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Transgenic varieties and productivity of smallholder cotton farmers in China*

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Genetically modified cotton varieties have greater production efficiency for smallholders in farming communities in China. We also find that the adoption of *Bacillus thuringiensis* (Bt) cotton varieties leads to a significant decrease in the use of pesticides. Hence, we demonstrate that Bt cotton appears to be an agricultural technology that improves both production efficiency and the environment. In terms of policies, our findings suggest that the government should investigate whether or not they should make additional investments to spread Bt to other cotton regions and to other crops.

1. Introduction

Farmers in developing countries, including China, have greatly increased production of food and fibre crops during the past several decades in no small part as a result of increases in the use of modern inputs, especially farm chemicals. Particularly after the spread of modern, semi-dwarf, high-yielding varieties in the 1960s and 1970s which increased greatly both the intensity of farming within a season and the intensity of the rotations on a plot within a year, China's producers began using increasingly higher levels of pesticides to offset and avoid damage inflicted by insects and diseases (Rola and Pingali

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1993). Although the lack of consistent data makes international comparisons difficult, a recent study by the authors argues that since the mid-1990s China has become the largest pesticide user in the world (Huang *et al.* 2000c).

While the rising level of pesticide use certainly has helped China raise production, the high, perhaps excessively high, levels of pesticide use may have had a number of adverse consequences. Pesticides may pose a serious danger to the soil and water quality of the agro-ecosystem (Smil 1993; Rozelle *et al.* 1997); human health (Rola and Pingali 1993; Pingali *et al.* 1997; Huang *et al.* 2000b); and food safety (Liu *et al.* 1995). In fact, the negative indirect effects and social costs in some cases may exceed the private cost of purchasing pesticides (Huang *et al.* 2000b).

Recognising the negative externalities of excessive pesticide use, China's government has made an effort to regulate pesticide production, marketing, and application since the 1970s. The experience with regulation, however, has shown that when officials only promulgate rules and monitoring costs are high, reductions in the use of pesticides, the elimination of banned toxic ones, or the increase in the adoption of safe application procedures do not always follow. In many regions of the country, and in the case of many crops, farmers still use high levels of sometimes highly hazardous pesticides (MOA 1990–1999; Huang *et al.* 2000b).

As a result, real reductions in the use of pesticides may have to depend on alternative approaches, such as the introduction of new technologies. For example, the spread of host-plant resistant varieties in the past two decades has effectively reduced pesticide use without affecting yields (Widawsky *et al.* 1998; Pray *et al.* 2001; Huang *et al.* 2000a). China's effort to produce and promote host-plant resistant varieties has successfully extended such varieties to almost 100 per cent of China's rice, wheat, and maize area.

Despite such success, challenges remain in China's battle against pests. One study provides evidence that the effectiveness of older rice varieties has fallen over time because of the rising resistance of pests (Widawsky *et al.* 1998). Interviews with wheat breeders revealed that breeding resistance to certain diseases takes up an increasing part of the effort of breeders. In some cases, most notably that of cotton, despite intensive conventional plant breeding efforts, the resistance of pests to the natural defenses of resistant varieties has built up to such an extent that crop damage has risen despite increasingly intensive pesticide spraying campaigns.

In response to both the previous successes in traditional plant breeding and the continuing difficulties of mounting resistance, since the late 1980s scientists in China have followed the lead of others in the USA and elsewhere and started developing crops that are genetically engineered to be resistant to important pests (Huang *et al.* 2001). One of the most successful genes to be inserted into plants is one from the bacteria *Bacillus thuringiensis* (Bt).

The Bt gene has been used as a natural pesticide for decades. Currently, China's breeders are developing and testing about 20 genetically modified crops (Huang *et al.* 2001).

Because of a perceived crises in the cotton sector – due to the ineffectiveness of cotton varieties produced by conventional breeding methods and the rising use of pesticides by farmers – in 1997 the Ministry of Agriculture approved the commercial use of cotton varieties that were genetically engineered with a Bt gene to produce the toxin that kills bollworms. Monsanto in a joint venture with the Hebei provincial seed company introduced an American cotton variety that had been genetically engineered. The Institute of Biotech Research of the Chinese Academy of Agricultural Sciences (CAAS) introduced and extended several local cotton varieties that were engineered to include Bt in the same year. The Chinese Cotton Research Institute of CAAS in Henan has also released Bt cotton varieties. Various estimates of Bt cotton area in 2000 ranged from 400 000 to 700 000 hectares. Whatever the estimate, it is clear that cotton producers are among the millions of farmers who are using transgenic varieties.

But despite the unprecedented release and adoption of genetically modified cotton varieties, little is known about the impact they have had on the farm households using them and on the overall agricultural economy in which they are being extended.[1] Has the adoption of Bt varieties of cotton affected the use of pesticides in China? If so, by how much? Once adopted and after accounting for pesticide use, has the adoption of Bt cotton affected yields? If so, by how much? And, more methodologically orientated, how should the impact of Bt cotton on yields be best measured?

To meet our goal, the rest of the paper is organised as follows. In Section 2, we describe the data set that we collected during a 1999 farm household survey. A total of 282 cotton farmers were randomly selected from 10 villages in five counties from Hebei and Shangdong. In Section 3, an overview of the pest-related crop yield losses and measures to control the pest problems in China are presented. Section 4 develops an empirical model that will be used to measure the economy of transgenic crops with resistance to pest. The models then are estimated using our data and the results of econometric estimation are presented. Conclusions and policy implications from this study are provided in the final section.

