Genetically Modified Rice, Yields, and Pesticides: Assessing Farm-Level Productivity Effects in China

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One of the early promises by the supporters of agricultural biotechnology was that this set of research tools could make a major contribution to the reduction of world hunger. It is now 25 years since some of those early promises were made and a decade since genetically modified (GM) crops were first grown commercially. But the only substantial way that biotechnology has contributed to the well-being of the hungry is through higher incomes from the production of GM cotton (Huang et al. 2002). Only a small set of countries have extended GM food crops, and most of them in a relatively minor way (James 2004, 2005). Now China is on the threshold of starting to fulfill the promise of more food for the poor through the introduction of rice varieties that can resist important insect pests and disease. This article presents the first evidence from the fields of farmers in the economic literature on whether GM rice can really start to deliver on its promise or whether this is another set of unfounded promises from the supporters of biotechnology.

Although the contribution of agricultural technology to the expansion of rice output and income growth in China and other developing countries during the past 40 years is substantial and well documented (Barker, Herdt, and Rose 1985; Lin 1994; Evenson, Herdt, and Mossain 1996), there is still a need in the future for both rapid rises in agricultural productivity and ways to reduce some of the adverse consequences of modern agricultural practices (Borlaug

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2000; Byerlee, Heisey, and Pingali 2000). From a nation facing widespread famine in the 1940s and 1950s, Green Revolution varieties, investments in water control, and the intensification of chemical input use in China raised food production to levels that no one would have dared predict (Stone 1988). Past success, however, does not guarantee abundant food and profitability in the coming decades. Rosegrant et al. (2001) estimate that China's cereal production must continue to rise by about 40% to satisfy most of the demand of the nation's population by 2020. The rise of biofuels will likely lead to further allocation of land away from the production of food crops. With most available cultivated land already in use, the future growth of output in China, as elsewhere in the developing world, will have to rely on rising productivity (Pingali, Hossein, and Gerpacio 1997; Jin et al. 2002). There also have been negative consequences associated with the use of conventional varieties. For example, the high levels of pesticide use (China is the largest pesticide user in the world), especially in the case of rice (rice farmers use more than 40% of all pesticides that are used on the nation's field crops excluding vegetable and fruits), have led to non–point source pollution and adverse health consequences (Pingali et al. 1997; Huang et al. 2001, 2005).

While most scientists believe that agricultural biotechnology can provide new sources of productivity growth and address some of the negative effects of conventional agronomic techniques for producers of rice and other basic food crops in China and other developing countries, at present biotechnology is primarily used for industrial crops such as cotton and grain for animal feed such as yellow maize and soybeans (James 2005). In the late 1980s and 1990s, government research in many developing nations often funded by the Rockefeller Foundation began ambitious rice biotech research programs to develop new rice varieties that would increase yields and nutrition, reduce input use, and make the rice plant (as well as those of other food crops) more tolerant to both biotic and abiotic stresses (Evenson et al. 1996). This research led to a major increase in knowledge about the rice plant and rice genetics and the development of conventional and GM rice varieties that could help producers in developing countries. New conventional varieties with resistance to bacterial leaf blight developed using molecular markers are now available to farmers in Indonesia and China. Scientists in China, India, and Costa Rica are conducting field trials for new GM varieties of insect and disease-resistant rice; GM rice has been commercialized in Iran (James 2005). However, because of government indecision, evolving biosafety regulations, consumer resistance, and trade concerns, no major GM rice varieties have been approved for commercial use anywhere other than Iran.

The difficulties of commercializing GM rice appear to be affecting the amount and direction of public and private biotech research also. According to interviews that one of our coauthors has been conducting in developing countries outside of China over the past several years, it has been noted that government scientists in India are faced with increasing difficulty in finding locations for the trials of GM rice. Because of increasing costs due to the need to protect the fields from antibiotech organizations, many research organizations are pulling back from trying to develop GM varieties and simply publishing their research results or working on industrial crops such as cotton where GM varieties can be commercialized. The private sector also is cutting back because of consumer resistance to GM products and the rising cost of commercializing new products. For example, Monsanto in the United States discontinued work on rice in the late 1990s, and other companies such as Syngenta and Bayer have sharply cut back on their rice research programs in recent years.

As a result, except for a number of relatively minor locations, no GM rice has been commercialized anywhere in the world (except for small areas in Iran), and little is in the pipeline in most countries. In fact, with the exception of Bt (*Bacillus thuringiensis)* white maize in South Africa, where Bt white maize is primarily being grown by large, relatively wealthy farmers (James 2004), there are few cases in which GM staple food crops are being grown. Even in China, a country that initially aggressively commercialized Bt cotton and invested heavily in research on GM food crops, policy makers have not allowed the commercialization of any major food crops despite the fact that GM crops have been in experimental trials since 1999.

In addition to the actions of small but vocal urban consumer groups that have actively discouraged the commercialization of GM food crops, one reason that commercialization has not proceeded (especially in developing countries such as China that are less pressured by anti-GM activist organizations) is that there has been little independent evidence on whether GM food crops would really improve the productivity of farmers, especially those who are poor. Often regulators and policy makers have to take the word of the government scientists and companies that developed and are promoting these GM products.

The objective of this study is to report on the results of an economic analysis that uses 3 years of data from key experiments in China's GM rice program that were carried out in the fields of small and relatively poor producers in two sites in China. The article attempts to answer two questions: Does GM rice help reduce pesticides in the fields of farmers? Do the new varieties of GM rice increase the yields of farmers? On the basis of the results, the article shows that the use of GM rice by farmers in preproduction trials allows farmers to reduce pesticide use and labor inputs. The evidence on yields is less clear,

TABLE 1
PUBLIC RESEARCH EXPENDITURES ON AGRICULTURAL BIOTECHNOLOGY IN CHINA, 1986–2003

Year	Total* (1)	Plant (2)	Rice (3)
	Million Yuan, RMB, in Real 2003 Prices		
1986	89	51	8
1990	204	118	16
1995	273	157	26
2000	861	450	72
2003	1,647	996	195
	Million U.S. Dollars		
2003:			
At official exchange rates†	199	120	24
Converted at PPP terms‡	953	574	115

Source. Authors' survey.
* Total agricultural biotechnology spending includes spending on animals, plants, and microorganisms.
† The official RMB-U.S. dollar exchange rate in 2003 was 8.277.
‡ The conversion rate of RMB to PPP in 2003 is calculated by dividing RMB by the official RMB-U.S. dollar exchange rate (8.277) and multiplying by 4.787.

and there is at most only a small (if any) increase in yields. The article concludes by arguing that the commercialization of GM rice in China could have consequences that exceed the direct impacts on China's farmers and could be a key step in breaking the world's current plant biotechnology logjam.

