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Can GM-Technologies Help the Poor? The Impact of Bt Cotton in Makhathini Flats, KwaZulu-Natal

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Summary. — The results of a two-year survey of smallholders in Makhathini Flats, KwaZulu-Natal show that farmers who adopted Bt cotton in 1999–2000 benefited according to all the measures used. Higher yields and lower chemical costs outweighed higher seed costs, giving higher gross margins. These measures showed negative benefits in 1998–99, which conflicts with continued adoption, but stochastic efficiency frontier estimation, which takes account of the labor saved, showed that adopters averaged 88% efficiency, as compared with 66% for the nonadopters. In 1999–2000, when late rains lowered yields, the gap widened to 74% for adopters and 48% for nonadopters.

Key words — KwaZulu-Natal, South Africa, Bt cotton, stochastic frontiers, efficiency

1. INTRODUCTION

Although there has been an adverse reaction to genetically modified (GM) plants in Europe and some developing countries, others, particularly China and South Africa, have followed the United States in rapidly adopting GM technologies. For Bt cotton, there is now evidence from China (Pray, Ma, Huang, & Qiao, 2001) and Mexico (Traxler, Godoy-Avila, Falck-Zepeda, & Espinoza-Arellano, 2002) of increased profits and positive impacts on the environment and health, due to reduced pesticide use. This study, based on a sample survey and farm records, investigates the farm-level impacts of the first use of Bt cotton by African smallholders.

Section 2 of this paper provides some background on GM crops, especially in South Africa and on Bt cotton, particularly in Makhathini Flats. Section 3 analyzes the sample of 100 farmers, in order to give a broad

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overview of the characteristics of the smallholders, but specifically concentrating on identifying the innate differences between adopters and nonadopters. Section 4 begins by reporting an adoption model, which is followed by farm accounting results, comparing yields, input levels, costs and gross margins of the adopters and nonadopters. A first major contribution of this paper is that with data for two seasons, the effects of the technology can be separated from the innate differences between adopters and nonadopters, so that the comparisons are not biased. But, both yields and gross margins are partial measures of efficiency, which fail to take account of major inputs such as labor. The second main contribution is efficiency measurement using stochastic efficiency frontiers. These model the efficiency with which all inputs are converted into outputs, using only the more reliable input and output quantity data and avoiding prices since there are none for land or family labor. The final part of this section notes that there are also social benefits, which are environmental and health improvements, and the final section offers concluding comments.

2. PROGRESS WITH GM CROPS

In 2001, the leading countries, by GM area planted, were the United States, Argentina, Canada, China, South Africa and Australia, with the first three accounting for 96% of the area (James, 2002). More than 85% of GM crops were bred for tolerance of specific herbicides and insecticides, but almost all the rest are insect-resistant corn (maize) and cotton. These crops contain the genes controlling the production of a natural insecticide, *Bacillus thuringiensis* (Bt), which acts specifically on Lepidoptera, including bollworm in cotton and stem borers in maize, and is harmless to all other insects.

A survey by Marra (2001) shows that the vast majority of GM crop studies have been conducted in the United States, typically using trial plot data from the biotechnology industry. Most studies of the performance of GM crops show increased yields and lower levels of labor and pesticide use (Fernandez-Cornejo & Klotz-Ingram, 1998; Gianessi & Carpenter, 1999). Fernandez-Cornejo, Klotz-Ingram, Jans, and McBride (1999) report that for cotton specifically, better quality and hence higher producer prices are a further benefit. The more analytical studies, such as Falck-Zepeda, Traxler, and Nelson (2000) apply economic surplus measures to determine the beneficiaries of GM crops, but again most are for the United States. The only application of an efficiency frontier is a data envelopment analysis of cotton in Georgia, United States, by Ward, Flanders, Isengildina, and White (2002). Much of the developing country literature is *ex-ante* studies, such as Qaim (2000), since data are only recently becoming available.

(a) *GM crops in South Africa*

South Africa is the only country in the African continent where GM crops have been commercially released. The GMO Act of 1997 approved the importation and use of GM seeds and the establishment of the institutions required for evaluation. Although there have been hundreds of crop trials, only herbicide-tolerant soybeans and cotton and Bt maize and cotton have gained commercial approval. Approximately 3,000 ha of Bt maize were planted in 1998 (James, 1999), rising to 50,000 ha in 1999 (Thompson, 1999). This yellow maize is grown by the commercial farmers and accounts for about 4% of the total crop. It is used for animal feed, cornstarch and corn syrup. Bt white maize, which is the staple diet of the African smallholders, was not released until 2001 and data are only now becoming available, but data for smallholder cotton were collected in 2000.

Cotton accounts for only about 1% of total South African agricultural production, generating approximately US$50 million annually (Kock, 2000). About two-thirds is grown under dry-land conditions, with 1,530 commercial farmers, mostly in Limpopo Province, but also in the Free State and KwaZulu-Natal, producing over 90% of the output. There were 100,000 ha grown in 1998–99, but the area was then reduced by about 50%, due to low world prices. We now turn to smallholder production, which is increasing.

(b) *Cotton in Makhathini Flats*

There are approximately 3,000 Zulu smallholders growing cotton in Makhathini Flats and about another 500 in Tonga, in Mpumalanga. Together, they account for nearly 98% of the smallholder cotton grown in South Africa (Hofs & Kirsten, 2002). By 2000–01, 3,000 ha of cotton were grown in Makhathini, producing 1,000 tons of lint, and 850 ha in Tonga, accounting for 300 tons of lint. Thus, almost 70% of smallholder cotton is grown in Makhathini. Compared with the rest of Africa, South Africa has a very low percentage of smallholder cotton producers, largely due to the reluctance of the pre-1994 government to promote commercial agriculture in the black communities. Makhathini Flats was a special case, however, as it was a large smallholder development scheme that was something of a show-piece for the international community (Hofs & Kirsten, 2002). As a result, the Makhathini Flats Scheme has an experimental farm and an extension service that is far better than in other areas and this must be taken into account when considering the wider applicability of the results.