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[1] Such issues have been explored in the USA (e.g., Marra *et al.* 2001), though they did not estimate the productivity gains from a production function perspective as we do.

2. Data

To examine the impact of biotechnology on pesticide use in the cotton sector, we collected our own data set in 1999. Our own data collection was necessary because China's government does not have a program to track the cost of production of transgenic crops. In total, we collected data on the production practices of 282 cotton farmers. As farmers use Bt and non-Bt varieties, we have information on 382 varieties.[2]

The enumeration team put in considerable effort to choose the sample. As 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 select our provinces and counties carefully. During fieldwork we discovered from interviews with agricultural bureau officials that in many counties 100 per cent of the farmers were growing Bt cotton; in other areas, the proportion of farmers growing Bt cotton was less. 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, according to breeders in CAAS, that is the only area in which its newest 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. As the Bt program started later in Shandong Province, farmers still had a significant area in non-Bt cotton varieties. After county selection, we randomly selected the villages and farmers within the villages. The final sample comes from nine villages in five counties in Hebei and Shandong Provinces.

Descriptive statistics illustrate that our sample of farmers are fairly typical (table 1, columns 1 and 2). Farmers cultivate an average of 0.78 hectares per household, higher than the average in Hebei and Shandong provinces (0.43 hectares), but nearly the same as the cotton production regions in Hebei and Shandong (0.7 hectares). Cotton area accounts for 0.42 hectares per household, about 39 per cent of total sown area in the five counties surveyed in Hebei and Shandong (rows 2 and 3).

Users of Bt and non-Bt cotton also appear to be fairly similar (table 1, columns 3–6). Although cotton area under Bt varieties in the sample region accounts for approximately 90 per cent of total cotton area and 86 per cent of households in 1999 (bottom row), there are no apparent systematic

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[2] It is possible as 382 varieties were grown by 282 farmers that when more than one variety was grown by a single farmer, there is a systematic correlation between certain observations. In results not shown, we account for this by including a 'cluster' effect. The results did not substantially change. We also estimated the sample using only one variety per farmer (choosing it randomly) and there also was little substantive difference in the results.

Table 1 Summary statistics of Bt and non-Bt cotton production in sample households in China, 1999

	All sample		Bt cotton		Non-Bt cotton	
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
Farm size (ha)	0.78	0.35	0.78	0.35	0.77	0.33
Cotton sown area (ha)	0.42	0.21	0.41	0.20	0.51	0.25
Cotton share in total crop sown area (%)	39	17	37	17	47	13
Age (years)	43.1	8.9	42.8	8.9	45.0	9.1
Education (years)	7.5	3.0	7.6	3.0	6.5	2.8
Yield (kg/ha)	3349	627	3371	584	3186	875
Cotton price (yuan/kg)	3.36	0.75	3.37	0.80	3.29	0.14
Ratio of phosphate fertilizer	0.30	0.20	0.31	0.20	0.23	0.14
Ratio of potash fertilizer	0.17	0.17	0.18	0.17	0.13	0.12
Fertilizer use (kg/ha)	399	195	407	200	339	147
Number of pesticide applications (times)	8.1	7.2	6.6	4.2	19.8	12.7
Amount of pesticide use (kg/ha)	17.5	28.9	11.8	13.7	60.7	60.5
Cost of pesticide (yuan/ha)	403	661	261	267	1465	1388
Pesticide price (yuan/kg)	34.5	46.6	35.9	49.4	23.9	8.0
Labor use (days/ha)	530	222	519	223	610	205
Number of observations (*n*)	382		337		45	

Note: The statistics in the table are from 282 households in five counties of Hebei and Shandong provinces. Some farmers use two or more than two varieties, including both Bt and non-Bt cotton varieties.

differences in the type of farmer that is using Bt cotton. T-tests (between columns 3 and 5) demonstrate that there are no statistically significant differences among Bt and non-Bt farms in terms of farm size, cotton area, or the age or education of the farm household head. Based on these comparisons, it appears as if there is little problem of selection bias in our sample.

3. Producing Bt and non-Bt cotton in China

Yields, prices and the mix of fertilizers used for the Bt and non-Bt varieties are mostly similar (table 1, rows 6–9). On average, the yield of Bt cotton is only 5.8 per cent higher than non-Bt cotton (and it is statistically significant at the 10 per cent level). The prices that farmers get for Bt and non-Bt varieties are virtually the same.[3] Although the mixes of fertilizers (the ratios

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[3] The differences between Bt and non-Bt cotton prices can be said to be statistically the same at the 95 per cent level of significance. In a follow-on survey the following year, the differences in prices between Bt and non-Bt varieties were even closer.

of phosphates and potash to total fertilizer use) are somewhat different, breeders believe that most of the differences had to be due to differences in the soil conditions in the sample areas; in field trials, Bt and non-Bt crops respond identically to phosphate and potash.

In other ways, the production technology of Bt and non-Bt vary sharply (table 1, rows 10–15). For example, Bt cotton farmers use more fertilizer. On average Bt cotton farmers apply 407 kilograms per hectare of chemical fertilizer, a level that is nearly 70 kilograms per hectare, or 20 per cent more, than that used by non-Bt cotton farmers.