I. China's GM Rice Research Program

China's modern biotechnology program, begun in the 1980s, has grown into the largest initiative in the developing world (Huang et al. 2002). A recent survey by the authors of agricultural biotechnology research investment in 2004 shows that the government's spending on agricultural biotechnology (including plants, animals, and microorganisms) reached *renminbi* (RMB) 1.647 billion, which is equivalent to US$199 million at current exchange rates and US$954 million in purchasing power parity (PPP) terms (table 1, col. 1). Between the mid-1980s and 2000, annual plant biotechnology spending also rose fast, more than doubling each 5 years for the first 15 years (col. 2). Between 2000 and 2003, plant biotechnology investment continued to accelerate, more than doubling during the 3-year period.

Although the success of GM cotton in China initially attracted the attention of research administrators that allocated cotton scientists nearly 15% of national plant biotechnology research expenditures (despite the fact that the crop accounts for only about 5% of China's sown area), rice scientists also have been provided with increasing financial resources (table 1, col. 3). In the late 1980s each year rice scientists were provided with US$2–$3 million (at the official exchange rates). By 2003 rice scientists were allocated nearly US$24 million (or $115 in PPP terms), accounting for nearly 20% of plant biotechnology spending (which in the case of rice is almost its sown area share). Although estimates of world spending on rice biotechnology are not available, given the low priority accorded by funding agencies to rice in nations with the largest biotechnology programs (e.g., the United States and the United Kingdom), China's public investment into rice biotech likely exceeds that of any other nation except perhaps Japan.

China's rice biotechnology research program has generated a wide array of new technologies that are at all stages of the research and development process. In China the Ministry of Agriculture must grant a company or research institute a permit before any GM plant can be commercialized. Before such a permit is granted, however, China's biosafety procedures require that transgenic crops pass through three phases of trials: field trials (equivalent to small-scale, contained trials in the United States); environmental release trials (equivalent to controlled farmer field trials in the United States); and preproduction trials (larger-scale, farmer field trials, which are not controlled by the scientist). Preproduction trials are not required in the United States.

Many types of transgenic rice varieties and hybrids have reached and passed the field trial and environmental release trial phases of China's biosafety testing since the late 1990s. Transgenic Bt rice varieties that are resistant to rice stem borer and leaf roller were approved for environmental release trials in 1997 and 1998 (Zhang, Liu, and Zhao 1999). In experimental fields in Wuhan in 1999, Bt hybrid Xianyou 63 yielded 28.9% more than nonhybrid Xianyou 63 in the presence of natural attacks of leaf rollers and natural and induced attacks of yellow stem borers; pesticides were not applied to either variety (Tu, Zhang, et al. 2000). Other scientists introduced the CPTi gene into rice, creating rice varieties with another type of resistance to rice stem borers; this product was approved for environmental release trials in 1999 (NCBED 2000). Transgenic rice with Xa21 and Xa7 genes for resistance to bacterial blight were approved for environmental release trials since 1997 (NCBED 2000). Trials of the International Rice Research Institute variety IR72 transformed to express the Xa21 gene in 1998 and 1999 were shown in experimental fields to give a high level of protection against outbreaks of bacterial blight (Tu, Datta, et al. 2000). Interviews also found that although environmental release trials have not begun, field trials have been under way since 1998 for transgenic plants with herbicide tolerance (using the bar gene) as well as varieties expressing drought and salinity tolerance in rice.

Of all of the work being done in field and environmental release trials, four transgenic rice hybrids, which have been engineered to be resistant to major pests in China, have advanced to the final stage of field trials, the preproduction trials stage. Two insect-resistant hybrids—GM Xianyou 63 and Kemingdao—contain stem borer–resistant Bt genes. According to experimental trial data, the Bt varieties are resistant to three stem borers in China: *Tryporyza incertulas* Walker, *Chilo suppressalis* Walker, and *Cnaphalocrocis medinalis* Guenee (Zhu, Huang, and Hu 2003). The hybrid GM II Youming 86 contains the CPTi gene, which provides resistance to six pests: the same pests that are targets of varieties containing Bt plus *Sesamia inferens* Walker, *Parndra guttata* Bremeret Grey, and *Pelopidas mathias* Fabricius. MOA (2002) reports that in 2000 and 2001, stem borers affected between 68% and 75% of China's rice area. Given that China's rice area is nearly 30 million hectares, this means that the main pests targeted by China's experimental GM rice varieties (that are currently in preproduction trials) affect more than 20 million hectares annually, nearly 13% of the world's total rice sown area. A fourth hybrid contains the Xa21 genes, which provide resistance to bacterial blight, one of the most prevalent diseases in rice production areas in central China (Zhu et al. 2003).

According to the scientists that have been working to develop the new GM rice technologies, several varieties have had successful agronomic, environmental release but to date have not been approved for commercial use (Zhu et al. 2003). It is claimed that approval has been held up by pressure from environmental and trade interest groups in China and by those that do not want to see China bear the risk of being the first large nation to commercialize a major GM food crop.

Before commercialization, a new GM variety that passes the environmental release stage of the biosafety testing process in China must also pass through preproduction trials. According to China's biosafety regulations, the total area for each preproduction trial should be more than 30 mu but not exceed 1,000 mu, or 66.7 hectares (MOA 2005). Preproduction trials are allowed to be carried out in no more than two provinces in which the environmental release trials were conducted. When the preproduction trials are carried out in the fields of farmers, the trials are largely unsupervised: farmers are given the seed, and except for periodic monitoring, scientists do not intervene in the cultivation process.