Since 1998, smallholders in Makhathini Flats, which is one of the lower potential cotton areas of South Africa, have been adopting a GM cottonseed variety, NuCOTN 37-B with Bollgard™. A Monsanto report (Bennett, 2002) shows that in 1998–99, there were 75 adopters, growing less than 200 ha of Bt cotton. In 1999–2000, this rose to 411 adopters with a little under 700 ha, and in 2000–01, to 1,184 adopters with about 1,900 ha. Thus, in only three years, 40% of the producers, representing almost two-thirds of the area planted, have adopted the new technology and preliminary results show that by 2001–02 over 90% had adopted Bt varieties.

Figure 1 summarizes the structure of production in Makhathini Flats. Monsanto owns the Bt gene, used by Delta Pineland in developing NuCOTN 37-B. The figure shows that several non-GM varieties are also available and in 2001–02 a further Delta Pineland GM variety called Opel was introduced. VUNISA Cotton is a private company that is the sole supplier of seed, chemicals and support services for the farmers through their extension officers, including credit for land preparation, chemicals and seed, based on their credit history. VUNISA buys cotton from the farmers at prices fixed by Cotton South Africa, but now has to compete with Danish-owned NSK, which has opened a cotton gin. Thus, VUNISA has already lost its monopsony power and given the success of Bt cotton in the area, is unlikely to maintain its monopoly of input supplies in this contestable market. The farmers also belong to

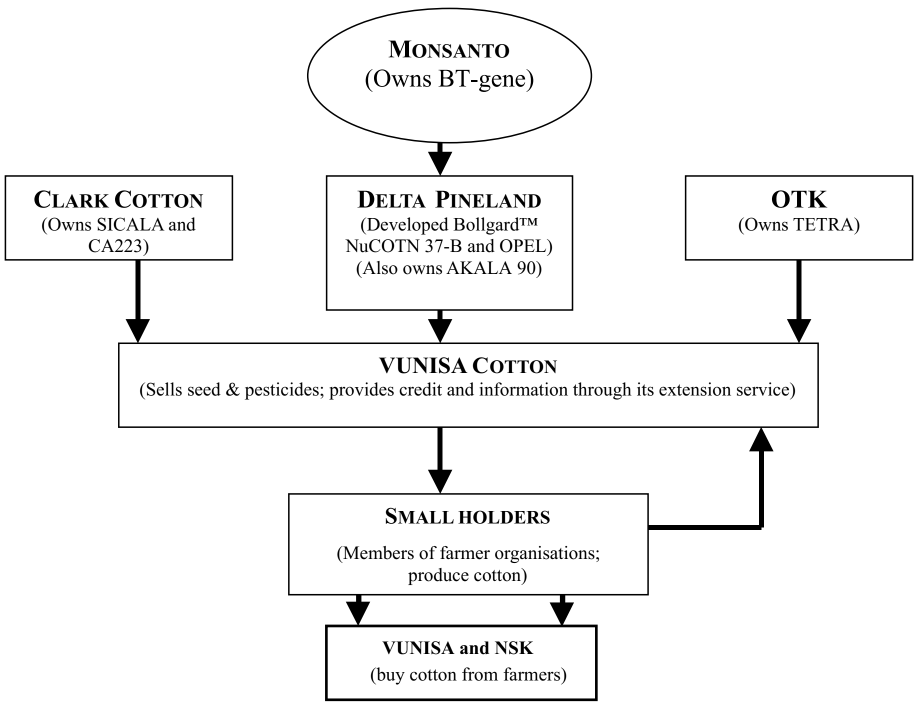

Figure 1. *Organizational structure of cotton production in the Makhathini Flats.*

farming associations, which provide essential support and information through organized meetings where farmers can discuss mutual concerns and problems.

3. THE MAKHATHINI FLATS SURVEY

Apart from the Makhathini Flats Scheme, the area is fairly typical of smallholder farming. The smallholders are all Zulus and there are no large commercial producers. The households cultivate land allocated to them by their tribal chiefs, so landholders face uncertain tenure arrangements, without guaranteed ownership succession within the family. Good quality cropping land is scarce, unfenced, and under threat from livestock that can devastate crops due to the communal grazing systems. Labor is also a problem in the rural areas, since male migration to the towns leaves a predominance of females, the elderly and children, a demographic pattern that can influence the types of technology that farmers will readily adopt.

The survey was conducted in November 2000, by the Universities of Pretoria and Reading, with the collaboration of Monsanto, VUNISA, Cotton SA and Innovation Biotechnology. Personal interviews were conducted with heads of households, using a questionnaire that covered household background, farming practices and problems, the reasons for adopting Bt cotton and input costs and returns. The information was combined with data from the farm records. The sample covered the 1998–99 season, when only 2.5% had adopted the Bt variety and 1999–2000, when adoption was still only 14%, so a random sample would have contained too few adopters. To give a sufficient number of adopters, 60 Bt cotton growers and 40 non-Bt producers were selected. Even so, of the 60 1999–2000 adopters, only 18 grew Bt cotton in the 1998 season.

The objectives of the research were to account for Bt cotton adoption, measure the economic performance of the Bt technology relative to the alternatives and assess the environmental, health and income distribution effects. If the Bt variety generates a yield advantage, the extra revenue, plus the savings on chemicals and labor, needs to be greater than the extra cost of the Bt seed for the new technology to result in an economic advantage. If fewer chemicals are used, there should also be less pollution and fewer health hazards.

(a) *Cotton production*

On the small plots, mixed cropping is common, with an assortment of maize, beans and vegetables, grown for subsistence, and cotton, which is usually the only cash crop. Only 10% of farmers grew a crop other than cotton for sale, and only 8% used any form of crop rotation. All the farmers had cultivated 1–25 ha of cotton, planted following the rains, between September and January. Harvesting is from April to June, some 5–7 months after planting.

Two-thirds of the farmers reported growing cotton because they needed cash income and the most common reason given by the remaining third was that their land was particularly suited to cotton. A minority said that the main reason was simply the ready market provided by VUNISA. The dominant cotton variety in the first season was Akala 90, which is not GM, grown by 47% of the farmers sampled. The 18% growing Bt cotton were the next largest group, although this reflects the deliberate bias of the sample. In the second season, Akala 90 remained the dominant non-Bt variety, grown by 23% of the farmers. None of the first-year adopters discontinued the Bt cotton in the second year, which indicates that the adopters were satisfied with the results. The adoption of Bt cotton slightly increased quality and hence the prices paid. Of the full sample of 100, 86% produced good or high quality cotton, with 80% of the nonadopters and 90% of the adopters in these categories.