The largest difference between Bt cotton and non-Bt cotton production is in the use of pesticides. Bt cotton farmers apply pesticide only 6.6 times per season compared to nearly 20 times per season by non-Bt cotton farmers. On a per hectare basis, the pesticide use of non-Bt cotton production is more than fivefold higher than Bt cotton in terms of both quantity and expenditures. Bt cotton farmers spend 261 yuan per season on pesticide for spraying for non-bollworm pests while non-Bt cotton users spend 1465 yuan. Because of the reduction of pesticide application in Bt cotton, Bt cotton farmers reduce their total labour output by 15 per cent when compared to non-Bt cotton farmers, including labour saved from pesticide application and pest monitoring in the fields.

3.1 Crop production loss and abatement

The frequency of pest outbreaks in the cotton sector has been increasing sharply over time in China, some estimating that the frequency of infestations have doubled over the last 10 years (Huang *et al.* 2000c). Increases in the intensity of crop production, longer periods of time when the crops are not monitored due to rising wages, and excessive pesticide use have led to higher pest populations and to higher resistance of pests to the pesticides that once effectively controlled them.

Because of the high incidence of pest infestations of China's cotton crop and the high levels of spraying, the amount of loss to the cotton crop and the amount of loss that was abated due to spraying is high and exceeds that of grain (table 2). Nationally, the Ministry of Agriculture's pest prevention teams estimate that cotton yields have been reduced by 5.3–14.0 per cent due to pest infestations in the 1990s (column 2). The levels of loss were higher in some of the important cotton producing provinces, such as Hebei Province (column 4). In fact, the infestations from pest and the loss that such infestation potentially could cause are even more severe (rows 6–10). Had farmers not sprayed, cotton yields in China would have fallen nationally by 19.0–38.1 per cent (column 2); those in Hebei and Shandong Provinces would have fallen even more (columns 4 and 6). The larger 'gain' (or, more

Table 2 Official estimates of pest-related losses and losses abated by pest control efforts in China, 1990–1997

	National		Hebei		Shandong	
Year	Grain	Cotton	Grain	Cotton	Grain	Cotton
Proportion (%) of losses due to pest infestations						
1990	3.2	5.3	2.9	11.6	5.0	5.1
1992	2.0	14.0	3.3	39.9	3.5	17.0
1994	2.0	11.8	1.9	9.7	3.5	8.9
1996	2.1	6.2	2.2	13.2	3.3	5.9
1997	2.4	6.3	2.2	13.7	3.4	5.1
Proportion (%) of losses to crop production abated by pest control efforts						
1990	7.6	19.0	6.6	32.6	10.1	21.5
1992	6.8	31.1	7.5	77.1	11.1	52.7
1994	7.2	38.1	6.9	43.8	11.4	43.5
1996	7.9	26.6	8.2	51.9	12.1	34.9
1997	9.3	29.1	8.6	73.2	12.5	31.9

Note: Actual crop production loss (a better term is 'official estimate of crop production loss') is due to inability of pest control effort by farmers. Crop production loss abated from the pest is the avoided loss after the existing pest control effort in the farm field.
Source: Computed by authors based on the data from Ministry of Agriculture, Agricultural Yearbook of China.

accurately, the avoidance of loss) of cotton farmers when compared to those of grain farmers come from the fact that pest infestations are more serious and pesticide use is higher than those of grain farmers. For example, pesticide use per hectare in cotton production was nearly fourfold in rice (Huang *et al.* 2000a).

China's data, in fact, are consistent with the observation that increasing pest populations have meant that farmers need to spray increasingly greater amounts of pesticides to control them (table 3). Measured in constant prices, per hectare, pesticide use on cotton rose nearly 300 per cent in two decades (row 1). The rise in pesticide use grew faster than the rate of the use of other inputs. The share of pesticide cost in the total cost of production inputs rose from 12 to 13 per cent in the early 1980s to more than 20 per cent after the mid 1990s (row 2). China's cotton farmers spent more than $500 million annually on pesticides to control pest-related problems in the late 1990s (row 3).

What are the costs of spraying? Without accounting for the effect on human health or the environment, Huang *et al.* (2000b) demonstrate that the gains by farmers from the pesticide use are much higher than the costs farmers paid for the pesticide. Hence, there is a high 'private' incentive for farmers to apply pesticide on crops, particularly on cotton crops.

Table 3 Pesticide use in cotton production in China, 1980–1998

	1980	1985	1990	1995	1998
Per hectare pesticide use (yuan/hectare at 1995 prices)	257	292	381	834	724
Share of pesticide cost in total material costs (%)	13	12	18	22	20
Total value of pesticide applied (million US$)	280	172	356	542	418

Note: Rural retail price index of pesticides is used to deflate the current value.
Source: State Economic Planning Commission and State Statistical Bureau (1998).

3.2 The spread of Bt cotton

China has pursued a policy that has encouraged the release of Bt cotton varieties perhaps because of the high level of pesticide use and the possibility that pests are becoming resistant to popular types of traditional chemical pesticides. By almost all indications, cotton has become the most widespread and aggressive transgenic crop program for smallholders in the world. In terms of sown areas, Bt cotton is the most extensively grown transgenic crop in China today. The official government estimates of Bt cotton area in 2000 ranged from 400 to 500 thousand hectares (personal communication with MOA officials in December 2000). During interviews with a number of industry analysts and executives, estimates had already reached one million hectares 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 industry estimates. Starting from only 2000 hectares in 1997, the area of Bt cotton grew to around 700 thousand hectares in 2000 (Huang *et al.* 2000a). By 2000, we estimate that farmers planted Bt varieties on 20 per cent of China's cotton increase. Whatever the source of the estimates, the growth of Bt cotton has been remarkable in China in the last 3 years.

