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Biotechnology as an alternative to chemical pesticides: a case study of Bt cotton in China

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Abstract

The overall goal of this study is to determine the extent by which genetically engineered (GE) crops in China can lead to reductions of pesticide use, the nature and source of the reductions, and whether or not there are any non-pecuniary externalities. One of the first studies of the effect of plant biotechnology on poor farmers, the study is based on a data set collected by the authors in 2000 in North China. The paper's descriptive, budget and multivariate analysis find that Bt cotton significantly reduces the number of sprayings, the quantity of pesticides used and the level of pesticide expenditures. All Bt cotton varieties—both those produced by foreign life science companies and those created by China's research system are equally effective. In addition to these input-reducing effects, the paper also demonstrates that such reductions in pesticides also likely lead to labour savings, more efficient overall production, as well as positive health and environmental impacts.

Keywords: Chemical pesticides; Bt cotton; Genetically engineered (GE) crops

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1. Introduction

The use of pesticides is a two-edged sword in all countries, including China, one of the most intensive pesticide-using countries in the world. The nation's farmers apply more chemical pesticides on their crops than producers in almost any country in the world (Huang et al., 2000a). Their annual applications have increased in recent years, rising from 211,000 metric tonnes (mt) of active ingredients in 1985 to 340,000 mt in 1996. While pesticides have played a role in increasing China's agricultural output, their use has created many negative externalities. The use, overuse and misuse of pesticides in China have led to poisonings of farmers, degradation of land and water, and increased levels of dangerous chemicals in China's food supply (MOA, 1983; Peng, 1998; Lei et al., 1998; Huang et al., 2000c).

Recognising the existence of negative externalities, China's leaders initiated a number of steps to control some of the most harmful aspects of pesticide use. China's plant breeders have successfully produced thousands of varieties with host-plant resistance to insects and diseases (Stone, 1988, 1993). Almost all newly released varieties in China in the past 20 years have high levels of host-plant resistance. At least in the case of rice, the use of these varieties has led to reductions in pesticides (Widawsky et al., 1998).

Unfortunately, despite such success, growing challenges remain in China's battle against pests. The

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effectiveness of older varieties has fallen over time because of the rising resistance of pests to the natural defenses of China's improved varieties and to chemical pesticides (Widawsky et al., 1998; Crook, 1999). In response to increasing pest resistance in the late 1980s, China's research system, following the lead of scientists in the US, began to develop crops that are genetically engineered (GE) to be resistant to important pests (Huang et al., 2001). Greenhouse testing began in the early 1990s. Currently, China's breeders and seed companies are developing and testing Bt varieties of rice, maize, cotton and vegetables.

The worsening crisis in the cotton sector—due to the ineffectiveness of varieties produced by conventional breeding methods and the rising use of pesticides—induced leaders in the Ministry of Agriculture to approve the commercial use of GE cotton varieties. Designed to express a toxin that kills the Asian bollworm, international agribusiness giants and domestic research institutes began selling their varieties in 1997. Literally millions of farmers have started to use the new Bt cotton varieties, making China the first nation in the world in which large numbers of small holders have commercially adopted GE varieties.

Despite the unprecedented release and adoption of Bt cotton, little is known about the exact nature of the impact that they have had on producers. How has the adoption of Bt varieties of cotton affected production practices—especially pesticide use? Has the impact on farmer pesticide use come in the form of a reduction in sprayings, the amount sprayed, or in the cost of pesticide application? Has any one type of Bt variety—foreign or domestic been more effective? Are there any non-economic benefits?

The overall goal of this study is answer these questions. In particular, we study China's experience of Bt cotton production to determine the extent by which GE crops can lead to reductions of pesticide use, the nature and source of the reductions and whether or not there are any non-pecuniary externalities. Although our relatively small sample size means that caution needs to be exercised when generalising to the rest of China or elsewhere in the world, we are able to show the impact of Bt cotton adoption on pesticide use and expenditures and provide preliminary evidence of significant health benefits. Showing the impact on food quality, chronic or acute morbidity, water quality or other environmental factors is beyond the scope of the paper.

To meet these goals and objectives, the rest of the paper is organised as follows. Section 2 provides a descriptive overview of pesticide use. Section 3 illustrates the correlations between the use of pesticides and the adoption of Bt cotton varieties in our study sites and examines the impact of Bt cotton adoption on pesticide use in a multi-variable context. Section 4 provides concluding remarks on the policy implications of the findings.

2. Pesticide use in China

The growing use of farm chemicals, especially inorganic fertilisers and pesticides, was a major factor in the rising production and productivity of China's post-transition farm sector (Ash and Kueh, 1995). Various kinds of pesticides have been used on a large scale to protect crops from damage inflicted by insects and diseases in China (Stone, 1988). Especially during the past two decades, per hectare pesticide expenditures in crop production has risen sharply for all crops (Table 1, rows 1–5). Moreover, the rate of increase of pesticides rose faster than other inputs, leading to a rise in its share of total costs (Table 1, rows 6–10). We estimate that by the late 1990s, China's farmers purchase and apply nearly US$ 5 billion of pesticides per year, making China one of the largest pesticide users

Table 1
Pesticide uses in major crop productions in China, 1980–1998[a]

Year	Rice	Wheat	Maize	Cotton	Tomato	Cucumber
Per hectare pesticide cost (US$ at 1995 prices)[b]						
1980	11	3	1	31	NA	NA
1985	14	3	1	35	NA	NA
1990	16	5	2	46	45	56
1995	25	8	7	101	105	97
1998	25	9	7	88	136	129
Share (%) of pesticide cost in total material costs of crop production						
1980	5.8	1.9	1.0	13.1	NA	NA
1985	6.0	1.4	0.8	11.5	NA	NA
1990	7.5	2.7	1.6	18.1	4.8	6.3
1995	7.0	2.8	2.7	21.7	7.9	9.2
1998	8.0	3.0	2.9	19.9	7.8	7.3

[a] State economic planning commission and state statistical bureau.