(b) *Characteristics of the smallholders and adoption*

The survey results provide information on the differences between the 40 farmers who did not adopt Bt cotton in either season, the 18 who adopted in the first year and the 42 who adopted in the second year. This matters, because the expectation is that the better farmers, with more resources, tend to be the early adopters and innate differences, such as experience and farm size, must be taken into account in evaluating the effects of the new technology. Table 1 first reports the gender of the head of the household, showing that 42% were female and 58% male. The next three columns differentiate between nonadopters, first-year adopters and second-year adopters. For the female-headed households, 45% were nonadopters, 12% adopted in the first year and 43% in the second year. For male-headed households, 36% were nonadop-

Table 1. *Characteristics of the farmers sampled*

Sample size		Total (%)	Nonadopters (%)	First-year adopters (%)	Second-year adopters (%)
Variable	Class				
Gender	Female	42	45	12	43
	Male	58	36	22	41
Age group	20–29	8	75	0	25
	30–39	16	44	25	31
	40–49	38	34	16	50
	50–older	38	37	21	42
Year of farming experience	0–5 years	37	59	11	30
	6–10 years	23	30	22	48
	11–15 years	28	25	25	50
	More than 16 years	12	33	17	50

ters, 22% adopted in the first year and 41% in the second year. In the first season, selected farmers were offered the Bt seed when they visited VUNISA and most of these were male. But having seen the effects of the Bt variety, the women were more successful in acquiring Bt seed in the second year.

The next section categorizes the sample into four age groups, showing that 76% of the farmers were over 40 years old. Of the youngest farmers, who tend to be resource-poor, 75% were nonadopters overall and none adopted in the first season. The older groups have a much higher percentage of adopters over the two seasons, suggesting that the more established farmers were regarded as better credit risks by VUNISA. Age and experience are normally positively correlated and the last section of the table shows that a lower proportion of the least experienced farmers were adopters.

(c) *Agricultural inputs and nonagronomic constraints to cotton production*

The first section of Table 2 categorizes the sample by farm size, showing that over 60% of the farmers owned less than five hectares of land, with the largest concentration, 37%, in the 2.5–5 ha group. Almost 50% of the farmers with less than five hectares failed to adopt, compared with 26% of those with more land. VUNISA appears to have favored the larger farmers, especially in the first year, where there is a positive correlation between farm size and

Table 2. *Agricultural inputs and nonagronomic constraints*[a]

Variable	Class	Total (%)	Nonadopters (%)	First-year adopters (%)	Second-year adopters (%)
Farm size	Less than 2.5 ha	25	48	8	44
	2.5–5 ha	37	49	19	32
	5–10 ha	23	30	22	48
	More than 10 ha	15	20	27	53
Livestock ownership	No	27	41	19	41
	Yes	73	40	18	42
Labor per hectare	Average, males	0.41	0.44	0.41	0.38
	Average, females	0.42	0.41	0.32	0.48
Production constraints	Lack of credit	64	41	23	36
	Land shortage	11	27	0	73
	Labor shortage	3	33	0	67
	Damage by animals	7	29	0	71
	No answer	15	–	–	–

[a] The labor variable is the average number of male and female laborers per hectare in the households, not percentages.

adoption, although in the second year, the smaller farmers do better.

The next section of Table 2 deals with livestock ownership, showing that 73% of households owned livestock (the household average was 13 cattle, 12 goats and 23 chickens). In most of southern Africa, livestock are a store of wealth. This may aid adoption, as livestock are a source of income and manure as well as traction, without which ploughing is not possible. Table 2 shows however that ownership of cattle was not a factor in Makathini Flats, where tractor services have replaced draught power and manure is a minor issue. The main interaction between animal and crop production is damage to crops by wandering animals.

The next section reports the availability of family labor, which is supplemented by hired labor when needed. In this study, family labor is defined as those on the farm who are 15 years old or more and not at school. But, children under 15 often help with on the farm, undertaking activities such as planting, weeding and harvesting. Weeding especially is a family labor task, whereas nonfamily labor is hired for specific activities. All the farmers hire a tractor and driver for ploughing, at a cost of 350 Rand (about $35 at that time) per hectare and most farmers hire labor for harvesting. Some of the small farmers also hire someone to spray their cotton, as they cannot afford knapsack sprayers. The labor variable used later is family labor plus the days of hired labor for harvesting and spraying. Ploughing was excluded from the analysis, as this is a common per hectare cost for all households.

Average family labor for the full sample was 1.88 females and 1.91 males per household, but Table 2 shows labor per hectare, since labor scarcity is relative to land and this may lead to adoption of this labor saving technology. The differences are not great, but the first-year adopters do have less of both male and female labor than the nonadopters. The second-year adopters have the least male and the most female labor per hectare, which may affect adoption since spraying is normally done by men.

The last section of the table reports the constraints to increasing output, as perceived by the farmers. Two-thirds cited lack of credit as the main constraint and 41% of these were nonadopters. VUNISA grants credit according to previous repayment history. Those who have repaid over 90% of their loans can get credit for land preparation and hiring labor for spraying and harvesting, in addition to that needed for seeds and chemicals. Those who have repaid less than 75% can get credit only for seeds and chemicals. Only 11% thought that lack of land was their biggest problem and, not surprisingly, none of these were the first-year adopters, with the largest farms. Only 3% ranked labor scarcity as the main problem, so it rates lower than damage by animals.

Although farmers always tend to complain about lack of credit, the first section of Table 3

Table 3. *Household income and credit*

Variable	Class	Total (%)	Nonadopters (%)	First-year adopters (%)	Second-year adopters (%)
Nonfarm income	No nonfarm income	75	45	19	36
	Nonfarm income	25	24	16	60
Source of farming credit	Family	2	50	0	50
	Other	2	0	50	50
	Stokvel (group) schemes	2	100	0	0
	Savings	8	25	0	75
	Vunisa	63	48	19	33
	Vunisa and Family	3	100	0	0
	Vunisa and savings	19	11	21	68
	No response	1	0	100	0
Source of credit for seeds	Credit	63	43	22	35
	Savings	32	31	6	63
	No response	5	60	40	0

supports the claim that credit is a constraint. Of the three-quarters of the farmers without nonfarm income, which is a substitute for credit, 45% did not adopt, whereas only 24% of those with nonfarm income were nonadopters and 60% of this group adopted in the second year. The next section shows that two-thirds depended on VUNISA alone for credit to buy seed and pesticides. Another 19% used VUNISA plus savings and the remainder relied on unspecified savings, group saving schemes and/or family credit. Therefore, all but one of the farmers reported some source of credit, but the majority complained it was inadequate. Last, for seed purchases, two-thirds relied on credit alone, but 43% did not adopt, as compared with 31% of the farmers who had savings and two-thirds of this group were able to adopt in the second year.