The expansion of Bt cotton across China, however, has not been even. For example, after being the only province to grow Bt cotton in 1997, cotton farmers in Hebei account for approximately 30 per cent of the sown area in 2000, 220 thousand hectares. Shandong Province ranks second in Bt cotton sown area at 170 thousand hectares. In contrast, other provinces, particularly those with lower levels of cotton bollworm infestation, have little or no area sown to Bt varieties.

4. Model and estimation

Several economic studies have questioned whether current patterns of pesticide use are economically and socially efficient (e.g., Pimentel and

Lehman 1992; Pingali and Roger 1995; Yudelman *et al.* 1998). Some studies show that the costs, both economic and social, related to pesticide use in crop production exceed the gains from the reduction of crop yield losses (Pingali and Roger 1995). While studies of pesticide productivity are relatively common, few researchers have assessed farmer pesticide use behaviour, and no study has been done on the productivity of varieties with built-in pesticides, such as genetically modified Bt varieties.

4.1 Damage control production function

In our study, we use a production function approach to estimate the impact of pesticide use and Bt cotton variety adoption on crop productivity. It attempts to determine the value and impact on cotton production of two different types of variables: first, abatement inputs such as chemical pesticide use and/or host plant resistant varieties, in particular Bt varieties; and second, traditional inputs such as fertilizers and labour. *Ceteris paribus*, the use of chemical pesticides and host plant resistant varieties does not increase yields per se. Instead their primary role is to abate damage or keep output from falling. In contrast, the use of inputs, such as fertilizer and labour, contribute by directly increasing yields.

In our study, we examine two damage abatement inputs: pesticides and Bt cotton varieties. Conceptually, Bt cotton varieties differ from chemical use only in the way that they control certain pests, because Bt cotton is a genetically engineered crop that produces a naturally occurring pesticide: the *Bacillus thuringiensis* (Bt) toxin. In this way, Bt varieties are acting as an input that can substitute for the use of pesticides. Practically, one of the main production outcome differences between cotton farmers that use Bt varieties and those that do not is the difference in the amount of pesticide required to control pests.

When working to model and empirically track the impacts of pesticides and Bt varieties on output, special attention needs to be given to the special nature of the inputs. In production function analysis, the effect of damage abatement inputs must be measured assessing the amount of yield or output that was ‘recovered’ by the use of damage abatement inputs. Following the works by Headley (1968) and Lichtenberg and Zilberman (1986), a damage abatement function can be incorporated into the traditional models of agricultural production. However, unlike all but several previous works (including our own work on rice – Widawsky *et al.* 1998), we will include host plant resistant varieties into our analysis within the damage abatement approach. We do this primarily by allowing for the interaction between pesticides and Bt varieties.

The nature of damage control suggests that the observed crop yield, Y, can be specified as a function of both standard inputs, X, and damage control measures, Z, as:

$$Y = f(X)G(Z), \tag{1}$$

where the vector X includes labour, fertilizer, other farm-specific factors that affect yields (such as the human capital characteristics of the farm household that are proxied by the household head's age and education level) and location-specific factors (a set of county dummy variables). The term, $G(Z)$, is a damage abatement function that is a function of the level of control agents, Z (in our case, Z includes the pesticides used by farmers to control pests during outbreaks). The abatement function possesses the properties of a cumulative probability distribution. It is defined on the interval of [0, 1]. When $G(.) = 1$, it means that there has been a complete abatement of crop yield losses due to pest related problems with certain high level of control agent; when $G(.) = 0$, it means that the crop was completely destroyed by pest related damage. The $G(.)$ function is non-decreasing in Z and approaches one as damage control agent use increases. If we assume a Cobb-Douglas production function, $f(X)$, and if we assume that the damage abatement function, $G(Z)$, follows a Weibull or Exponential specification[4] then equation (1) can be written as:

$$Y = a_0 \Pi_i^n X_i^{a_i}[1 - \exp(-Z^m)], \qquad \text{(Weibull)} \tag{2}$$

$$Y = b_0 \Pi_i^n X_i^{k_i}[1 - \exp(-cZ)], \qquad \text{(Exponential)} \tag{3}$$

where a_0, a_i, m in (2), and b_0, k_i, c in (3) are parameters to be estimated, and m and c are restricted to be positive. The i indexes inputs, including labour and chemical fertilizer. The variable Z represents pesticide use. The models in equations (2) and (3) could be estimated for Bt cotton and non-Bt cotton separately.

However, because Bt cotton differs from non-Bt cotton mainly in the pest control efforts that farmers use to control bollworms, it is possible to explicitly model the interaction.[5] To do so, we can pool data on Bt and non-Bt cotton to estimate a more general damage control production function

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[4] We use different functional forms in our analysis, because as shown in Fox and Weersink (1995), results can be sensitive to functional form.