[b] Rural retail price index of pesticides is used to deflate the current value.

in the world. For example, with the exception of Japan, where rice farmers use up to 10.8 kg ha^{-1} (including herbicides), the level of pesticide application of China's farmers (e.g. 2.2 kg ha^{-1} for rice) far exceed those of farmers in Philippines and other countries (e.g. 1.3 kg ha^{-1}, Rola and Pingali, 1993; Widawsky et al., 1998).

Cotton producers are among the largest pesticide users in China in terms of both aggregate and per hectare use (Table 1, column 4). Per hectare pesticide cost reached US$ 101 in 1995 for cotton, much higher than that for rice, wheat or maize.[1] Only tomato and cucumber growers use more on a per hectare basis. The gross amount of pesticides used in rice production in China is greater than the amount used for cotton production only because five times more acreage is planted to rice than to cotton. Cotton production consumes nearly US$ 500 million in pesticides annually.

2.1. Benefits and costs

The dramatic rise in the use of pesticides has been shown to have both substantial benefits and costs beyond its direct impact on cotton's crop budget. Recent studies of pesticide use in China have shown that pesticides do make an important contribution to agricultural production of major crops such as rice (Huang et al., 2000b). China's pest management officials estimate that pesticide spraying and pest control methods save China millions of tonnes of food and fiber per year from pest damage (MOA, 2000).

Pesticide use, however, has several potential drawbacks. For example, the application of pesticides may pose a serious danger to the agro-ecosystem. Pingali et al. (1994) has produced evidence of the adverse effect that pesticide use has on human health. Their results demonstrated that the health and other costs could exceed the private costs of purchasing the product. Huang et al. (2000c) have performed their own study of pesticide use on human health in China and have come to similar conclusions.

In fact, pesticide use in farming in China have even been linked to serious illnesses and death. Across China, poisonings of farmers and their labourers have resulted in 45,000 cases of serious illness and more than 500 deaths annually from 1987 to 1996 (Huang et al., 2000c). Officials in the Ministry of Agriculture claim that the exceptionally high level of deaths in 1995 (741) can in part be traced to the substantial increase in pesticide use in cotton production in the North China Plain as boll weevil infestations have risen after 1990.

Heavy pesticide use also can lead to health problems for consumers if they eat foods sprayed with harmful and slowly-degrading pesticides. Liu et al. (1995) conducted the most recent national study in China of pesticide residuals in food in 1992. The study concentrated on the food safety effects of farm-level use of chlorinated hydrocarbons (CH pesticides), the family of pesticides that includes DDT. The most persistent of pesticides, officials banned the use of CH pesticides in 1983. Although the use of CH pesticides have declined sharply since the mid 1980s, the study found farmers still were using them in the early 1990s and China's food supply revealed traces of contamination. Other recent studies have confirmed the finding that pesticide contamination in China's food markets is still a problem for vegetables, fruits, and food grains (e.g. Liu et al., 1993).

2.2. Regulatory and technological efforts to reduce pesticide's negative effects

Since recognising the seriousness of many pesticide-related problems in the 1970s, the government has taken steps to regulate pesticide production, marketing and application. Initially, regulators made considerable progress by introducing less persistent compounds as substitutes for highly hazardous pesticides (Huang et al., 2000b). The Ministry of Agriculture also began a campaign to teach farmers about the safe use and management of in-field pesticide use. The promulgation of rules and regulations, however, does not guarantee improvements in the quality of pesticide products on the market or their proper and safe handling. Casual observation in China's farming areas provides convincing evidence that a vast majority of farmers have not changed the way that they handle and apply pesticides in recent years. Most pesticides are mixed by hand, applied without any protective clothing or breathing apparatus and residues are discarded in irrigation ditches and other commonly used water sources. Moreover, despite legal and regulatory

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[1] In the rest of the paper, we report all value figures in US$, converting Chinese values at the rate: US$ 1 = 8.25 yuan

bans, factories still produce and farmers (in our sample) still use highly hazardous pesticides.

China's leaders also invested in and promoted alternative ways to control pests, many of which hold promise for reducing pollution. The research system greatly expanded host-plant resistance technology in China's crops in the 1970s and 1980s (Stone, 1993). Although the record of IPM has been mixed, improvement of host-plant resistance in new varieties has helped in reducing pesticide use without reducing crop yields (Widawsky et al., 1998).

However, with increasing pest pressures, in part from rising resistance to conventional control methods, China also has aggressively invested in agricultural biotechnology, believing that it offers a number of new ways of dealing with pest problems. Scientists believe that biotechnology can improve China's grain, horticulture and cotton varieties by making conventional plant breeding more efficient through the use of genetic mapping and molecular markers to identify useful traits during the breeding process. Biotechnology techniques also can allow breeders to make use of traits in wild and weedy relatives of cultivated plants, other crops, bacteria, and animals by introducing genes from the organisms into varieties of China's main crops.

China's agricultural research system has made an impressive effort to improve varieties of many crops using biotechnology and has moved some of the new transgenic varieties into commercial use by farmers (Huang et al., 2001). Grain, cotton and tobacco breeding programs have most closely coordinated their biotechnology and conventional research programs. In recent years, researchers have directed more of their work towards improving vegetables and oilseeds using biotechnology.