(d) *Agronomic constraints to cotton production*

Table 4 shows that 57% of the farmers rated pests as the dominant agronomic problem in the area, with 24% ranking too much rain first and 11% finding weeds to be the biggest problem. Only 8% were more worried by droughts, floods, soil quality and plant diseases. However, the survey was conducted in November 2000, after a season when planting was delayed by unusually heavy late rains, so the importance of too much rain may be overstated. Particularly, 50% of those who regarded rain as the main problem did not adopt, partly due to the bad weather.

The major pests in the region are bollworms, cotton aphids and jassids, or leafhoppers. Red bollworm (*Diparopsis castenea*) and Spiny bollworm (*Earias biplaga*, *Earias insulana*) are the two species that cause the most damage. Their mature larvae reduce yields by feeding on developing buds, squares, flowers and cotton bolls. Cotton aphids (*Aphis gossypii*) and jassids (*Jacobellia fasciallis*) feed on the plant sap, again reducing yields. The lower section of Table 4 shows that 58% of the farmers regarded the bollworm as the major pest, 16% were more concerned about aphids and 20% considered jassids to be the major problem. Thus, the area is a prime location for trials of Bt cotton, since it provides immunity to the most common pest in the region.

(e) *Reasons for adoption and future intentions*

The survey included questions on the reasons for adoption and the intentions of those who had not yet adopted. Of the 60 adopters, 69% considered that Bt cotton was a major benefit, because of higher yields and savings on pesticides and labor costs. When asked to give a single reason for adoption, 58% gave more effective pest control as the main reason, only 10% gave higher yields, 20% were attracted by lower labor requirements and only 7% by reduced chemical costs. No problems were raised concerning Bt cotton, except the high cost of seed. Within the nonadopter group, 78% said they intended using the Bt variety in the future, 15% said they would not and the remainder were undecided. Their main reasons for nonadoption were the high technology fee incorporated in the seed cost and uncertainty about the new variety.

Table 4. *Agronomic problems and pests*

Variable	Class	Total (%)	Nonadopters (%)	First-year adopters (%)	Second-year adopters (%)
Greatest agronomic problem	Excessive rain	24	50	4	46
	Disease	2	0	0	100
	Weeds	11	45	36	18
	Pests	57	39	18	44
	Drought	3	67	33	0
	Floods	1	0	100	0
	Soil quality	2	0	50	50
Greatest pest problem	Boll worm	58	50	10	40
	Aphids	16	13	31	56
	Jassids	20	20	30	50
	No response	6	–	–	–

4. ADOPTION, YIELD, COST, PROFITABILITY AND EFFICIENCY OF ADOPTERS AND NONADOPTERS

(a) *Adoption model*

The analysis of the survey data in the previous section has included the variables that appear to explain adoption. In the first year, VUNISA offered the Bt variety to a chosen minority of farmers and attempts to model adoption were unsuccessful, due the inherent selection bias and the small number of adopters. In the second season, farmers choose whether or not to adopt and a limited dependent variable model is appropriate. Thus a multivariate logit model was fitted to the second season data. Formally, the model to estimate the probability of adoption can be stated as

$$\text{Prob}(Y = 1) = \frac{\exp(\beta' x)}{1 + \exp(\beta' x)} = \frac{1}{1 + \exp(-\beta' x)}, \quad (1)$$

where Y, adoption or nonadoption, is the binary dependent variable, the x vector contains a selection of the variables discussed in the previous section and β is a vector of coefficients. Several specifications were tested. Table 5 reports the results, showing that of all the factors considered, only farm size, nonfarm income, farmer experience and the proportion of female labor to total were significant in jointly determining adoption.

The positive signs on the coefficients indicate that all these factors increase the likelihood of adoption. Nonfarm income has the largest coefficient, indicating its importance as an alternative to credit in providing the money needed to buy the Bt seed, which costs twice as much as the other varieties. Nonfarm income may also have a stronger effect because the households with nonfarm income are likely to be less risk averse. More experienced farmers and those with larger farms are more likely to be granted credit. Thus, the logit model confirms the survey results on experience and farm size and the responses that lack of capital is the biggest problem. Unfortunately, the credit variable itself was insignificant, since almost all farmers had some credit and the levels were not known. The only variable that is not credit-related is the proportion of family labor that is female, which had the highest significance level. Spraying one hectare of cotton takes the better part of a day and entails walking at least 20 km (Bennett, 2002). Since it is necessary to spray for bollworm eight times a season and the Bt variety can cut this to two, this is clearly attractive to households that are short of male labor.

There appear to be no agronomic problems to prevent wider adoption the Bt variety, if it is affordable. The only serious barrier to adoption appears to be credit and *ex-post* it is appears that VUNISA has resolved this problem. As Section 2(c) reported, over 90% had adopted by 2001–02.

The adoption model and the previous section confirm the usual presumption that the early adopters tend to be the more experienced farmers with larger farms. Thus, in any productivity comparisons, if all the differences are attributed to the new technology, the results will be biased. Smaller farms are worked more intensively, but not necessarily more profitably or efficiently and farm size, experience and technology adoption all explain substantial differences in production efficiency and profit-

Table 5. *Adoption model: logit model of adopter characteristics*

Variable	Parameter	Value	Standard error	z-Statistic	Probability
Farm size	β_1	0.084	0.046	1.80*	0.071
Nonfarm income	β_2	1.23	0.54	2.28**	0.023
Farmer experience	β_4	0.51	0.24	2.14**	0.032
Female labor	β_3	0.48	0.19	2.61***	0.009
Constant	β_0	−1.67	0.53	−3.16***	0.001
Mean of dependent variable		0.60	S.D. dependent variable		0.49
Restricted log likelihood		−66.37	Hannan–Quinn criterion		1.29
LR statistic (4 degrees of freedom)		19.85	McFadden R^2		0.17

* Significant at the 10% confidence level.
** Significant at the 5% level.
*** Significant at the 1% level.

ability. There are too many factors influencing efficiency to control for them all, so the effects of the Bt variety are determined by comparing the adopters and nonadopters when they are using the same technology and when the adopters have switched to the Bt variety.