[5] It is possible that we could allow all parameters to vary by Bt and non-Bt crops. However, the descriptive statistics show that the other inputs are used at levels that are approximately the same levels in both Bt and non-Bt cotton. Crop breeders and extension agents also claim that one of the factors that has helped in the success in the spread of Bt is that it is used almost identically to that of traditional non-Bt varieties. Hence, in the rest of the present paper we assume that the response of Bt and non-Bt yields differ only by its response to pesticide. The relatively small sample of non-Bt users is a practical factor that reinforces this assumption.

with the following assumptions on the nature of the Bt and pesticide interactions:

$$m = m_0 + m_1 Bt \tag{4}$$

$$c = c_0 + c_1 Bt \tag{5}$$

where *Bt* is a dummy variable with a value of 1 for Bt variety and 0 otherwise. The models (2) and (3) combined with the working hypotheses (4) and (5) are estimated by non-linear methods. In order to compare the results from the traditional production approach, we estimate a Cobb-Douglas production function using OLS, where pesticide use and Bt cotton adoption are specified the same as other inputs such as labour and fertilizer.

Marginal impacts of pesticide use on cotton yield for the preceding models can be estimated as:

$$\mathrm{MP}(Z) = a_0 \Pi_i^n X_i^{ai}[\exp(-Z^m) m Z^{m-1}], \qquad \text{(Weibull)} \tag{6}$$

$$\mathrm{MP}(Z) = b_0 \Pi_i^n X_i^{ki}[\exp(-cZ)(c)], \qquad \text{(Exponential)} \tag{7}$$

The impacts of Bt cotton on the marginal products of pesticide use can be examined through the equations (6) and (7) by using the different values of the parameters associated with Bt and non-Bt varieties from equations (4) and (5). The optimal pesticide use level can also be estimated for both Bt and non-Bt cottons based on the assumption that the efficient use of pesticide requires that the value of its MP equals its price. Finally, the impact of Bt cotton on the crop yield can be measured as:[6]

$$\mathrm{DY} = a_0 \Pi_i^n X_i^{ai}[\exp(-Z^m)\ln(Z) Z^m m_1], \qquad \text{(Weibull)} \tag{8}$$

$$\mathrm{DY} = b_0 \Pi_i^n X_i^{ki}[\exp(-cZ) Z c_1]. \qquad \text{(Exponential)} \tag{9}$$

4.2 Empirical specification and estimation of pesticide use equation

The models specified above do not account for one potential statistical problem: the endogeneity of pesticide use in the production function. As pesticides are applied in response to pest pressure (which is not controlled for in the analysis), high levels of infestations may be correlated with lower yields. Hence, it is possible that the covariance of *Z* and the residuals of the yield function is non-zero, a condition that would bias parameter estimates of the impact of pesticides on output. In other

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[6] Given that the Bt and non-Bt varieties are only assumed to have different abatement functions, the differences in productivity of the two varieties are actually the difference in the two outputs ($Y_{Bt} - Y_{non\text{-}Bt}$), and our estimates are most accurate when cZ is small.

words, pesticides used by farmers may be endogenous to yields and a systematic relationship among plant pests, pesticide use, and cotton yields may exist.[7] Because of the nature of potentially omitted variables and correlations, not accounting for the endogeneity could lead to a bias in the coefficient.

To avoid this possible econometric problem, we adopt an Instrumental Variable (IV) approach. To develop an instrument for pesticide application that is correlated with actual pesticide use but does not affect output except through its impact on pesticides, a pesticide use model is estimated. The predicted values of the pesticide use can then be used in the estimation of models (2) and (3). As long as a set of variables in the pesticide use equation exists to explain pesticide use, and these variables do not have any independent explanatory power on yields, the IV approach should allow us to better examine the impacts of Bt and pesticides on cotton output and the interactions of these two pest control technologies.

To implement the IV identification strategy, we hypothesise that a number of control variables – such as *age* (to proxy for experience), *education* (measured in years of schooling attained), and four county dummy variables – can be included in both the yield and pesticide use equations. In addition, we posit that pesticide use depends on the profitability of its use.[8] We include three measures to pick up this effect: the price of pesticides (*Price* – measured as yuan per kilogram); the farmer's perception of the severity of his farm's pest infestation problem (*Yield Loss* – measured as the per cent of the crop that the farmer believed would have been lost if he had not sprayed); and the amount of information the farmer has about infestation from interactions with extension agents (*Extension Agent* – a dummy variable that is equal to one if the farmer met with an extension agent during the year

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[7] Theoretically, farmer's adoption of Bt cotton should also be treated as the other endogenous variable. However, the adoption of Bt cotton in our sampled areas is strongly associated with the commercialisation policy of GMO products in China and the public seed distribution system within the region where Bt cotton has been approved for commercialisation. Estimation of Bt cotton adoption was tried, but no robust results were obtained and all damage control models with Bt cotton as an endogenous variable could not converge at reasonable levels of convergence criteria.

[8] Beach and Carlson (1993) show that farmers are also motivated in their use of Bt varieties by their concerns for water and health quality. While this may well be true for farmers in our sample (which would mean we should include variables that reflect such concerns), our survey did not collect information that could be used to create variables to control for these factors. Although unfortunate, the main reason for estimating the pesticide use equation is for identifying the effect of pesticide use in the yields equations. Hence, as long as the instruments that we do have are successful as instrumental variables, an incomplete specification of the pesticide use equation is of less concern.

about pest problems, and zero otherwise). Although we have only a single cross section of households, large variations in the price of pesticides exist among the respondents, reflecting the differences in pesticide quality, pesticide prices at different times during the cotton growing season, and the pesticide composition. *Price* is measured as the unit value price of pesticide purchased by the farmer. We calculate the unit value price for each household by dividing the value of their pesticide purchases by the quantity that they purchased.[9] Logically, the three IV meet the criteria of appropriate instruments (they affect the endogenous variable, *Pesticide*, but not yields, except through their impact on pesticide use). The IV also pass the Hausman-Wu exclusion restriction statistical tests.