Scientists have made greatest headway in using biotechnology to improve insect resistance of crops, although considerable work is also being done to improve disease resistance. Interestingly, this focus on insect and disease resistance is peculiar to China's biotechnology program. The nation's public-dominated research system has given China's researchers a strong incentive to produce GM crops that increase yields and prevent pest outbreaks. In China, more than 90% of field trials target insect and disease resistance. In contrast, in industrialised countries, where much of the plant biotechnology is privately finance, 45% of field trials are for herbicide tolerance and improving product quality; only 19% are for insect resistance (Huang et al., 2001).

Table 2
Area and source of Bt cotton in China, 1997–2000[a]

	1997	1998	1999	2000
Area of Bt cotton (1000 ha)				
China	2	67	420	700
Hebei	2	50	190	220
Shandong	0	10	90	170
Other provinces	0	7	140	310
Sources of Bt varieties (%)				
CAAS varieties	30	25	35	39
Monsanto varieties	70	75	65	61

[a] Preliminary estimates by authors based on the interviews with officials from the provincial agricultural bureaus and provincial seed companies.

Although China has released a number of minor crops, such as tomatoes, sweet peppers and petunias, for commercial production, cotton has become the most successful transgenic crop program. According to official government estimates 400,000–500,000 ha were planted in Bt cotton in 2000. Industry analysts and executives estimate that farmers planted nearly 1 million ha in 1999. Our estimates of Bt cotton area, which are based on interviews with provincial agricultural bureaus, extension officials and seed companies, fall in the middle of the official and industrial estimates (Table 2, row 1). Starting from only 2000 ha in 1997, Bt cotton sown area grew to around 7,000,000 ha in 2000. By 2000, 20% of the China's farmers planted Bt cotton. Indeed, regardless of the source of the estimates, the growth of Bt cotton areas has been remarkable and more small, poor farmers grow GE crops in China than any country in the world.[2]

The expansion of Bt cotton across China, however, has not been uniform (Table 2, rows 2–4). For example, after being the only group of farmers to have Bt cotton in 1997, cotton farmers in Hebei account for around 30%, or 220,000 ha, of the sown area in 2000.

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[2] According to James (2000), after the US, by far the largest users of GE crops (72% of the world's total), Argentina (17%) and Canada (10%) have the largest areas in GE crops. China is fourth, with 1%. It should be noted, however, that GE crops in Argentina are almost exclusively used by large, commercial farmers. In recent years, small farmers in Mexico and South Africa have also begun planting GE crops.

Farmers in Shandong Province rank second, planting 170,000 ha of Bt cotton. In contrast, other provinces such as Xinjiang, particularly those with lower levels of cotton bollworm infestation, have little or no area sown in Bt varieties.

Perhaps one of the main reasons for the rapid spread of genetically engineered varieties is the competition that has taken place among alternative suppliers of Bt cotton. The largest share of China's Bt cotton area is planted with a genetically engineered variety extended by a joint venture between Monsanto and the Hebei Provincial Seed Company (Table 2, row 5). Their share, however, has fallen slowly over time, from 70% in 1997 to 61% in 2000.

During this same period, however, China's research community has responded by releasing several of its own GE products. For example, a commercial subsidiary of the Biotech Research Institute (BRI) of the Chinese Academy of Agricultural Sciences (CAAS) introduced several domestically-created GE cotton varieties. Using a somewhat different approach to insert the Bt gene into the cotton, the varieties of BRI rapidly spread to many provinces across the North China Plain. Shortly thereafter, the China Cotton Research Institute (also a CAAS-affiliated research institute) in Henan Province also released Bt cotton varieties, which spread mainly throughout Henan, Shandong and Jiangsu Provinces. Together, the varieties released by CAAS institutes have increased their area share from 30% in 1997 to 39% in 2000 (Table 2, row 6).

3. Pesticide use and Bt cotton production in study sites

3.1. The data

To examine the impact of biotechnology on pesticide use in the cotton sector, we collected our own data set in 1999. Our data collection was necessary because China's government does not have a program to track the cost of production of transgenic crops. China's statistical system also does not measure the impact that technology adoption has on the rural household or community beyond on-farm production. In total, we collected data on the production practices of 282 cotton farmers.

The enumeration team put in considerable time in choosing the sample. Since one of our main objectives was to compare the differences in production practices of Bt and non-Bt varieties (and among Bt varieties), we had to carefully select our provinces and counties. In many counties 100% of the farmers were growing Bt cotton; in other areas the proportion of farmers growing Bt cotton was lower. The coverage of specific varieties tended to be concentrated in certain areas. We chose Hebei Province because it is the only province in which Monsanto varieties had been approved for commercial use in the survey year. Within Hebei Province, we selected Xinji county because that is the only area where the newest CAAS genetically engineered variety was being cultivated. We chose the sample counties in Shandong Province because one of CAAS's most successful Bt cotton varieties, GK-12, was grown there. Since the Bt program started later in Shandong Province, farmers in Shandong Province still had significant area in non-Bt cotton varieties. After county selection, we randomly selected the villages and farmers within the villages. The final sample came from nine villages in five counties in Hebei and Shandong Provinces.

On average, farmers in our sample sites cultivate 0.78 ha per household. This is higher than the Hebei and Shandong averages (0.43 ha), but nearly the same as in other cotton production regions in Hebei and Shandong (0.7 ha). Cotton and wheat are two of the three most important crops in these provinces and represent two of the most important crops for farmers. One of the most common cropping patterns is winter wheat followed by cotton. Cotton area accounts for 0.42 ha per household, about 39% of total sown area in the five counties surveyed in Hebei and Shandong (Table 3, row 3, column 1).