(b) *Farm accounting measures of the impact of Bt cotton*

The farm accounting efficiency measures, based on VUNISA's data, are reported in Table 6, beginning with the first season. The first column covers the 18 Bt adopters and the second, the 82 nonadopters. Then, the nonadopters are split between the 40 farmers who did not adopt in either year and the 42 who adopted Bt in the second season. This division allows the innate differences between farms to be separated from the effects of the Bt technology. The first row shows that in the first season the adopters produced an average of 475 kgs per hectare, as compared with 457 for the nonadopters. Neither the 40 nonadopters nor the 42 second-year adopters are using Bt seed in this first year and they averaged 423 and 493 kgs per hectare, respectively. Thus, there is no clear yield advantage to the Bt variety, as the second-year adopters have the highest yields, 4% higher than the adopters, as well as being 16.5% higher than the group who never adopt, and who are using the same technology. The lack of advantage may be partly explained by the seeding rate (seed used per unit of land) of 0.43 bags per hectare, which is 22% lower than for the full set of nonadopters, probably because of the cost of the seed (197 Rand per hectare compared with 119 Rand for all the nonadopters). But, pesticide costs are lower for the adopters (93 Rand per hectare, compared with 132 Rand). The extra cost of seed can be set against the savings on pesticides and the increase in output, since the gross margin is defined as the value of output minus the costs of intermediate inputs.

The gross margins show that the nonadopters were actually 10 Rand per hectare better off, because although the Bt adopters got almost 100 Rand per hectare more than those who never adopt, they are over 100 Rand worse off than the second-year adopters. Thus, neither yields nor gross margins explain why none of the adopters discontinued the Bt variety and a further 42 adopted in the next year. The obvious flaw in these commonly used measures of productivity and profitability is that the cost saving in labor used for spraying is not taken into account and 20% of the farmers rated this as the main reason for adoption. Net margins do include labor and land costs, but cannot be calculated since although the survey data include the quantities of labor and land, neither land nor family labor has a price. Quantities alone are however, sufficient for the efficiency estimates in the next section.

The right-hand side of Table 6 reports the results for the second season, when the lower yields are attributable to late heavy rains, which were 50% above average, compared with the lower than average rain at the beginning of the previous year. Whereas the first season was good for the cotton crop, the second was not (KwaZulu-Natal, various years). The average yield of the nonadopters fell to 304 kgs per hectare, a decline of 28%. The first important outcome is that all adopters had an average

Table 6. *Comparison of nonadopters and adopters: costs and returns (per hectare)*

Averages per category	First season 1998–99				Second season 1999–2000			
	Bt cotton	Non-Bt cotton			Bt cotton			Non-Bt cotton
	First-year adopters	All non-adopters	Adopted neither year	Second-year adopters	All adopters	First-year adopters	Second-year adopters	Adopted neither year
Number of farmers	18	82	40	42	60	18	42	40
Yield (kg/ha)	475	457	423	493	425	433	421	304
Bags (25 kg) of seed/ha	0.43	0.55	0.55	0.53	0.46	0.46	0.46	0.57
Yield (kg)/kg of seed	50	37	32	42	44	40	46	23
Seed cost/ha (Rand)	197	119	1 24	115	214	211	214	127
Chemical cost/ha (Rand)	93	132	145	120	83	83	83	129
Gross margin/ha (Rand)	781	791	687	890	675	673	676	428

yield of 425 kgs per hectare, which is 40% higher than the nonadopters, leaving little doubt that the Bt variety yields better in a wet year, when bollworm are a greater problem, because the rain washes the pesticide residue off the plants. But, since by these measures the second-year adopters appear to be the best farmers, what proportion of this 40% increase is actually attributable to the Bt variety?

The second-year adopters, who had 16.5% greater yields than the nonadopters, when using the same seed, now have a 38.5% yield advantage after adopting the Bt variety. Thus, the yield benefit due to the Bt variety appears to be 22%, or close to 70 kgs per hectare. The percentage gain is in line with Monsanto's field trials (for the first season, which was a good year) that show a 27% yield gain for the Bt variety (Bennett, 2002, Table 1).

The second result is that the decline for those who used Bt in both years was only from 475 to 433 kgs per hectare (a 9% fall), whereas for those who changed to Bt in the second year, the fall was from 493 to 421 kgs per hectare (a 15% fall). Despite switching to the Bt technology, the second-year adopters now have lower yields than the first-year adopters, which suggests that there is learning by doing by the second season. Average seed costs per hectare were 68% higher for adopters in this second season. But, chemical costs fell by 36%, from 129 Rand for nonadopters to 83 Rand for adopters. Monsanto's field trials show a reduction from 220 Rand per hectare for the non-Bt variety to 23 for Bt cotton, a reduction of almost 90%. Therefore, much of the trial plot gains in chemical reduction have not occurred at the farm level in this bad season.

Even so, the second-year results are far clearer and the outcome entirely unambiguous. The yield gain of 40% and the lower chemical cost easily offset the extra seed cost, so that the average gross margin for the adopters is 675 Rand compared with 428 Rand for the nonadopters, 58% higher. The share of this that is attributable to the Bt variety can be calculated as it was for yields. The advantage of the second-year adopters was 30% when the two groups used the same seed and is now 58%, so 28% can be attributed to the Bt variety, which is worth 190 Rand per hectare. Again, this result can be compared with Monsanto's trial results, which showed a gain of 944 Rand per hectare, due to higher trial plot yields and a greater reductions in chemical use.

(c) *Production efficiency of adopters and nonadopters: stochastic production frontiers*

The analysis in section (b) fails to show that there are yield or gross margin benefits from using Bt cotton in the first season, but does so for the second year. Both measures are inaccurate indicators of the gains and say very little about the reasons for any observed differences between farms. Yield is a partial measure of productivity and is of limited use when the levels of nonland inputs used, such as labor and fertilizer, differ between farms. Gross margins take account of intermediate inputs, but ignore the efficiency with which the major inputs, labor and land, are used. Net margins require land and labor costs, which are not available, so a production frontier approach was taken which only requires input and output quantities.