In summary, following our above discussion, farmer's pesticide adoption (*Pesticide*) model can be explained by the following equation:

$$\begin{aligned} \mathit{Pesticide\ Use} = f(&\mathit{Yield\ Loss}, \mathit{Price}, \mathit{Extension\ Agent}; \mathit{Variety\ Dummy},\\ &\mathit{Age}, \mathit{Education}, \mathit{County\ Dummies}) \end{aligned} \tag{10}$$

where the first three variables on the right hand side of equation (10) are the instruments, and the others are the control variables. More specifically, in equation (10), we include *Variety Dummy*, a dummy variable with a value equal to 1 when the farmer uses Bt cotton, and 0 otherwise. We also include *Age*, *Education*, and *County Dummy* variables. In equation (10), the dependent variable, *Pesticide Use*, is defined in terms of quantity (measured as kilograms per hectare). An alternative specification, using pesticide cost (yuan per hectare), generates similar results. Therefore, only the results from one of these two specifications is presented. The two-equation system model is estimated using a three-stage, iterative least squares estimation procedure.

5. The results

While the focus of the present paper is on the impact of pesticides and Bt cotton varieties on yields, we begin with a brief discussion of the pesticide use equation. In addition to the statistical importance of the estimation of the first stage equation, examining the determinants of pesticide use is interesting in its own right. After discussing the results of the pesticide use equation, we then discuss the cotton yield functions.

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[9] In the survey we tried to weight quantities of pesticides by their kill-rate dosage. Unfortunately, not all farmers knew the strength of the pesticides that they had purchased and we obtained the information for only a subset of farmers. Consequently, our measure of pesticide quantity is an unweighted sum of the purchases. However, because the correlation coefficient between the unweighted measure and the weighted measure for those farmers that reported the complete information was greater than 0.50 (and significantly different from zero), we do not believe the use of unweigthed measures will cause problems.

5.1 Pesticide use

The results of the pesticide use equation demonstrate that the first stage of our model generally performed well in explaining pesticide use (table 4, column 1). OLS versions of the same model (not shown) show that the model has a relatively high explanatory power, with adjusted R-squared values that range between 0.50 and 0.60, levels that are reasonable for cross-sectional household data. The results of the alternative functional forms (also not shown) demonstrate that the results are robust, as are most of the results for the different versions of the model using alternative specifications of the dependent variable. Most of the signs of the estimated coefficients of the control variables are as expected.

Most importantly, the regression analysis illustrates the importance of Bt cotton in reducing pesticide use (table 4, column 1). The negative and highly significant coefficient on the Bt cotton variable means that Bt cotton farmers sharply reduce pesticide use when compared to non-Bt cotton farmers. *Ceteris paribus*, Bt cotton use allows farmers to reduce pesticide use by 35.4 kilograms per hectare. Given that the mean pesticide use of non-Bt cotton producers is 60.7 kilograms per hectare (table 1), the adoption of Bt is associated with a 58 per cent reduction of pesticide use. Bt varieties, at least in the sample areas and during the years of their use by farmers that are included in the study, lead to significant pesticide reductions. With the same set of data, Huang *et al.* (2001) demonstrate Bt cotton adopters spray 67 per cent fewer times and reduce pesticide expenditures by 82 per cent.

5.2 Impacts on cotton production

Our analysis of the impact of Bt cotton and other pest control methods also shows the effect on cotton production, although the results are relatively sensitive to the methodological approach. To explore the importance of the choice of methodology, we first present the results that treat pesticide use and Bt cotton adoption as traditional inputs using a Cobb-Douglas functional form. We then turn to our non-linear estimate approach in which we analyse the effect of pest control efforts within a damage control production function framework. Following the discussion in the methodological section, we use two alternative functional forms of the damage abatement function.

The production function analysis generates results that are typical of household studies done on China's agricultural sector (Ye and Rozelle 1994; Putterman and Ciacu 1994; Li 1999). In all of the specifications, we find strong and significant impact of human capital variables, age and education, on cotton output (table 4, columns 2–5). The coefficients on the labour and fertilizer variables confirm that the output elasticities of both labour and

Table 4 Estimated parameters for pesticide use and cotton yield using Two-Stage Least Squares and Damage Abatement Control Methods

	(1) Amount of *Pesticide Use* (kg/ha)	(2) Cobb-Douglas yield function Ln–Yield (kg/ha)	Damage control yield function Ln–Yield (kg/ha)	
			Weibull (3)	Exponential (4)
Intercept	46.980 (9.24)***	7.229 (0.28)***	7.811 (0.28)***	7.201 (0.40)***
Perception of *Yield Loss* (%)	0.042 (0.04)			
Before flowering				
After flowering	0.148 (0.03)***			
Average pesticide *Price* (yuan/kg)	−0.020 (0.03)			
Age (years)	0.061 (0.14)	0.11 (0.05)**	0.117 (0.05)**	0.127 (0.07)*
Education (years)	−0.67 (0.44)	0.014 (0.01)**	0.010 (0.01)**	0.013 (0.01)*
Labor (days/ha)		0.042 (0.03)	0.041 (0.03)	0.056 (0.04)*
Fertilizer (kg/ha)		0.012 (0.02)	0.009 (0.02)	0.010 (0.03)
Pest management information – from *Extension Agent* (dummy)	−0.090 (0.09)			
Bt cotton *Variety Dummy*	−35.351 (4.07)***	0.150 (0.04)***		
Predicted *Pesticide Use* (kg/ha)		0.011 (0.01)		
Damage control function parameter estimates				
m_0 (pesticide parameter in Weibull model)			−0.050 (0.02)**	
m_1 (Bt variety parameter in Weibull model)			0.070 (0.02)***	
c (pesticide parameter in exponential model)				0.219 (0.09)***
c_1 (Bt variety parameter in exponential model)				5.96 (0.95)***