3.2. Cotton pests and control strategies for conventional varieties

During the fieldwork, it was important for the enumeration team to understand the past and current pest control practices of the sample farmers. Cotton farmers in North China typically spray for aphids and red spider mites early in the season (June–July). In the second half of the season (August–September) farmers spray for cotton bollworm, the crop's major pest.

Table 3
The importance of cotton production in the sampled households by county, 1999[a]

	Five counties	Xinji county	Shenzhou county	Lingxin county	Xiajin county	Liangshan county
Farm size (ha)	0.78 (0.35)	1.16 (0.29)	0.83 (0.24)	0.61 (0.20)	0.74 (0.33)	0.59 (0.28)
Cotton sown area (ha)	0.42 (0.21)	0.47 (0.19)	0.44 (0.15)	0.25 (0.13)	0.50 (0.24)	0.42 (0.21)
Cotton share in total crop sown area (%)	39 (17)	26 (11)	39 (15)	26 (11)	51 (13)	48 (15)

[a] Standard errors in the parentheses. The statistics in the table are from 282 households in five counties of Hebei and Shandong provinces.

At times, farmers must also spray for spider mites later in the season.

The strategy for controlling the bollworm has changed over time, becoming increasingly difficult during the 1990s. Until the early 1990s, farmers could effectively control bollworms with synthetic pyrethroid pesticides. However, by the mid 1990s, bollworms had developed fairly high levels of resistance to pyrethroids. In order to control bollworms farmers increased the number of times they sprayed and mixed the pyrethroids with older organophosphate and organochlorine pesticides, some of which had been banned. During our interviews in 1999, some of the farmers using non-Bt varieties reported they sometimes sprayed their fields every other day during the middle and late part of the season when pest infestations were at their peak. Some farmers estimated that they sprayed 40 times during a single season. At such high levels of spraying, and considering the way most of China's cotton producers purchased, prepared and used pesticides, makes it easy to understand how current pest control methods could lead to fairly serious impacts on health and the environment.

3.3. *The spread of Bt varieties*

Certainly in no small part because of the need for costly, time consuming, and potentially dangerous pesticides for conventional cotton varieties, local officials aggressively extended Bt varieties when they became commercially available. The cotton area under Bt varieties accounted for 91% of total cotton area in 1999 of the sampled farmers (Table 4, rows 1 and 2, column 1). Despite the high level of overall adoption, the rate of adoption varied among the sampled counties, from 100% in the two Hebei counties to 74% in Xiajin county in Shandong Province.

The mix of Bt varieties demonstrates the competition among the producers of Bt cotton. The most common Bt variety used by farmers was that sold by the Monsanto joint venture, 33B (Table 4, columns 2–5). Accounting for 51% of total cotton area, the Monsanto variety covered a greater area than the varieties developed by the Biotech Research Institute of CAAS, GK-12 (24%) and GK-321 (11%), and other varieties sold by other domestic commercial entities in the GK series (6%). According to our survey, however, there

Table 4
Varietal adoption in cotton production in the sampled households, 1999[a]

	Total	Bt				Non-Bt
		33B	GK-12	GK-321	Other Bt	
Total	0.292 (100)	0.149 (51)	0.070 (24)	0.033 (11)	0.017 (6)	0.023 (9)
Hebei						
Xinji	0.306	0.154	0.000	0.152	0.000	0.000
Shenzhou	0.445	0.445	0.000	0.000	0.000	0.000
Shandong						
Lingxian	0.203	0.191	0.000	0.000	0.000	0.011
Xiajin	0.309	0.109	0.080	0.005	0.045	0.079
Liangshan	0.256	0.003	0.212	0.003	0.035	0.003

Values shown are in hectares.

[a] The figures in the parentheses are the varietal area shares (%).

is not a one to one correspondence between the sown area share of a variety and its market share of cotton seed sales through formal seed sales networks. In other words, many farmers are saving and reusing seed from the previous year's harvest or are buying seed from other farmers in informal markets.

3.4. Bt versus non-Bt varieties: pesticide use and profitability differences

If farmers follow the recommended planting and agronomic care directions of the seed companies, the adoption of Bt cotton varieties should lead to large, although not complete, reductions in pesticide use. The design of the genetic structure of Bt cotton should make the cotton crop from being harmed by cotton bollworm, but should not be expected to affect aphids, red spider mites or other insect pests in cotton fields. Seed sellers recommend that farmers continue to chemically control the other insects with traditional spraying methods. For example, the package containing Monsanto's 33B varieties recommends that farmers spray three times in the early part of the season to control aphids and red spider mites.

Even with the continued need to spray for some pests, one of the most remarkable findings of our survey of North China cotton farmers is that those who use Bt varieties sharply reduce their use of pesticides (Table 5). It is clear that these farmers spray fewer times, use less quantity of pesticides and spend less money on them. For example, farmers who did not use Bt varieties sprayed pesticides on average 20 times per season (column 2, row 7). Some households applied pesticides as many as 40 times—virtually every 2–3 days during the middle of the season. In contrast, Bt cotton users *on average* only sprayed 6.6 times per year (row 2), ranging between 3.9 and 9.2 times per season depending on the type of variety (rows 3–6). Alternatively, the quantity of formulated pesticide used on Bt varieties also fell substantially relative to non-Bt users (column 3). For example, farmers using Bt varieties applied 11.8 kg ha^{-1}, less than one-fifth the quantity used by non-Bt cotton farmers (60.7 kg ha^{-1}). The lower pesticide quantities also translated into substantial cost savings for farmers. Bt users spent only about US\$ 31.6 ha^{-1} on pesticides; non-Bt users spent US\$ 177.6 ha^{-1} (column 4).