Bravo-Ureta and Pinheiro (1993) review the applications of frontier analysis to developing countries, showing that this method of measuring farm-level efficiency has become commonplace. Whereas ordinary least squares (OLS) estimation takes the average line of best fit through the observations (hence it is sometimes called a mean response function) and tacitly assumes that all the farms are efficient, this can be misleading if there are considerable differences in efficiency levels. Tests can show if the appropriate approach is a production frontier, which will give results that are more accurate and also generate efficiency levels for all the farms.

The approach can be deterministic, where all deviations from the frontier are attributed to inefficiency, or stochastic, which discriminates between random errors and differences in inefficiency. This section fits a stochastic frontier model, of the type originally proposed by Aigner, Lovell, and Schmidt (1997), which is extended to include the characteristics of the farms that specifically explain inefficiency levels, following Battese and Coelli (1995). First, the frontier model determines the efficiency levels of the sample farms, with respect to those that represent best practice and then the inefficiencies are explained. The method of maximum likelihood is used to estimate the unknown parameters, with the stochastic frontier and the inefficiency effects estimated simultaneously. The theory is not explained here as the method is reviewed by Coelli (1995), fully documented in Coelli, Rao, and Battese (1998) and many applications to agriculture are

Table 7. *Summary statistics on output and inputs by season and by type of technology*

	Output (kg)		Seed (kg)		Chemicals (Rand)		Labor (days)		Land (ha)	
	Adopt	Non-adopt	Adopt	Non-adopt	Adopt	Non-adopt	Adopt	Non-adopt	Adopt	Non-adopt
First year										
Minimum	1,244	170	25	25	0	0	4	2	2	1
Mean	3,059	1,726	76	50	526	413	21	19	9	6
Maximum	8,011	8,878	225	200	2,279	2,690	48	40	25	20
Standard deviation	2,024	1,743	62	33	529	340	11	8	7	5
Second year										
Minimum	340	43	25	25	0	0	6	2	1	1
Mean	1,983	1,183	55	48	317	403	22	19	7	5
Maximum	9,333	8,500	250	150	1,505	2,690	51	40	25	15
Standard deviation	1,598	1,495	51	32	267	439	9	9	6	3

reviewed in Battese (1992) and Bravo-Ureta and Pinheiro (1993).

The output and input data are summarized in Table 7, which reports the mean, minimum and maximum values and the standard deviations of the variables. The variations in the data are clearly sufficient to allow the estimation of production relationships for both growing seasons.

The dependent variable is bales of cotton, a physical measure of output. The independent variables in the production function are: land (hectares), chemicals (in value terms following aggregation of the different types), seed (25 kg bags) and labor (days of family labor plus hired labor used for spraying, weeding and harvesting). The inputs of land, chemicals and seed are well recorded in VUNISA's farm accounts and so is hired labor. Fertilizer is not used and animal manure is of minor importance, so missing variables are not an issue. Nor is quality adjustment a major problem, as the land is not very different between farms. The weakness, which is common in this type of survey, is that family labor is labor available, rather than actually used and there are no records on the output of subsistence crops, such as maize, or animal outputs. Thus, if a farm has more or less than the average of other outputs, the family labor attributed to cotton will be biased. The efficiency with which labor is used is important, as 20% of the farmers ranked saving labor as the main benefit of Bt cotton.

Model selection was based on three hypothesis tests. Generalized likelihood ratio (LR) tests were used to confirm the adequacy of the functional form of the model, to determine whether the appropriate model is a frontier or a mean response function and to determine the presence of inefficiencies effects. [1] First, the functional form of the stochastic frontier was determined by testing the adequacy of the log-linear Cobb Douglas model relative to the less simplistic translog, which includes crossproducts and square terms to allow for interactions and nonlinearities in the data. The first section of Table 8 shows that for both seasons, the log-linear model is accepted as an adequate representation of these data, as the additional terms in the translog function are jointly insignificant.

The next test reported is the t test on $\gamma = 0$, which determines whether the frontier model is appropriate, since values near to zero indicate that OLS is adequate. The values are reported in the next table and discussed below. For both years, the test shows that the frontier model is preferred to a mean response function. This result is confirmed by testing jointly the null hypotheses that both the frontier parameter (γ) and all the coefficients (δ_i) on the variables that explain the inefficiencies are jointly zero (inefficiency effects are not present in the model). [2] This is also clearly rejected, meaning that the frontier model, with variables to explain the inefficiencies, is the preferred model for both seasons.

The left side of Table 9 reports the results of fitting a stochastic frontier model for the 1998–99 growing season. The R^2 of 0.50 means that 50% of the variance is explained in the OLS version of the model, which here is a preliminary step essentially to identify the starting points prior to the frontier estimation. Since the

Table 8. *Log-likelihood ratio tests for the stochastic frontier and inefficiency model*

	First year	Second year
Choice of functional form—H_0: $\beta_{ij} = 0$, $i, j = 1, \ldots, 4$. Test statistic: $\chi^2_{v,0.95}$, where v = number of additional restrictions = 10		
Test statistic	9.94	16.12
Critical value	18.31	18.31
Test result	Accept H_0: Cobb Douglas is adequate	Accept H_0: Cobb Douglas is adequate
Choice of stochastic frontier *vs.* mean response function—H_0: $\gamma = 0$. Test statistic: One-tailed t-statistic; 95% confidence level		
Test statistic	8.097	21.17
Critical value	1.96	1.96
Test result	Reject H_0: It is a frontier	Reject H_0: It is a frontier
Presence of inefficiency effects—H_0: All inefficiency coefficients (δ_i) and $\gamma = 0$. Test statistic: mixed-$\chi^2_{v,95\%}$ confidence level, where v = number of restrictions (five in 1998–99 and three in 1999–2000)[a]		
Test statistic	12.25	24.48
Critical value	10.36	7.05
Test result	Reject H_0: It is an inefficiency model	Reject H_0: It is an inefficiency model

[a] Critical values for the mixed χ^2 are from Kodde and Palm (1986).