Over time the number of villages with Bt rice preproduction trials has grown. For example, according to our contacts in Hubei Province, the number of villages in which farmers cultivated GM Xianyou 63 (which were developed by scientists from Central China Agricultural University) rose from four in 2002 to seven in 2003 and to 11 in 2004 (table 2). Because the locations of the counties and villages sometimes change over time (especially between 2003

TABLE 2

DISTRIBUTION OF SAMPLE COUNTIES AND VILLAGES HOSTED Bt RICE PREPRODUCTION TRIALS IN CHINA

Year	Number of Counties and County Names	Number of Villages and Village Names
	Hubei Province (GM Xianyou 63)	
2002	3	4
	Xiantao	Qianqiao
	Jiangxia	Laowuye, Tangtu
	Jingmen	Xinglong
2003	5	7
	Xiantao	Qianqiao
	Jiangxia	Laowuye, Tangtu
	Jingmen	Xinglong
	Xiangyang	Huangci, Jiawan
	Huangpi	Xiangjazui
2004	5	11
	Xiantao	Qianqiao
	Jiangxia	Laowuye, Tangtu, Huashanwu
	Jingmen	Donggou
	Xiangyang	Quanshuiyian, Baiyun, Qinglong, Xuwan
	Xiaochang	Qingshui, Ergong
	Fujian (GM II Youming 86)	
2002	Shunchang	Shixi
2003	Shunchang	Shixi
2004	Shunchang	Shixi
2004	Taining	Nanhui
Total	8	17
Hubei	5	15
Fujian	3	2

Note. The total number of counties and villages is less than the sum of the villages from each year because the experiment teams kept some villages for more than 1 year during the sample period; others were added and others were dropped. The preproduction trials of GM II Youming 86 were also conducted in four experiment stations (three experiment stations located in Fujian and another located in Hubei). Observations from the experiment stations were not included in our sample since the farming operations were not operated by individual households.

and 2004), in total we visited 15 preproduction trial villages located in six counties in Hubei between 2002 and 2004. The preproduction trials for GM II-Youming 86 developed by the Chinese Academy of Sciences and the Fujian Academy of Agricultural Sciences were initially being conducted by technicians in only four rice experimental stations; three of the stations were in Fujian Province and one was in Hubei Province. In 2002 and 2003, scientists carried out preproduction trials for GM II-Youming 86 in one village in Fujian Province (Shixi Village in Shunchang County; table 2). In 2004, the trials expanded into one additional village (Nanhui Village in Taining County). In total, then, preproduction trials between 2002 and 2004 for GM Xianyou 63 and GM II Youming 86 were being carried out in 17 villages located in eight counties (table 2, bottom rows) and four experiment station locations (table 2, note). In this study only GM rice plots (as well as non-GM rice plots, which are used as controls) that are cultivated by individual farmers who live in villages outside experiment stations are analyzed. Before collecting data, we confirmed by in-depth interviews with local leaders and farmers that farmers in these areas are provided only seed and are cultivating GM rice without the assistance of breeders or their staffs. In contrast, we did not conduct surveys in experimental stations since rice plots in the preproduction trials in the experimental stations are being cultivated by farmers-cum-technicians working under the direction of the scientists.

II. Data

Our 3-year survey was conducted in 2002–4 by enumeration teams trained and led by the authors and was designed to collect information allowing the comparison of the performance of GM rice and non-GM rice under field conditions. The total number of observations from the 3 years of survey work includes 320 rice-producing households: 73 in 2002, 104 in 2003, and 143 in 2004. These households were randomly chosen by the authors from the population of all the farmers in the preproduction village (whether they were included in the Bt rice experiment or not). According to the protocol of the preproduction trials, households in the sample were randomly assigned to be in the project. Although this occurred in some villages, it is unclear whether the random assignment was carried out strictly in all villages. Therefore, in our analysis we compare the nature of Bt and non-Bt rice households in order to understand if the characteristics of Bt-rice-producing households differ from those of non-Bt-rice-producing households.

In addition, we also designed the survey so that the enumerators, using standard, sit-down interviewing techniques relying on producer recall of inputs and outputs (for the current year), collected information at the plot level in order to be able to distinguish production practices (including level of inputs) that are used on plots with both GM and non-GM rice. Given the focus on insect-resistant varieties, respondents were asked detailed questions about the total amount of pesticides used on each plot, the value of the pesticide, and the number of sprayings. In total, the survey obtained data from 584 rice production plots: 211 plots planted with GM rice and 373 plots planted with non-GM rice. Among the 73 households in the 2002 survey, 37 planted non-GM rice only, 25 planted both GM and non-GM rice varieties, and 11 planted GM rice only. In 2003, of the 104 households, 36 planted non-GM rice only, 52 planted both GM and non-GM rice varieties, and 16 planted GM rice

TABLE 3
SAMPLE HOUSEHOLDS AND THE STATUS OF Bt AND NON-Bt RICE FARMERS, 2002–4

Year	Only Bt Rice	Both Bt and Non-Bt Rice	Only Non-Bt Rice	Total
2002	11	25	37	73
2003	16	52	36	104
2004	41	42	60	143
Total	68	119	133	320

Source. Authors' survey.
Note. In addition to the 119 households that planted both Bt and non-Bt rice during the same year, a number of households that were included in at least 2 years of the survey (74 households) changed at least one of their plots from Bt rice to non-Bt rice during the years of the survey.

only. In 2004, of the 143 households, 60 planted non-GM rice only, 42 planted both GM and non-GM rice varieties, and 41 planted GM rice only (table 3). Therefore, in total during the 3 years of the study, we have 119 household-level observations (25 + 52 + 42) in which the household cultivated both GM and non-GM plots during a single year.

In addition, there was also variation over time among the sample households in their status as a household that cultivated Bt rice or not. Among the total 213 different households that were interviewed, there were 41 households that were in the survey for 2 years and 33 households that were in the survey for all 3 years. Of these, 35 households at some point during the survey switched the status of at least one plot from GM rice to non-GM rice (or vice versa). Since the survey also was designed to track plots over time, in the sample we have 107 households that at some point of time in the survey have produced both GM and non-GM rice (in some cases it was producing one Bt plot and one non-Bt plot during a single year; in other cases it was producing Bt on one plot during one year and producing non-Bt on the plot during the next).