Table 5
Pesticide use by cotton varieties in the sampled households, 1999[a]

Variety	Sample size[b] (*n*)	Pesticide use per hectare		
		Number of application	Quantity (kg)	Cost (US$)
Total	382	8.1	17.5	49
Bt cotton	337	6.6	11.8	32
33B	178	5.8	10.5	30
GK-12	77	9.2	15.0	41
GK-321	42	3.9	4.4	16
Other Bt	40	7.7	18.6	40
Non-Bt	45	19.8	60.7	178

[a] *Source*: Survey.

[b] Sample size refers to the number of varieties used by 282 sample households. If a farmer planted Bt in one plot and non-Bt variety on another plot, each plot entered sample separately.

Crop budgets for Bt and non-Bt varieties illustrate that the main benefit from moving to Bt from non-Bt varieties comes from pesticide costs savings and from the labour associated with spraying (Table 6). On the revenue side, Bt and non-Bt varieties perform similarly (rows 1–3). The yields of the major Bt and non-Bt varieties are statistically indistinguishable except for GK-321.[3] Since prices for Bt and non-Bt cotton were virtually the same in 1999, total gross revenues of the various varieties are also almost the same.

With the exception of pesticides and labour inputs, the other input costs for Bt and non-Bt varieties are similar. Somewhat surprisingly, seed costs of Bt varieties are not much higher than those of non-Bt cotton (row 6). Despite the higher price per kilogram of Bt seed, the lower seed use per hectare and the use of saved Bt cotton seed nearly offset the price difference.[4] At least in the early stage of adoption, the lack of a significant difference in seed costs alleviates the concerns of some officials that seed companies would capture most of the gains from the new Bt varieties through

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[3] The GK-321 first was adopted by the farmers in our sample villages in 1999. The seed was delivered to the farmers 2 weeks later than the regular planting season, this may have had a negative impact on yield, according to local extension station officials.

[4] The market price of Bt cotton seed was more than US\$ 4.85 kg^{-1} in 1999. Because some farmers in our sample villages were contractors of Bt cotton seed reproduction, and some farmers saved seed or exchange seed after Bt cotton was adopted in the villages, on the average, farmers spent only US\$ 1.77 kg^{-1} on Bt cotton seed and US\$ 0.78 kg^{-1} on non-Bt cotton seed.

Table 6
Per hectare yields of cotton and input of the sampled households, 1999[a]

	Bt				Non-Bt
	33B	GK-12	GK-321	Other	
Total revenue $(\text{US\$}\,\text{ha}^{-1})$	1371	1430	1239	1387	1273
Yield $(\text{kg}\,\text{ha}^{-1})$	3439 (530)	3495 (581)	2814 (532)	3415 (562)	3186 (874)
Cotton price $(\text{US\$}\,\text{kg}^{-1})$	3.29	3.38	3.63	3.35	3.30
Total costs	10730	10625	9905	9289	13636
Non-labour cost $(\text{US\$}\,\text{ha}^{-1})$	609	597	717	558	783
Seed cost $(\text{US\$}\,\text{ha}^{-1})$	66	44	69	69	63
Amount $(\text{kg}\,\text{ha}^{-1})$	30	49	16	50	81
Paid price $(\text{US\$}\,\text{kg}^{-1})$	2.21	0.89	4.33	1.38	0.78
Fertiliser $(\text{kg}\,\text{ha}^{-1})$	1306	1089	2134	997	988
Pesticide cost $(\text{US\$}\,\text{ha}^{-1})$	30	41	16	40	178
Amount $(\text{kg}\,\text{ha}^{-1})$	10.5 (12.66)	15.0 (11.6)	4.4 (3.8)	18.6 (22.0)	60.7 (60.5)
Price $(\text{US\$}\,\text{kg}^{-1})$	2.8	2.7	3.6	2.1	2.5
Labour cost	5705	5701	3990	4683	7178
Amount $(\text{days}\,\text{ha}^{-1})$	554	513	441	460	610
For pesticide use	23	33	19	28	117
Wage (US$ per day)	1.2	1.3	1.1	1.2	1.4
Net revenue $(\text{US\$}\,\text{ha}^{-1})$	104	180	74	267	−270
Return to land and labour $(\text{US\$}\,\text{ha}^{-1})$	762	833	522	828	490
Total costs per kg cotton[b] $(\text{US\$}\,\text{kg}^{-1})$	0.38	0.37	0.43	0.33	0.52

The figures in the parentheses in the yield and amount rows are the standard errors.

[a] *Source*: Authors' survey. Total observations are 382 because some of the 282 households planted more than one variety. The sample distributions are 178 for SSB, 77 for GK-12, 42 for GK-321, 40 for other Bt, and 45 for non-Bt.

[b] Total costs include both labour and non-labour costs.

high seed prices. Fertiliser costs also are nearly the same for Bt and non-Bt varieties (row 9).

The budgets reinforce and amplify the above findings: the main cost savings from Bt varieties show up not only from lower pesticide use (see Tables 5 and 6 row 10), but also in the form of lower labour cost (rows 14 and 15). On average, farmers use 117 days ha^{-1} spraying pesticides on non-Bt varieties compared to 20–30 days for Bt varieties. Most of the difference in total labour use between Bt and non-Bt varieties arise from differences in labour used for pest control. Although labour savings of farmers may not be of immediate benefit, if farmers do not have any alternative activities in which they can engage, in the longer run such gains will turn up in productivity increases and will be key in keeping China's farmers competitive.