Table 9. *Production frontier and inefficiency model*

Variable	First year			Second year		
	Coefficient		t-Statistic	Coefficient		t-Statistic
Production frontier	Adjusted $R^2 = 0.50$ (from OLS)			Adjusted $R^2 = 0.73$ (from OLS)		
Dependent variable: bales of cotton						
Constant	−1.874***		−2.103	0.643**		1.816
Land	0.211*		1.583	0.276****		2.823
Chemicals	0.265****		2.4	0.059**		1.818
Seed	0.177*		1.404	0.282****		2.671
Labor	0.476****		3.538	0.341****		3.002
Sum of elasticities	1.129			0.958		
Explaining the inefficiencies						
Adoption	−0.444*		−1.383	−2.755**		−1.64
Planting date	0.41*		1.282			
Experience	−0.118***		−1.955			
σ^2	0.89		2.818	1.06		1.672
γ	0.81		8.097	0.94		22.171
Sample	First year			Second year		
	Mean	Minimum	Maximum	Mean	Minimum	Maximum
Full sample: Mean	0.70	0.15	0.92	0.64	0.10	0.91
All non-Bt: Mean	0.66	0.15	0.89	0.48	0.10	0.91
All Bt: Mean	0.88	0.80	0.92	0.75	0.33	091
Bt year 1: Mean	0.88			0.74		
Bt year 2: Mean	0.70			0.76		
Nonadopters: Mean	0.62			0.48		

*Critical t-value at 90% confidence level = 1.29; **95% = 1.66; ***97.5% = 1.96; ****99% = 2.32.

variables are in natural logarithms, the coefficients can be interpreted as elasticities, and are therefore bounded between zero and unity to conform to production theory, making one-tailed significance tests appropriate. The sum of the elasticities is 1.129, which is an indication that there may be increasing returns to scale, since if all the inputs were increased by 1%, output would rise by 1.13%. This would indicate that the farms are currently too small and would achieve greater efficiency if they were larger. But the χ^2 test shows that the null hypothesis of constant returns to scale (elasticities sum to unity) cannot be rejected, so the coefficients may also be interpreted as factor shares in output.

All the elasticities are significantly different from zero and labor has the biggest impact (0.476), followed by chemicals (0.265), land (0.211) and then seed (0.177). The elasticity for labor of 0.476 indicates that a 1% increase in labor would increase output by 0.48% and the t-statistic shows this estimate is significantly different from zero at the 1% confidence level. In this first season, when only 18% of the sample had adopted, the importance of pesticides is indicated by a large and significant coefficient, which is greater than those for land or seed.

The variables that explain the inefficiencies in the second stage of the model are the decision to adopt Bt cotton, the month planting took place and the farmers' years of experience in growing cotton. Adoption of Bt cotton has a negative sign, meaning that it reduces inefficiency. The planting date variable indicates that the later farmers planted, the less output they got, which is a common result in African agriculture. Indeed, a USAID study of Kenya in the mid-1980s showed that timely planting had a greater impact than using fertilizer or improved seed. The negative sign on farmer experience means that the more experienced farmers were less inefficient.

The γ statistic is used to determine whether this is indeed a frontier model and not simply a mean response function. Here $\gamma = 0.81$, which is close to unity and highly significant, which corroborates the second LR test in Table 8, again indicating that the frontier model is appropriate. This implies that one or more of the firms in the sample determine a frontier of best practice, while the remainder are some measurable distance from this efficiency frontier.

This is not surprising, since the last section of Table 9 shows that the mean level of efficiency of the full sample was 0.70. [3] The adopters had a far higher mean efficiency of 0.88, as compared with the mean of 0.66 for those who did not use Bt cotton. This suggests that when all the inputs are included in the efficiency calculations, the adopters are 30% more efficient. Indeed, the last rows of the table show that the adopters are the most efficient group with a 0.18 advantage over the second-year adopters. The minimum efficiency level among the adopters was 0.80, as compared with 0.15 for the nonadopters. These results suggest that despite the slightly lower gross margins for adopters, the Bt variety performed better, when the land and labor inputs are taken into account. This explains why none of the adopters discontinued the Bt variety and 42 more adopted in the second year.

The same exercise was repeated for the 1999–2000 season, for which the data should be better, since the harvest had just been collected when the survey was conducted. This is reflected in the R^2, which shows that 73% of the variance in output is now explained in the OLS model, which is unusually high for cross section data of this nature. The stochastic frontier results are reported in the right-hand side of Table 9, which shows that labor again has the biggest impact, with an elasticity of 0.34, followed by seeds and land, while the impact of chemicals is far lower than in the first year. With 60% adopters in the sample, the share of pesticides in explaining output falls to 5.9%, while that of seeds rises to 28.2%. The seed input is now significant at the 1% confidence level, while the significance of pesticides is reduced. Indeed, all the frontier variables are significant at the 95% level or better. The sum of the elasticities is 0.96, which suggests that there is now decreasing returns to scale, so if anything, the farms are too large. However, 0.96 is very close to unity and the χ^2 test shows that the null hypothesis of constant returns to scale cannot be rejected. Thus, farm size does not appear to be an important factor for this sample, which is not surprising since all the farms are small and unlike mechanical technologies, the Bt seed variety should be scale neutral, giving the same per hectare gain from Bt for all farm sizes.

The next section of the table shows that the only variable that was significant in explaining the inefficiencies in the second year was adoption of Bt cotton, which is now highly significant and has a positive effect on efficiency. The γ statistic is 0.94, which is even closer to unity and is again highly significant, indicating that the frontier is the preferred model. The last section of the table begins by showing that the mean efficiency for the full sample is now 0.64, which is 9% lower due to the wet growing season. The average for the nonadopters falls to 0.48, a decline of 27% and for the adopters, 0.74, a smaller reduction of 16%, indicating the Bt variety is less affected by the weather. [4] The key result is that the efficiency advantage of the adopters has now risen to 54%, compared with 33% in the first season. There is also higher dispersion in efficiencies in this poor season, around a lower mean efficiency level of 0.64, with the minimum efficiency falling to 0.10 for nonadopters and 0.33 for adopters.

The last three rows of Table 9 split the results by adopter group. In the first season, the second-year adopters were 13% (0.70 compared with 0.62) more efficient than those who adopt in neither year, when using the same technology. In the second year they are 58% more efficient, so 45% of the difference can be attributed to the Bt variety. Thus, the stochastic frontier analysis, which takes account of the efficiency with which all the inputs are used, produces results that show unequivocally that the Bt variety resulted in efficiency gains, both in the first season with good weather, and the wet second season. The results conform with the theoretical restrictions, the logic of how the Bt seed should affect production and the observed pattern of rapid adoption.