Besides collecting plot-specific information on inputs and outputs, the survey also contained a number of questions focused on understanding the economic effects of using insect-resistant rice varieties. Farmers recounted the prices paid for all inputs and the prices that they received for their output. All the transactions, except for the provision of the seed to the farmers, were conducted on free markets with no assistance from the research team or local government officials. These data are used mainly to calculate whether or not there were any productivity effects associated with the adoption of GM rice within the sample households.

III. GM Rice Adoption and Pesticide Use

Data from the surveys of all 320 sample households demonstrate that, as designed, the study is examining producers of GM and non-GM rice that are

TABLE 4
SUMMARY STATISTICS OF GM AND NON-GM RICE PRODUCERS IN PREPRODUCTION TRIALS IN CHINA, 2002–4

	Entire Sample (320 Households and 584 Plots)			Sample That Grow Both GM and Non-GM Rice (119 Households and 293 Plots)		
	Average (1)	GM Rice[a] (2)	Non-GM Rice (3)	Average (4)	GM Rice[a] (5)	Non-GM Rice (6)
1. Farm size (ha)	1.03	1.04	1.03	1.22	1.22	1.22
	(.86)	(.88)	(.84)	(.96)	(.96)	(.96)
2. Rice share in crop area (%)	56	54	58	55	55	55
	(24)	(25)	(24)	(22)	(25)	(25)
3. Age of household head (years)	46.8	47.5	46.4	47	47	47
	(11)	(10.9)	(9.6)	(9)	(9)	(9)
4. Household head's education (years)	7.0	7.0	7.0	7.3	7.3	7.3
	(2.7)	(2.8)	(2.7)	(2.7)	(2.7)	(2.7)
5. Rice price (yuan/kg)	.63	.62	.63	.62	.60	.63
	(.12)	(.12)	(.13)	(.12)	(.11)	(.12)
6. Pesticide price (yuan/kg)	15.0	12.7	16.3	16.3	14.8	17.4
	(14.5)	(15.9)	(13.6)	(16.1)	(17.1)	(15.2)
7. Fertilizer use (kg/ha)	1,331	1,292	1,354	1,314	1,271	1,346
	(548)	(609)	(509)	(541)	(538)	(542)
8. Pesticide sprayings (times)	2.61	.60	3.70	2.63	.60	4.17
	(2.17)	(.97)	(1.81)	(2.31)	(.86)	(1.81)
9. Cost of pesticide (yuan/ha)	192	45	275	159	40	249
	(208)	(87)	(210)	(189)	(49)	(205)
10. Pesticide use (kg/ha)	16.1	3.0	23.5	13.6	3.0	21.6
	(18.3)	(4.9)	(19.0)	(16.4)	(4.2)	(17.5)
11. Pesticide spray labor (days/ha)	6.9	1.4	10.1	6.4	1.0	10.5
	(7.8)	(3.4)	(7.8)	(7.9)	(1.6)	(8.2)
12. Yield (kg/ha)	6,541	6,688	6,457	6,609	6,645	6,581
	(1,355)	(1,234)	(1,414)	(1,326)	(1,197)	(1,418)
13. Observations (plots)	584	211	373	293	126	167

Source. Authors' survey.
Note. The numbers in the parentheses are the standard deviations.
[a] GM rice includes two varieties: GM Xianyou 63 and GM II-Youming 86.

operating in similar environments (table 4, cols. 1–3). This is important since there might be a question about how the farmers within villages were selected (although, as stated above, by protocol they are supposed to be randomly assigned). In particular, the nature of rice farms, the characteristics of rice producers, and the market prices faced by households using GM rice and non-GM rice are nearly identical. The descriptive data show that there is no statistical difference between the size of the farm (on average 1.03 hectares per household: 1.04 for GM rice households and 1.03 for non-GM rice households), the mix of rice and other crops (54% rice in GM rice households, 58% in non-GM rice households), and the age and education level of the household head (measured as years of educational attainment) for GM rice and non-GM rice producers (rows 1–4). The prices paid for pesticides and the price received for their output also did not differ significantly (rows 5 and 6). Although the point estimate of the level of fertilizer used on GM rice (1,292 kilograms per hectare) is lower than that for non-GM rice (1,354 kilograms per hectare), the difference is statistically insignificant.

In contrast, there are large differences between GM rice and non-GM rice production in the use of pesticides (table 4, cols. 1–3, rows 8-11). GM rice farmers apply pesticide less than one time per season (0.6 time) compared to 3.7 times per season by non-GM rice farmers (a level that is statistically significant). On a per hectare basis, the pesticide use in value terms in non-GM rice production (275 yuan/hectare) is more than six times higher than for GM rice (45 yuan per hectare). The quantity in physical terms differs by nearly eight times (3 kilograms per hectare for GM rice farmers compared to 23.5 kilograms per hectare for non-GM rice farmers). Because of the reduction of pesticide use, GM rice farmers were able to reduce significantly their labor allocation to pesticide spraying, expending only 1.4 days per hectare for the production of GM rice versus 10.1 days per hectare for non-GM rice. Interestingly, although the pattern of pesticide reduction for those that adopt GM rice is similar to the reductions for those that adopt Bt cotton (i.e., there is a significant drop in the number of sprayings, the quantity of pesticides uses, the cost of spraying, and the labor used in pest control; see Huang et al. 2003), there is one important difference. While Bt cotton producers all continue to apply pesticides to control for a number of nontargeted pests, in the case of 62% of the sample GM rice plots, farmers did not apply pesticides at all (i.e., their quantity in physical terms, value of expenditure, and time allocated to pesticide spraying were zero). The point estimates of yields for GM rice-producing households are also higher than those for non-GM rice-producing households (although the results are not significant at the 5% level).