Hence, the cost savings from lower pesticide use and the associated labour savings lead to substantial efficiency gains for Bt cotton farmers, especially since gross revenues do not differ much (the last three rows, Table 6). The returns to land and labour for Bt varieties exceed those for non-Bt varieties by more than US\$ 242 ha^{-1}. After adjusting the returns for labour use, evaluated at the local wage, net revenues of Bt users are higher than those of non-Bt users. Whereas farmers that use Bt varieties earn *on average* more than US\$ 121 ha^{-1}, those that continue using non-Bt varieties actually lose US\$ 270 ha^{-1}. In terms of cash and labour costs per kilogram of cotton output, Bt varieties cost US\$ 0.38 kg^{-1}, about 28% lower than the total cost per kilogram for non-Bt varieties (US\$ 52).

3.5. *Multivariate analysis: farmer pesticide adoption analysis*

The descriptive statistics and budget analysis clearly demonstrate that the main gains from the use of Bt come from pesticide reductions. To increase our understanding of the main source of Bt cotton's efficiency gain, in this section we extend the analysis by explaining pesticide use in a multivariate analytical framework. Specifically, we seek to isolate the impact of Bt cotton adoption on pesticide use, after holding other factors constant.

In our multivariate model of pesticide use, in addition to an indicator representing the adoption of Bt cotton,[5] we include variables that measure how profitable the use of pesticide will be, including a measure of the average pesticide price and an assessment of how much of their crop farmer believed that they would lose due to pest problems.[6] We also include a number of characteristics of the farm household, including the education and age of the household head. A variable is included if the household received advice from the local extension service (the variable equals 1 if yes, and 0 otherwise). Finally, we to control for all unobserved, region-specific effects, our empirical model includes a set of county dummy variables. Our farmer's pesticide use (*Pesticide*) model can be specified as

$$\begin{aligned} \mathit{Pesticide} = f\{&\text{profitability (Pmix; Yloss); farmer}\\ &\text{human capital (education and age);}\\ &\text{extension advice; environmental factors}\\ &\text{(county dummies); and the cotton}\\ &\text{variety}\}, \end{aligned} \tag{1}$$

where the dependent variable, *Pesticide*, was defined in three ways: frequency of spraying (times), quantity (kg ha^{-1}), and cost (yuan ha^{-1}) of pesticide application for cotton. To estimate the model in Eq. (1), we use an ordinary least squares (OLS) estimator.[7]

The results of the OLS estimation of Eq. (1) show that our model generally performed well in explaining pesticide use (Table 7). All models have relatively high adjusted R^2 values, ranging from about 0.42 to 0.50, levels that are reasonable for cross-sectional household data. Moreover, a number of the signs of the estimated coefficients of the variables are as expected. For example, the perception of the farmer of the size of yield loss that would result if they did not use pesticides was consistently positive and significant for all three equations (Table 7, row 2). In other words, when farmers expect to incur large losses from cotton bollworms, they spray more.

Most importantly, however, the regression analyses clearly demonstrate the importance of the new products of China's and the world's biotechnological research efforts in reducing pesticide use (Table 7, rows 8–11). Regardless of what measure of pesticide use was used, all of the Bt varieties reduce pesticide use. With all of the other factors in the model held constant, farmers spray 9–13 times less when they use Bt varieties than when they use non-Bt varieties. Pesticide use on Bt varieties falls by 30–44 kg ha^{-1}. Expenditures on pesticides for Bt varieties fall by at least 777 yuan ha^{-1} (US$ 94). All of the results are significantly different than zero. The regression results strongly support the descriptive budgetary analysis: Bt varieties, at least in the sample areas and at least during the early years of their use by farmers, lead to significant pesticide reductions.

Two of our findings, however, suggest that China's past and future efforts in pesticide reduction may have to rely on new technologies, such as Bt, since traditional policy channels are less effective. First, the low *t*-ratios on the coefficients of the price variable in the 'frequency', 'quantity' and 'cost' linear equations suggest that farmers are not responsive to the price change in their application of pesticide (Table 7, row 4). One explanation is that given the farmer's perception of potential of crop loss from pests (that is accomplished in the regression by including the variables in rows 2 and 3), farmers will apply as much pesticide as necessary, regardless of the marginal price change. If so, the scope for reducing pesticides by using policies that would increase the price of pesticides, such as a tax on the input, might have little impact on its use.

Second, the coefficients of the variable representing the contact that farmers have had with the extension service are not significantly different than zero (Table 7, row 7). Despite the mandate of the extension agents to promote IPM and many years of support by the Ministry of Agriculture, it appears that frequent

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[5] To differentiate the impact of various varieties from the different seed sources, a dummy variable was included for the type of cotton variety of cotton that was used by each farmer. The excluded dummy variable group is the one for those farmers using non-Bt varieties.

[6] To get this measure of expected pest pressure, during the survey, enumerators asked farmers to provide them with a percentage yield loss that they would expect to suffer from pest should they not spray.

[7] We tried two functional forms, a linear model and log linear model. The results are nearly identical. In the following discussion, only the results from the linear model are discussed.