(d) *Social benefits: environment and health*

The previous section establishes that Bt cotton has improved productive efficiency in Makhathini, but there are also social benefits from reduced pesticide use. Environmental and health benefits may be gained from adoption and the survey included questions on these issues. The cleaning of equipment and disposal of chemical waste are a problem, in that 92% of farmers dumped waste and washed their empty spraying equipment either in the fields or in the household refuse hole.

Although 74% of farmers indicated that they wear protective eyewear and masks when they apply chemicals, 17% did not and 53% of these were nonadopters, who spray more often. Only 3% reported eye problems, and 72% were unaware of any health problems resulting from chemical application. The local hospitals records show, however, that about 150 cases of burns and sickness due to agricultural chemicals were treated in the 1998–99 season, but by the 2000–01 season, when adoption became widespread (1,184 users), this had fallen to about a dozen. Therefore, there may be substantial health benefits not revealed by the survey and not included in the calculation of the private benefits in this section.

5. CONCLUSIONS

The results of this survey of 100 smallholders in the Makhathini Flats region of KwaZulu-Natal give considerable cause for cautious optimism regarding the impacts of Bt cotton. The data have the advantage of combining the farm records, kept by the company that supplied the inputs and bought the output, with a sample survey that identifies the characteristics of the farmers and their perceptions. Fortunately, the data are for the same farmers, for two years, which allows the innate differences between adopters to be separated from the effects of the technology. This matters because analysis of the data shows that the early adopters tend to be the more experienced farmers, with larger farms, which could bias the impact assessment. These were the farmers who were more likely to be granted credit, or were able to finance the higher seed costs from savings or other income sources. Indeed, almost all in the sample said they would adopt Bt cotton if they had the financial resources to do so and there did not appear to be any agronomic or other technical impediments to adoption. So, the survey gave every reason to expect that the adoption levels would rise further. The recent evidence shows that adoption has increased from 411 in the second year of this study, to 1,184 in the next growing season. Thus, over a third of the farmers in the Makathini Flats had adopted a Bt variety in 2000–01 and this has increased to over 90% in 2001–02.

The usual farm accounting measures fail to show that the Bt variety was superior in the first season, when the weather was good for cotton. The 18 adopters actually had lower yields and gross margins than the 42 farmers who adopted in the next season, which begs the question: why did all the adopters continue with the variety and 42 others followed the next year? In this second, wet, growing season the adopters benefited, according to both measures. The increase in yields and reduction in chemical application costs outweighed the higher seed costs, so that gross margins were considerably higher. This was a bad year, due to unusually heavy rainfall and the Bt adopters suffered lower yield reductions than those who did not adopt. This supports Monsanto's claim that the use of Bt cotton reduces the effect of weather on bollworm control, as rains wash off the pesticides and necessitate respraying.

Both yields and gross margins are useful, but they are partial measures of efficiency and in this case are at odds with the empirical evidence because they do not take account of labor saved. Thus, this study fits a stochastic production frontier, to consider the efficiency with which all inputs are converted into outputs and estimate the efficiency level of each farm. The results show that once labor savings are taken into account, the Bt cotton adopters were considerably more efficient than those that did not adopt these varieties, in both seasons. This technique, which has been widely used in measures of agricultural efficiency, although not GM adoption, seems to be well suited to such studies.

Makathini Flats is a low potential area for cotton production, but is atypical in that the biotech companies are locally present and support services are unusually good, which affects the wider applicability of this study. Since majority rule, South Africa has abolished the marketing boards that controlled agricultural production and has encouraged both competition between private companies and foreign involvement. VUNISA, which has provided extension advice and credit, supplied the inputs and purchased the output, has played an important role, showing how well a private company can function. In addition, in this competitive environment, it has already lost its monopsony power, as a Danish-owned company has opened a cotton gin. VUNISA's monopoly of formal credit and input supply is unlikely to last long.

Research is now being undertaken on smallholder Bt cotton in Tonga, which is also supplied by VUNISA, but is more typical as the seed companies are not locally involved. Here adoption is less rapid, but 34% of the sample now using Bt cotton. Surveys of Bt cotton grown by commercial farmers have also been conducted, showing that the yield advantage from the GM seed is lower than in the second year of this study, at less than 10%. There are also surveys of Bt yellow maize, being grown by commercial farmers and in the last season, of Bt white maize, which has just been released to smallholders. Research on the changing market structure and the distribution of the gains between farmers, input suppliers and seed companies is also well advanced. This will determine if the seed suppliers are appropriating a greater share of the benefits by raising their prices. There is also research in progress on the actual and potential reduction in chemical inputs, but it is too early to determine if there are adverse environmental effects, such as gene transfers to other plants, or damage to the insect ecology.

On a much wider scale, there are about 2.5 million hectares planted to cotton in Africa, most on small plots of less than 10 ha. These results here show a gain of about 250 Rand per hectare (without the savings in labor). If there was widespread use of the Bt variety across the continent, it could generate additional incomes of about six billion Rand, or US$600 million, for some of the world's poorest farmers. Given that advice, credit, input supplies and marketing are important constraints in Africa, VUNISA's operation should be investigated as a possible model for other countries. But, a private company's performance is dependent on its environment and the good governance and competitive position in South Africa are unlikely to be replicated in most other African countries.

NOTES

1. The likelihood-ratio test statistic, $\lambda = -2 \times \{\log(\text{Likelihood}(H_0)) - \log(\text{Likelihood}(H_1))\}$ has approximately χ^2_v distribution with v equal to the number of parameters assumed to be zero in the null hypothesis.

2. Since γ takes values between 0 and 1, any LR test involving a null hypothesis which includes the restriction that $\gamma = 0$ has been shown to have a mixed χ^2 distribution, with appropriate critical values from Kodde and Palm (1986).

3. An average efficiency level of 70% is a reasonable result for South African smallholders, especially if some have alternative sources of income. Indeed, it is rather

higher than in similar production studies of smallholder farming in South Africa, such as Piesse, Thirtle, Sartorius von Bach, and van Zyl (1996), which considered efficiency in the former Homelands of the Northern Transvaal.

4. The drop in efficiency for the full sample is less that the average of the two subsamples, which seems odd, but this results from the change in the relative sizes of the two subsamples over the two years.

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