Columns 4–6 of table 4 demonstrate that when a subset of 119 households that produced both GM rice and non-GM rice (out of the overall sample of households used) were sampled, the basic results found for the entire sample remain unchanged. The comparisons of GM rice- and non-GM rice-producing households may be even more meaningful since in the case of all these households the farmer produced GM rice on at least one plot and non-GM rice on at least one plot during the same season. But, as for the entire sample, the household characteristics are all the same (statistically), whereas pesticide use differs statistically between GM rice plots and non-GM rice plots. Interestingly, although there still is a yield gap (the yields of GM rice producers are higher than those of non-GM rice producers), the gap is narrower and also not statistically significant.

IV. Multivariate Approach to Estimating Pesticide Demand and Yield Effects (Approach 1: Village Effects)

Because other factors might affect pesticide use when one is comparing GM rice and non-GM rice producers from sample survey data, multivariate analysis is needed to determine the net impact of the adoption of GM varieties on farm-level pesticide demand. To estimate a demand function for pesticide by China's rice farmers in our sample areas, the following farmer pesticide adoption model is proposed:

$$\begin{aligned}\text{Pesticide Use} = f(&\text{Pesticide Price, Producer, and Farm Characteristics;}\\ &\text{Weather Effects; Other Plot-Specific Effects;}\\ &\text{Year Effects; Village Effects; and GM Rice Effects).}\end{aligned} \quad (1)$$

In implementing this model (which has been used elsewhere in the analysis of pesticide demand inside and outside of China, e.g., Pingali and Carlson [1985] and Huang et al. [2003]), we use data from the survey to create variables to use in the empirical estimation of equation (1). The dependent variable for the multivariate analysis in this article is the quantity of pesticides used per season (although substantively identical results are generated when using either the number of sprayings per season or the value of pesticide use). The price of pesticides is given in yuan per kilogram. To hold constant the producer and farm characteristics, the regression model includes the age (in years) and education (in years of education attained) of the household head, whether or not a household head is a village leader (1 if yes, 0 if no), and the size of the farm (in hectares). Weather effects are controlled for by including a natural disaster dummy, which is equal to one if the farmer reported that his or her rice plot was affected by either drought or flood (or some other disaster) during the season. We also control for other plot-specific characteristics, including the size of the plot (measured in hectares) and a subjective measure of each plot's quality, which was solicited by asking each farmer if the plot was "high," "medium," or "poor" quality. Year effects are controlled for by including two year dummies (2003 and 2004 year dummy) that are equal to one for 2003/4 and zero for 2002.

Importantly, the net effect of GM rice varieties on pesticide use, the main goal of the analysis, is measured by including a single dummy variable (GM rice) that equals one if the farmer used either GM Xianyou-63 or GM II-Youming 86. In an alternative specification (not shown), the use of GM rice is measured by including two GM variety-specific dummy variables (GM

Xianyou 63 and GM II-Youming 86) and two non-GM variety dummy variables (conventional Xianyou 63 and II-Youming 86). We do not report the results of the regression analysis that uses variety dummy variables, but, in general, they produce the same results. We do, however, include two interaction variables (GM rice × 2003 year dummy and GM rice × 2004 year dummy) in order to analyze if the effect of GM rice on pesticide use changes over time.

In the version of the regression analysis that is based on equation (1), while pesticide use and other plot-specific characteristics and the GM dummy variables are measured at the plot level (the other control variables are measured at the household level), we control for all unobserved village effects by adding a set of village dummy variables, one for each of the villages in the sample (with one of the Hubei Province villages dropped as the base village). Implicitly when we specify the model this way, we are assuming that the GM and non-GM rice farmers were randomly assigned within the village (as intended by the preproduction trial's original design). Because practice may have diverged from theory, the assumption is relaxed below in the next section.

A. Approach to Measuring the Effect of GM Rice on Yields

In addition to the effect of GM rice on pesticide use, we also are interested in understanding the effects on yields. The descriptive data in table 4 (cols. 2 and 3, row 12) show that there is a marginal net increase in yields for users of GM rice (6,657 kilograms per hectare) compared to non-GM rice users (6,440 kilograms per hectare), a gain of 3.3%. In the descriptive results, however, the difference is not significant. Because we are aggregating across a large number of households that are producing in a large number of preproduction trial villages, there may be other effects that are confounding the difference between GM and non-GM rice.

To measure the net effect of GM rice on yields, we specify a second equation (also from Lichtenberg and Zilberman 1986; Huang et al. 2003):

$$\begin{aligned}\text{Yields} = f(&\text{Producer and Farm Characteristics; Input Use, Including}\\ &\text{Pesticide Use; Weather Effects; Other Plot-Specific Effects;}\\ &\text{Year Effects; Village Effects; and GM Rice Effects}),\end{aligned} \tag{2}$$

where the specification of equation (2) is the same as equation (1) except for several elements. First, we replace the dependent variable, pesticide use, with yields, which are measured at the plot level (in kilograms per hectare). In addition, we include plot-specific levels of input use as additional control variables. As in equation (1), we include village effects and assume that within villages the GM rice plots were randomly assigned.[1]

B. GM Rice, Pesticide Use, and Yields: The Multivariate Results with Village Effects

The results of the pesticide use equation demonstrate that the model generally performed well in explaining pesticide use (table 5, col. 1). The model has a relatively high explanatory power, with adjusted R^2 values that are between 0.42 and 0.52, levels that are reasonable for cross-sectional household data (row 22). Most of the signs of the estimated coefficients of the control variables (i.e., those variable included in addition to the GM rice dummy variables) are as expected. For example, the coefficient on the farm size variable in the yield equations (cols. 2 and 3, row 8) shows that there are modest economies of scale in the production of yields. Interestingly, the scale economies relate to the overall size of the farm, but not the size of each plot (see the insignificant sign on the coefficient of the plot size variable in row 10).