Notes: The figures in the parentheses are standard errors of estimates. ***, **, * denote significance at 1%, 5% and 10%, respectively. The model includes four *County Dummy* variables to control for county-specific effects, but the estimated coefficients are not included for brevity.

fertilizer are low; our estimated labour elasticities are approximately 0.04–0.06. Farmers in our sampled areas apply 399 kilograms of fertilizer per hectare, one of the highest application rates in the world. Labor use also exceeds 500 man-days per hectare. Therefore, such insignificant marginal contributions of fertilizer and labour to cotton production may be expected.

The results of the Cobb-Douglas function approach indicate that although Bt varieties raise cotton yields, pesticide use is not effective in raising yields (table 4, column 2). Although the descriptive statistics are statistically indistinguishable (i.e., the unconditional yields of Bt cotton users are statistically the same as the unconditional yields of non-Bt cotton users), when other inputs and human capital variables are accounted for, Bt cotton users get 15 per cent higher yields (see the coefficient for the Bt cotton dummy variable in table 4 column 2). The low *t*-ratio on the coefficient of the pesticide, however, can be interpreted to mean that the marginal impact of pesticide use in cotton production is zero when pesticide is treated as a traditional yield-increasing input.

Among the two alternative specifications of the damage control functions, the ones that use the Weibull and Exponential damage control functional forms show similar results for the effect of Bt cotton (table 4, columns 3–4). If these specifications reflect the true underlying technology, our results suggest that Bt cotton is effective in helping pesticides reduce the damage from pest infestations and keeping yields higher than they would have been without Bt adoption. In other words, Bt cotton increases the productivity of cotton production.

The results of the models that treat pesticides as a damage abating input produce mixed results. In the model using the Exponential function, pesticides are seen to affect yield. In contrast, the coefficient in the equation that uses the Weibull functional form has the wrong sign. In both cases, the marginal impact is small. If our data and econometric approaches are sound, one assessment of the results is that farmers are using so much pesticide that even when they adopt Bt cotton their marginal effect is near zero.[10]

Using the parameters presented in table 4, the associated output elasticities, average and marginal products of pesticide use, and optimal

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[10] Interestingly, in the developed country literature, Fernandez-Cornejo *et al.* (1998) review a series of studies that estimate marginal products of pesticide use. Many of them find high marginal products which would mean the farmers in these studies, unlike those in China's cotton producing sector, are underusing pesticides. While we have no basis for assessing the differences of these results, in part, they may be due to differences in risk preferences, difference in the ability to bear risk and/or difference in the information on which pesticide use decisions are made.

Table 5 Estimated productivity measures of pest control management using alternative approaches

	Cobb-Douglas	Weibull	Exponential
Bt cotton			
Marginal product at sample mean	0.315 (1.67)[a]	10.89 (1.85)	11.95 (3.70)
Actual pesticide use (kg/ha)	11.8	11.8	11.8
Optimal pesticide use (kg/ha)	0.34	4.20	1.20
Non-Bt cotton			
Marginal product	0.01 (1.54)	–	7.24 (2.39)
Actual pesticide use (kg/ha)	60.7	60.7	60.7
Optimal pesticide use (kg/ha)	0.094	–	21.24
Impact of Bt cotton on yield (kg/ha)	514	250	224

[a] The figures in the parentheses are t-ratios that are generated by bootstrapping methods (using 100 repetitions in algorithm computed in SAS).

Note: Productivity increases use parameters from table 4. Marginal products and actual application levels are calculated using means of all variables. Optimal pesticide application is calculated as marginal product values equal pesticide price.

pesticide applications for both Bt and non-Bt cottons are computed and presented (table 5).[11] While the point estimates of the marginal products and elasticities vary, the most notable result – for both Bt and non-Bt varieties, is the gap between actual and optimal pesticide use (rows 2 and 3). In all cases, but especially for the case of non-Bt varieties, farmers are using pesticides far in excess of their optimal levels. For example, in the case of the estimates that use the exponential functional form, Bt cotton users use 10 kilograms per hectare more than is optimal; non-Bt users use nearly 40 kilograms per hectare more (column 3).

Figure 1 shows the trend of cotton's marginal product value with respect to pesticide use evaluated at means of all non-pesticide variables. These results show both the overuse of pesticides and the superiority of Bt cotton in its ability to lead to lower levels of pesticide use. Increases in the value of an additional kilogram of cotton output approach zero as pesticide use increases to a level above 20 kilograms per hectare for Bt cotton varieties under a Weibull specification; it approaches zero even more rapidly when using the parameters from the exponential function. For non-Bt cotton, the exponential function specification shows that the marginal product value of pesticide use approaches zero after the pesticide use level reaches 30 kilograms per hectare. These results illustrate that pesticides are being over used by both Bt and non-Bt users. If users were to use pesticides up to their optimal levels, Bt cotton users would use far lower levels of pesticides.