Table 7
Estimated parameters for farmers' pesticide application in cotton production in Shandong and Henan, China

Variables	Pesticide applications (model in linear form)		
	Number (time)	Amount (kg ha^{-1})	Cost (yuan ha^{-1})
Intercept	20.166 (2.23)***	54.581 (5.65)***	1273.230 (5.97)***
Farmer's perception on yield loss (%)			
The first and second generations of bollworms	−0.003 (0.01)	0.042 (1.04)	0.804 (0.90)
The third and fourth generations of bollworms	0.026 (3.39)***	0.142 (4.32)***	3.090 (4.26)***
Average pesticide price (US$ kg^{-1})	−0.004 (0.62)	−0.022 (0.86)	0.345 (0.61)
Age (years)	−0.021 (0.69)	0.045 (0.33)	1.218 (0.41)
Education (years)	−0.034 (0.34)	−0.707 (1.61)*	−10.926 (1.13)
Bt varieties (dummies variables)			
33B	−8.717 (8.44)***	−30.303 (6.76)***	−777.380 (7.85)***
GK-12	−10.797 (9.11)***	−43.871 (8.53)***	−1091.300 (9.61)***
GK-321	−10.881 (7.50)***	−34.885 (5.55)***	−878.200 (6.32)***
Other Bt varieties	−12.149 (9.26)***	−39.537 (6.95)***	−1082.510 (8.61)***
Advice from extension service (dummy variable)	−0.024 (1.18)	−0.090 (1.02)	−2.425 (1.25)
Xinji county	−4.788 (3.45)***	−16.286 (2.71)***	−374.020 (2.82)***
Shenzhou county	−7.031 (5.07)***	−20.384 (3.39)***	−456.660 (3.43)***
Lingxian county	−6.552 (5.12)***	−21.699 (3.91)***	−521.950 (4.26)***
Xiajin county	0.666 (0.68)	0.733 (0.17)	40.250 (0.43)
Adjusted R^2	0.502	0.416	0.452

Note: The figures in the parentheses are *t*-test values.
* Denote significance at 10%.
*** Denote significance at 1%.

contact between extension agents and farmers has not resulted in the adoption of pesticide-reducing technologies. This result, although unfortunate from the perspective of those interested in non-chemical methods of promoting pest control, should not be surprising.[8]

4. Summary, implications and policy suggestions

The main finding of our analyses is simple but strong and consistent: the spread of Bt cotton substantially reduced pesticide use of our sample farmers. In contrast, extension contact and pesticide prices had little effect on pesticide use. Thus, two alternative means of reducing pesticide use do not appear to be very useful. According to our results—assuming we can use them to generalise about the rest of China—any reduction in the use of pesticides in the recent years (or in the future) was most likely due to the spread of Bt cotton. This also would mean that if pesticide reductions can be associated with improvements to human health, these improvements must also be at least partially credited to the spread of Bt cotton.

According to this logic, Bt cotton may already have had fairly major effects on China's use of pesticides

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[8] Nyberg and Rozelle (1999) have summarised the literature (e.g. Huang et al., 2000a,b,c) that has examined the operation of China's extension system. During the 1990s, although the duties of the extension system did not change (i.e. they were still supposed to be extending new technologies, such as IPM), agricultural officials cut the salaries of extension agents and reduced the responsibility of the budget office to pay their wages. In return, however, the 'reforms' allowed extension agents to sell farm chemicals to farmers, keeping part of the profits as compensation for their extension service efforts. However, as pointed out by Park and Rozelle (1998), such a system frequently contains a set of adverse incentives. Because upper level officials have trouble monitoring the actions of the on-the-ground agents, the agents' policy duties can be ignored if they conflict with his/her other personal objectives (such as income generation). If so, in the case of addressing their pest control responsibilities, it is easy to understand why extension agents might have an incentive to recommend high levels of spraying, since such recommendations could lead to higher pesticide sales and higher income for the extension agent-cum-pesticide dealer. At the same time, the agent could decide to not seriously push technologies such as IPM, because they would not necessarily contribute to the agent's income.

and even may have improved human health. Hebei Province agriculture bureau officials told us in interviews that 80% of cotton farmers in the province were using Bt cotton in 2000. Industry executives concur. Our own observations also support such a supposition. Likewise, in Shandong Province, in the second year after Bt was approved for commercial use, more than half farmers were growing Bt cotton.

Assuming the adoption trends are accurate, an examination of the government's data on pesticide use (SDPC, 1997–2000) demonstrates the aggregate impact that Bt cotton may be having on pesticide use. Cotton producers in Hebei and Shandong Provinces are by far the largest users of Bt cotton. Measured in real terms, farmers have continuously reduced their use of pesticides from US\$ 123 and 117 ha^{-1} in 1996 to only US\$ 40 and 84 ha^{-1} in 1999, a reduction of 69 and 27%, respectively. During the same 4-year period cotton farmers in Zhejiang and Hunan Provinces (provinces that had not had access to commercially approved Bt varieties) increased per hectare pesticide use by 50% in Zhejiang and 16% in Hunan. In fact, the introduction of Bt most likely contributed to a reversal of the rankings of provinces in terms of their pesticide use. Pesticide use per hectare in Bt-adopting provinces went from more than double the levels of non-Bt provinces in 1996 to levels in which Bt cotton farmers used 15% less pesticide per hectare than non-Bt cotton farmers in 1999. The regional trends are almost completely responsible to the fall in national per hectare pesticide use between 1998 and 1999.

The size of the total reductions in pesticide use and expenditure due to Bt also is impressive. After controlling for other factors, in our sample, Bt cotton farmers on average reduced pesticide use by 37 $\mathrm{kg\,ha}^{-1}$ or US\$ 116 ha^{-1}. If such unit reductions are representative of the areas that are using Bt cotton reported in Table 2, our findings suggest that Bt cotton has reduced pesticide use by more than 44,000 t or about US\$ 138 million in the first 4 years of the variety's adoption. With the potential to extend Bt cotton to Hubei, Anhui and Jiansu and other major cotton production regions in North China and Yangze River regions in the near future, the economic (and associated environmental) benefits of Bt cotton are expected to increase significantly.