Most important, the regression analysis illustrates the importance of GM rice varieties in reducing pesticide use (table 5, col. 1, rows 2–4). The negative and highly significant coefficient on the GM rice variable means that GM rice farmers sharply reduced pesticide use in 2002 when compared to non-GM rice farmers. Ceteris paribus, GM rice use allowed farmers to reduce pesticide use by 12.26 kilograms per hectare in 2002 (col. 1, row 2). Given that the mean pesticide use of non-GM rice producers is 23.5 kilograms per hectare (as seen in table 4, col. 3, row 10), the adoption of GM rice in the first year of the preproduction trials was associated with a 50% reduction of pesticide use. When we examine the impact of the specific varieties (GM Xianyou 63 and GM II-Yuoming 86; results not shown), in both cases the fall in pesticide use is similar. Interestingly, in subsequent years of the survey (2003 and 2004) there seems to be a tendency for GM rice farmers to further reduce their pesticide use (as shown by the negative signs on the interaction terms in rows 3 and 4).

[1] Since it is possible that the coefficient on the pesticide use variable is affected by endogeneity bias when estimating eq. (2) using actual pesticide use, we also tried to control for this bias. To do so we include pesticide price (which is a unit value measure created by dividing total pesticide expenditures by pesticide quantity) in eq. (1). In eq. (2), instead of actual pesticide use, we use predicted pesticide use. The exclusion of pesticide price from eq. (2) means that we are identifying the effect of pesticide on yields through the inclusion of this instrumental variable in eq. (1). The results (not shown for the sake of brevity) are almost identical. In fact, since the pesticide use variable in eq. (2) is not the focus of our analysis and since it is possible that the pesticide price variable itself is measured with error (unit values are not always equal to the market price), we report the results of the analyses without the inclusion of pesticide price in eq. (1) and with the actual pesticide use in eq. (2).

TABLE 5

ESTIMATED PARAMETERS FOR THE EFFECT OF GM RICE ON PESTICIDE USE AND RICE YIELDS USING OLS AND DAMAGE ABATEMENT CONTROL ESTIMATORS

Variable	Amount of Pesticide Use (kg/ha) (1)	Cobb-Douglas Function: Log (Yield) (2)	Damage Control Function—Weibull: Log (Yield) (3)
1. Intercept	8.36	8.28	8.78
	(1.88)*	(36.81)***	(41.02)***
2. GM rice (yes = 1; no = 0)	−12.26	.09	.12
	(4.64)***	(2.34)*	(2.56)**
3. 2003 year × GM rice	−6.77	−.03	−.03
	(2.06)	(.66)	(.57)
4. 2004 year × GM rice	−10.30	−.03	−.02
	(3.14)	(.66)	(.45)
5. Household head age (years)	.11	.06	.05
	(1.76)	(1.47)	(1.22)
6. Education (years of attainment)	−.12	.00	−.00
	(.55)	(.69)	(.48)
7. Village leader dummy (leader = 1; no = 1)	.10	−.03	−.02
	(.05)	(.86)	(.64)
8. Farm size (ha)	−1.27	.04	.04
	(1.36)	(2.46)**	(2.43)**
9. Natural disaster (affected = 1; not affected = 0)	9.04	−.50	−.50
	(3.54)***	(13.56)***	(16.46)***
10. Plot size (ha)	8.81	−.84	−.84
	(.23)	(1.49)	(1.15)
11. Plot soil quality (high quality)	.52	.04	.04
	(.31)	(1.69)	(1.74)*
12. Plot soil quality (medium quality)	1.01	.03	.03
	(.56)	(1.04)	(1.11)
13. Labor (days/ha)		−.00	−.00
		(.01)	(.09)
14. Fertilizer (kg/ha)		.04	.04
		(1.60)**	(1.46)*
15. Machine (yuan/ha)		−.00	−.00
		(.43)	(.24)
16. Other inputs (yuan/ha)		.01	.01
		(1.40)	(1.35)
17. 2003 year dummy	2.11	−.03	−.04
	(1.10)	(1.23)	(1.45)
18. 2004 year dummy	7.25	.04	.04
	(3.38)***	(1.40)	(1.18)
19. Predicted pesticide use		.00	
		(1.22)	
Damage control function parameter estimates:			
20. e_0 (pesticide parameter in Weibull model)			.03
			(2.58)**
21. e_{bt} (Bt variety parameter in Weibull model)			−.02
			(2.20)*
22. R^2	.52	.42	.42
23. Observations	584	584	584

Note. The figures in the parentheses are *t*-values. The model includes 17 village dummy variables to control for village-specific effects, but the estimated coefficients are not included for brevity.
* Significant at the 10% level.
** Significant at the 5% level.
*** Significant at the 1% level.

Beyond the pesticide-reducing effects, we also are interested in measuring the effects of GM rice on yields. Because we do not know the precise functional form, we specify the yield equation (eq. [2]) two ways: (*a*) in log form (i.e., including the log of yield as the dependent variable in eq. [2]) and (*b*) using a damage control functional form, a form suggested by Lichtenberg and Zilberman (1986). The damage control functional form may be more appropriate in our analysis since perhaps it is more correct to model pesticide use as a way of reducing damage from pests rather than as a way to increase yields directly.

Regardless of the functional form, however, from our analysis that controls for village-level effects, we can show that the adoption of GM rice in the preproduction sample villages increases yields somewhat, ceteris paribus (table 5, rows 2–4). When we use the log of yields as the dependent variable and control for village effects (col. 2), the adoption of GM rice increases yields by 9%. When we use the damage control functional form (col. 3), the adoption of GM rice increases yields by 12%. The yield gains are statistically consistent across the sample years (2002–4, as seen from the insignificant signs on the interaction terms in rows 4 and 5). Hence, in terms of production, in the preproduction trial villages, when we assume that farmers within villages are randomly selected to cultivate GM rice, there is a win-win outcome in production: GM rice producers not only reduce pesticide use, but also achieve slightly higher yields.