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[11] The optimal use of pesticides is calculated by solving for the optimal level of pesticide use, given the price of pesticide and the value of its marginal product.

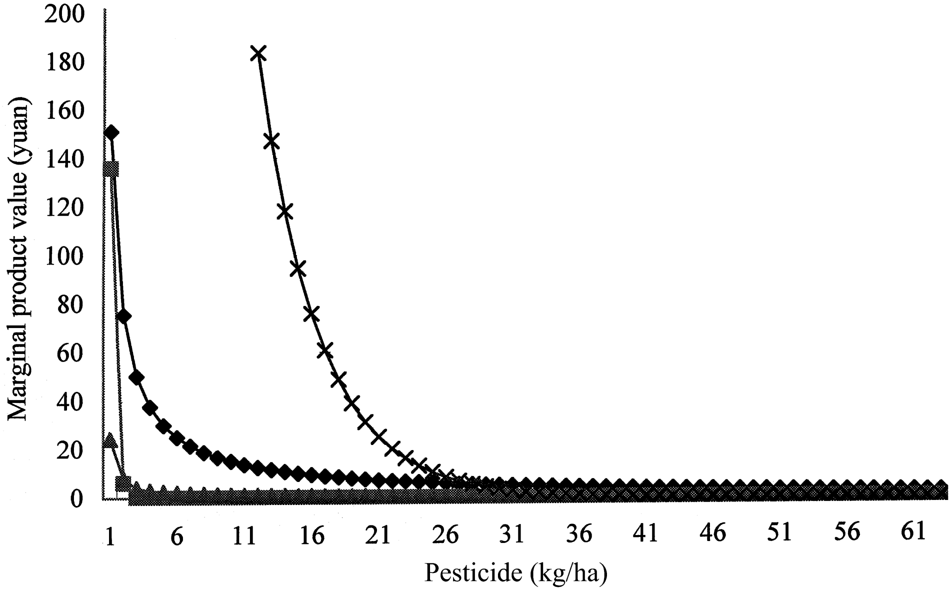

Figure 1 Marginal product values of pesticide use in cotton production.
Note: See note to Table 5 for description of calculation; functions evaluated at means levels of all other variables. –◆– Weibull:Bt; –■– Exponential:Bt; –▲– C-D: all; –×– Exponential:non-Bt.

6. Concluding remarks

Intensive cultivation and broad adoption of fertilizer responsive varieties have led to widespread pest infestations in China and in every other developing country over the past several decades (Pingali *et al.* 1997). The extent of pest-related diseases has grown several-fold during the past 2 decades in China. Rising pest problems and the availability of relatively inexpensive pesticides as China's markets have developed have contributed to the use of pesticides in crop pest management. Although statistics are difficult to compare, China is most likely already the largest pesticide user in the world, and pesticide use is still rising. Among all the major crops in China, cotton producers have traditionally used pesticides in the most intensive ways. Hence, it is important to understand why and how cotton producers use pesticides and to explore how alternatives to pesticide use have performed in recent years.

One of the results of our work is that even without alternatives, cotton producers most likely could reduce pesticide use without affecting yields or profits. Although a discussion of why farmers overuse pesticides is beyond the scope of the present paper, it is clear that such behaviour is systematic and even exists when farmers use Bt cotton varieties. One thought is that farmers might be acting on poor information given to them by the pest control station personnel. In fact, such a hypothesis would be consistent with the findings of work on China's reform-era extension system in general (Huang *et al.* 2000d).

During the past decade or more, extension agents have had their salaries cut and have been forced to rely on income generated from sales of inputs to farmers, including, in no small way, farm chemicals. Hence, it may be that agents have an incentive to push farmers to apply more than the optimal amount of pesticide as a way to increase their sales and supplement their incomes. Such a hypothesis would also support the observations of foreign seed company managers who report that such agents often resist the spread of Bt varieties because of their lower requirement for pesticides. When farmers have adopted Bt, such agents also suggest that farmers apply pesticides in the later parts of the season, even though the seed company agronomists believe such sprayings are unnecessary.

Our results show the impact of Bt cotton varieties on pesticide use, the effectiveness of pesticides' impact on yields, and Bt cotton's independent effect on yields. In other work, we have shown that the recent fall in the provincial use of pesticides in Hebei and Shandong Provinces can almost all be attributed to the spread of Bt cotton in these two areas. If health and environmental outcomes also improve with the fall in pesticide use, the benefits from extending Bt cotton exceed the production efficiency gains found here. In addition, we find that Bt cotton users also get an independent increase in yields. Although Bt cotton is relatively new in China and the long run effect of Bt use in China is not known, it appears to be an agricultural technology that improves both productivity and environmental outcomes.

In terms of policies, our findings suggest that the government may want to consider investing the funds that can help spread Bt to other cotton regions and to other crops. The important caveat is that government investments in regulation of biotechnology will have to be increased to ensure that widespread use of Bt does not lead to the rapid development of resistance of the pest populations that Bt cotton is fighting.

The second implication of these findings is that the government plant protection system does not appear to be meeting the goal of reducing pesticide use. This fits with anecdotal evidence that we picked up from seed companies and farmers that the plant protection people often recommend that farmers not use Bt cotton and they consistently recommend more pesticide applications than the seed companies that sell Bt cotton. One recommendation would be to suggest that the government separate the IPM activities and staff of the Plant Protection System from the pesticide sales activities and staff. Once this is accomplished, the government must give the extension service incentives to promote IPM technology.

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