The evidence is quite clear that Bt cotton reduces pesticide use, at least in the short run. But the impact of reducing pesticide use on human health and the environment depends in part on which pesticides were reduced due to the adoption of Bt cotton. If the reduction is the form of relatively safe pesticides like the synthetic pyrethroids or malathion, we would not expect much impact on human health. If the reduction occurs in the form of more dangerous pesticides, such as any of the CH pesticides or organophosphate parathion, we would expect that poisonings of farmers would decline and that the impact on the environment to be greater because many of the chemicals are persistent in the environment.

Table 8
Average quantity ($\mathrm{kg\,ha}^{-1}$) of farmers' pesticides use by type of pesticide

	Average quantity ($\mathrm{kg\,ha}^{-1}$)		Decline in use (%)
	Bt varieties	Non-Bt varieties	
Organochlorines	0.21	1.84	88
Organophosphates	9.33	51.92	82
Amino-formic acid esters	0.35	0.16	Increase
Pyrethroids	0.79	14.48	95
Organosulphates	1.37	2.24	39
Other insecticides	0.54	1.26	57
Fungicide	0.33	0.00	Increase
Herbicide	0.57	1.15	50
Sum	13	73	82
Sample size	276	44	

Source: Calculated from authors' survey.

Table 8 shows that in our sample villages, the use of organophosphates fell the most. Thus, we would expect to see fewer poisonings of farmers who use Bt cotton. The use of organochlorines was also reduced, but the level of reduction was relatively small, in part because they were already at a low level of use. The decline in the use of organochlorine varieties of pesticides should lead to a fall (or at least a slowing) in the level of some of the worst types of pesticide residues in China's rural soil and water.

Our data also contain some preliminary evidence that a reduction in pesticide use also might help improve human health (Table 9).[9] Farmers were asked

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[9] Given our small sample size, we understand that there is almost certainly no statistical significance in our findings. We present the findings mainly as a way motivate the types of improvements in

Table 9
Environmental and health impacts, 1999

Varieties of cotton cultivated	No. of farmers	Pesticide quantity[a] (kg ha^{-1})	Number and seriousness of poisonings[b] reported in 1999 season (% farmer household)
Only Bt varieties	236	10.3	4.7
Both Bt and non-Bt varieties	37	29.4	10.8
Only non-Bt varieties	9	57.8	22.2

Farmers were asked if they had a headache, nausea, irritated skin or digestive problems after applying pesticides.

[a] *Source*: Authors' survey.

[b] Total pesticide (active + inert ingredients).

if they had headaches, nausea, skin pain or digestive problems when they applied pesticides. Of the cotton growers who only used Bt cotton 4.7% reported poisonings. Of the farmers who planted both Bt and non-Bt cotton 11% of the farmers reported poisonings. Of the farmers who only grew conventional cotton, 22% reported poisonings. These results, although based on a very small sample, are consistent with the findings of Rola and Pingali (1993) and Huang et al. (2000c), two papers which demonstrate that the longer term impacts of pesticide exposure is significant.

Could genetic modified crops have an impact on pesticide use in other crops? Huang et al. (2001) show that nearly 20 genetically modified crops developed by Chinese scientists with resistant to various insects and diseases are in the pipeline, and have been approved for either field trial or environmental release. Bt maize, which is designed to resist corn borer has been tested in field conditions for several years in northern China. It is expected that this could have a major impact in the northeast where corn borers are a problem. Bt rice, in particular, varieties that were bred for resistance to yellow stem borer, striped stem borer and leaf folders have been tested in the field since 1998 in China (Huang et al., 2001; Cohen et al., 2000). Since these pests are important in large areas of China, Bt could have an important impact on the production. More pesticides per hectare are applied to rice than any other crops and farmers apply high levels of pesticides per hectare (Table 2). Thus, Bt varieties of rice could lead to even greater reductions in chemical use in the future. The reduction of pesticide use in food crops should not only have an important impact on reducing poisoning of farmers, it should also contribute to human health by reducing the residual pesticide that is left on food.

Overuse of pesticides in China has been well documented in the literature. The government has succeeded mostly in shifting farmers away from the use of organochlorines in favour of less persistent pesticides. China has made a major investment in a national plant protection system that is supposed to promote integrated pest management. Unfortunately, it has had little success in reducing chemical pesticide use. Biotechnology, however, appears to offer a product that can dramatically reduce pesticide—Bt and other GE crop varieties. Even with relatively limited investments of government money in research, extension and seed production, Bt cotton varieties are spreading rapidly. These varieties were developed and popularised by several foreign and domestic companies and research institutes. Farmers have adopted them because they reduced the costs of production without reducing total revenues and because they reduce their exposure to dangerous chemicals.

The findings suggest that the government may want to invest the money necessary to spread Bt to other cotton regions and to other crops. The important caveat is that government investments in regulation of biotech will have to be increased to ensure that widespread use of Bt does not lead to the rapid development of bollworms that are resistant to it.

The second implication of these findings is that the government plant protection system is not meeting the goal of reducing pesticide use. This fits with anecdotal evidence that we heard during our interviews with seed company managers and farmers. Plant protection people often recommend that farmers not use Bt cotton or at most recommend more pesticide applications

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human health that might result from such high levels of pesticide use reduction. Further research, however, is needed. In our other work (Huang et al., 2000a,b,c), we do find statistical correlation between pesticide use and human health—both acute and chronic effects.

than the seed companies. The government needs to separate IPM activities and staff of the plant protection system from the pesticide sales activities. The government also must give the extension service incentives to push IPM and other non-pesticide-related forms of pest control. One option would be to substantially increase the salaries of the IPM staff to compensate for the loss of income from pesticide sales and provide them with bonuses for reducing chemical use.

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