V. Multivariate Approach to Estimating Pesticide Demand and Yield Effects (Approach 2: Household Effects)

While the results from the preceding analysis suggest that GM rice is a win-win proposition on the production side, such a finding, in part, may arise because the sample selection by the scientists in the preproduction trial villages was not random. For example, despite the appeals of scientists, it could be that because better farmers within the preproduction trial villages were more aggressive in their efforts to be signed up for the program, part of the effect that we are measuring is due to management bias and not to the effectiveness of GM rice. In order to control for the unobservables that could be affecting the results, in this section we redo the analysis for pesticide demand and rice yields and include a set of household dummy variables for any household in the sample that at some time during the study cultivated at least one plot of GM rice and at least one plot of non-GM rice (henceforth, the household fixed-effects model). Specified this way, we are able to purge all household-specific unobservables (as well as all village and above unobservables) and in essence look at the results of the "experiment" of how much pesticide use and yields differ among two or more plots of the same farmer.[2]

According to the results from the household fixed-effects models, although the impact of GM rice on pesticide use and yields changes somewhat (when compared to the results reported in table 5, the results using village fixed effects), in general, the nature of the results are the same (table 6). The average within-household, between-plot, effect on pesticide use is −18.90 (col. 1, row 2). This means that when a household cultivates both GM rice and non-GM rice, on average, the use of pesticide on the GM rice plots falls by nearly 20 kilograms per hectare, a reduction of nearly 85%. When pesticide reduction effects are allowed by year, the results show that the reduction in pesticide falls progressively year by year (col. 2, rows 2–4). In 2004, farmers producing GM rice actually reduced pesticide use by 9.57 kilograms per hectare more than in 2002 (row 4). Since pesticide use rose to 26.93 kilograms per hectare for non-GM rice in 2004, this means that by 2004 GM rice farmers were able to reduce their pesticide use by more than 90%. Although we do not know the exact mechanism, the results are consistent with the fact that as farmers have begun to become familiar with GM rice technology, they could be learning that they can use less pesticides.

In contrast, the results of the yield equations from the household fixed-effects model differ somewhat from those when only village effects are controlled for. Although the coefficients on the GM rice variables are positive, they are not significantly different from zero (table 6, cols. 3 and 4).[3] According to the experience in the rest of world (in the case of other GM crops), the absence of yield effects should not be surprising. A report by the Food and Agricultural Organization (FAO 2004) reported that yields usually do not rise after the adoption of Bt crops. The reason is that the Bt gene does not change the yield potential of the crop; it only reduced the lower tail of the yield distribution. Importantly, regardless of the approach, GM rice adoption leads to large reductions in pesticide use; yields, at the very least, do not diminish.

If it is assumed that GM rice would be equally effective across large parts of China (those areas affected by stem borers, in particular), the simultaneous

[2] While there is a possibility that the GM rice plots were systematically different from those that were used for non-GM rice, we were assured by the design of the program that the plots were randomly assigned. To confirm that there is no bias in the selection of plots, we ran a regression of plot characteristics on the GM rice dummy variable (GM rice dummy $= a_0 + a_1 \times X_{\text{plot characteristics}} + e$) and discovered that the R^2 coefficient was less than 0.01 and none of the coefficients were significant.

[3] Therefore, as seen by the comparisons between the village fixed-effects approach and household fixed-effects approach, there appears to have been some selection bias when it comes to identifying the effect of GM rice on yields.

TABLE 6

ESTIMATED PARAMETERS USING A HOUSEHOLD FIXED-EFFECTS MODEL FOR ESTIMATING THE EFFECT OF GM RICE VARIETIES ON FARMERS' PESTICIDE APPLICATION AND YIELDS OF HOUSEHOLDS IN PREPRODUCTION TRIALS IN CHINA (BASED ON THE FULL SAMPLES)

	Pesticide Use (kg/ha)		Yields (kg/ha) in Log	
Variable	Model I (1)	Model II (2)	Model I (3)	Model II (4)
1. Intercept	23.04	21.17	7.82	7.82
	(11.76)***	(10.43)***	(26.57)***	(26.09)***
2. GM rice dummy	−18.90	−12.94	.04	.05
	(15.28)***	(5.47)***	(1.56)	(1.06)
3. 2003 year × GM rice		−6.20		−.02
		(2.18)**		(.28)
4. 2004 year × GM rice		−9.57		−.04
		(3.18)***		(.93)
5. Natural disaster dummy (affected = 1)	7.19	7.87	−.53	−.52
	(2.41)**	(2.66)***	(11.53)***	(10.96)***
6. Plot size (ha)	1.12	.63	.00	−.00
	(.41)	(.24)	(.01)	(.02)
7. Plot soil quality (high quality)	−4.63	−3.97	.02	.02
	(2.11)**	(1.82)*	(.66)	(.58)
8. Plot soil quality (medium quality)	−3.28	−3.08	.03	.02
	(1.47)	(1.40)	(.74)	(.68)
9. 2003 year dummy	.13	1.97	−.05	−.05
	(.09)	(1.21)	(2.32)**	(1.85)*
10. 2004 year dummy	5.13	8.06	.03	.04
	(2.59)***	(3.72)***	(.84)	(1.20)
11. Labor (log)			.09	.09
			(2.08)**	(2.10)**
12. Fertilizer (log)			.06	.06
			(1.56)	(1.55)
13. Machine (log)			.00	.00
			(.78)	(.80)
14. Other inputs (log)			.02	.02
			(2.30)**	(2.33)**
15. Pesticides (log)			.00	−.01
			(.01)	(.26)
16. Household dummy variables	Included but not reported			
17. Observations	584	584	584	584

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

rises in output (or absence of fall of output) and reductions of inputs mean that GM rice varieties would lead to absolute rises in productivity. In fact, the potential gains to China's economy could be large. Even after considering general equilibrium effects (e.g., the price of rice would fall when rice became more profitable and the area expanded), Huang et al. (2004) show that the annual gain to China's economy would be US$4.2 billion if GM rice were to be fully adopted in the future.

VI. Multivariate Results Using the More Restricted Sample

When restricting the sample to only those households that planted at least one plot of GM rice and at least one plot of non-GM rice, we find that the results remain almost unchanged (table 7). The results of the household fixed-effects model show that pesticide use fell sharply (by 18.45 kilograms per hectare) in all years of the study (col. 1, row 2). Like the results in table 6 (which uses the full sample), the results in table 7 demonstrate that pesticide use also is falling increasingly over time. In table 7 the effects of GM rice on yields, like those in table 6, also are insignificant from zero. Hence, regardless of using the full or more restricted sample, although yields are not rising, GM rice clearly is still leading to rising productivity, but this is mostly due to the reduction of pesticides.

