improvement, since these recognize that pesticides are a *damage abatement* rather than *productivity-enhancing* input. Perhaps the most daunting task is to improve our understanding of the interactions of pest populations and traits, especially as problems with secondary pest resistance emerge. Several authors have insisted on the importance of monitoring practices daily, in order to develop a more realistic picture of the full range of biotic pressures (several bollworms, sucking insects, and other fungal diseases).

For these methodological reasons, the overall balance sheet, though promising, is mixed. Economic returns are highly variable over years, farm type, and geographical location. They depend on initial practices, pest infestations, seed costs, and other attributes of farmers and farm production. Thus, findings cannot be generalized. One hypothesis emerges strongly from the cross-case comparison of studies: institutional and marketing arrangements for supplying the technology and marketing the product may be the single most important determinant of Bt impact at the farm-level, even when the trait is shown to be effective.

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