VII. Conclusion: The Future of GM Rice in China

China is still struggling with issues of biosafety of GM rice and is considering the issues of international and domestic acceptance. Many competing factors are putting pressures on policy makers to decide whether they should approve commercializing GM rice or not. The nation has already invested several billion U.S. dollars in biotechnology research and the development of a stock of GM technologies. Many of the new events have already been through several years of environmental release and preproduction trials. As competitive pressures inside China build in the agricultural sector because of the nation's accession to the World Trade Organization in 2001, and as leaders search for ways to increase rural incomes, there will be a continuing demand by producers for productivity-enhancing technology. The past success in developing technologies and high rates of return to public research investments suggest that products from China's plant biotechnology industry could be an effective way to both increase competitiveness internationally and increase rural incomes domestically.

The analysis in this article shows that in preproduction trial sites the costs of those farmers who adopt insect-resistant GM rice fall and their yields either rise or at least do not fall. Hence, the article provides evidence that GM rice does improve productivity significantly. Given that the farmers in the sample are small and relatively poor (the average per capita income of the households in the sample is less than $3 per day), leaders concerned with agricultural productivity and farmer income should seriously consider commercializing GM rice.

TABLE 7

ESTIMATED PARAMETERS USING A HOUSEHOLD FIXED-EFFECTS MODEL FOR ESTIMATING THE EFFECT OF GM RICE VARIETIES ON FARMERS' PESTICIDE APPLICATION AND YIELDS OF HOUSEHOLDS IN PREPRODUCTION TRIALS IN CHINA (BASED ON HOUSEHOLDS THAT GROW ONLY BOTH GM AND NON-GM RICE)

	Pesticide Use (kg/ha)		Yields (kg/ha) in Log	
Variable	Model I (1)	Model II (2)	Model I (3)	Model II (4)
1. Intercept	21.86	18.74	8.40	8.42
	(7.20)***	(5.66)***	(17.56)***	(17.44)***
2. GM rice dummy	−18.45	−12.56	.01	−.01
	(13.66)***	(4.23)***	(.25)	(.32)
3. 2003 year × GM rice		−6.38		.05
		(1.84)*		(.82)
4. 2004 year × GM rice		−8.12		.02
		(2.20)**		(.38)
5. Natural disaster dummy (affected = 1)	12.02	12.81	−.63	−.63
	(2.74)***	(2.93)***	(9.22)***	(9.17)***
6. Plot size (ha)	49.16	39.28	−.03	−.03
	(1.08)	(.86)	(1.63)*	(1.66)*
7. Plot soil quality (high quality)	−4.75	−3.88	−.01	−.01
	(1.56)	(1.26)	(.27)	(.15)
8. Plot soil quality (medium quality)	−2.32	−1.88	.03	.03
	(.73)	(.60)	(.62)	(.64)
9. 2003 year dummy	−.72	2.37	−.07	−.09
	(.31)	(.83)	(2.01)**	(2.14)**
10. 2004 year dummy	2.40	5.91	−.00	−.02
	(.67)	(1.53)	(.05)	(.24)
11. Labor (log)			.01	.01
			(.14)	(.18)
12. Fertilizer (log)			−.01	−.01
			(.09)	(.17)
13. Machine (log)			.03	.03
			(2.53)**	(2.48)**
14. Other inputs (log)			.03	.03
			(.72)	(.72)
15. Pesticides (log)			−.00	.00
			(.23)	(.09)
16. Household dummy variables	Included but not reported			
17. Observations	293	293	293	293

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

Should China's leaders continue to commit large R&D investments to the GM rice program? At China's current stage of development, there is a question whether the nation needs any more rice or not. Since the late 1990s, rice consumption has fallen as rural and urban residents shift their diets to meat and other nonstaple goods. China's rice consumers are also demanding higher-quality rice, which calls into question the breeding strategy of the GM rice scientists who generally are inserting the Bt genes into relatively lower-quality hybrid rice cultivars. Hence, while the results of this article suggest that GM rice will raise productivity, the nature of the investments also has to account for the changing consumer preferences or there will be fewer gains from the development of the new varieties because demand by consumers will be lower.

While such considerations are worthy of analysis, several factors suggest that in the longer run the current research strategy will still bring a lot of benefits to China's farmers. Although China's rice scientists are developing the first generation of GM rice in hybrid varieties, which may indeed be suffering from falling demand, they are doing so because of the relatively weak intellectual property rights environment inside China. The use of hybrid varieties allows for some degree of protection from piracy since the GM hybrid varieties are more difficult for other farmers and seed companies to duplicate. However, if China can improve intellectual property rights or if the government were to step in and support research without regard to the question of whether the new GM rice varieties can be protected or not (since they may have a benefit to society as a whole), the current technology can be used in all varieties, not just hybrids. This means that as market demand changes, the GM rice traits can be used far beyond the current restricted set of varieties. The changes in market demand also mean that there will be less sown area in rice as farmers shift to other crops. Under such market conditions, farmers will still benefit from adopting more efficient varieties (as consumers will because of lower prices). In addition, although demand for hybrid rice in general is lower, poor farmers are more likely than richer farmers to cultivate hybrid rice. Hence, the current strategy—which may have been pursued for different reasons—in fact, may be pro-poor.

Should China decide to commercialize GM rice, the implications could far exceed the effect on its own producers and consumers. Paarlberg (2003) suggests that if China were to commercialize a major crop, such as rice, it is possible that it would set off a chain reaction in the world. For example, if China were to commercialize rice, it possibly would clear the way for the production of GM wheat, maize, and other crops inside China. If China proceeded in this direction, this could encourage the large grain-producing nations, such as Canada, the Unted States, and Australia, to continue to expand their programs in GM wheat and other crops, since China is a likely target for their exports in the future. In addition, the commercialization of rice and other crops may induce other developing countries, such as India or Vietnam, to expand their plant biotechnology programs. On the one hand, other developing countries might follow China in an effort to remain competitive. On the other hand, with a clear precedent, other leaders might be willing to adopt

GM food crops to increase the income of their farmers as well as to improve their health. It is in this very real sense that the future of GM rice in China may have an important influence on the future of GM crops in the world.

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