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Pesticide productivity, host-plant resistance and productivity in China

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Abstract

Pesticides are used as the primary method of pest control in Asian rice production. Conditions in China have led to demand for high and increasing rice yields, resulting in intensive cultivation and adoption of fertilizer responsive varieties. The consequence has been widespread pest infestations. Many studies have estimated pesticide productivity, but few have estimated the productivity of alternative methods of pest control, namely host-plant resistance. None have estimated the substitutability between these methods of pest-control. The productivity of pesticides and host-plant resistance, and the substitutability between them is measured using two-stage Cobb–Douglas and translog production functions. Under intensive rice production systems in eastern China, pesticide productivity is low compared to the productivity of host-plant resistance. In fact, returns to pesticide use are negative at the margin. Host-plant resistance is an effective substitute for pesticides and substantial reductions in pesticide use could be achieved, with no loss in rice production, through improvements in host-plant resistance. These results suggest that pesticides are being overused in eastern China and host-plant resistance is being under-utilized. Government policies to promote increased pesticides in rice might be ill advised given the low productivity and negative returns, particularly in light of well known negative externalities associated with pesticide use. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: Pesticides; Host-plant resistance; Chinese rice production

1. Introduction

Farmers around the world are engaged in a constant battle, the battle against crop destroying pests. Pests can cause crop damage and diminish farmers' welfare. Fortunately, producers can mitigate the impacts of crop pests, and do so most commonly by applying chemical pesticides. Reliance on pesticides as the

primary or sole means of pest control, however, may not be the most profitable or sustainable strategy, and may have a number of harmful side effects. In the battle against pests, pesticides are a double-edged sword.

Since the mid-1970s, researchers have described unintended consequences from pesticide use in agriculture, particularly in developing countries, and several economic studies have questioned whether current patterns of pesticide use are economically and socially efficient. Policy makers in many countries have begun to regulate pesticide use, and have taken

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interest in alternative methods for controlling agricultural pests. One method of non-chemical pest control in field crops is the development and dissemination of varieties with host-plant resistance. A resistant crop variety suffers smaller yield losses than non-resistant varieties when subjected to pest infestation. Host-plant resistance may also substitute for and/or complement chemical pesticides in reducing pest losses and increasing crop yields.

The role of host-plant resistance as a pest control alternative raises several important concerns about commonly observed farming practices. For example, if currently available varieties are already resistant to damaging pests, why do farmers continue to use heavy doses of pesticides? In the presence of host-plant resistance, do pesticide-based reductions in pest damage justify the cost of the pesticide? Agronomic evidence suggests that in some cases they do not; common rates of pesticide usage may be inefficient in the presence of host-plant resistance (Buntin et al., 1992; Robinson et al., 1978; Teetes, 1994).

While studies of pesticide productivity are relatively common, few researchers have assessed the production impacts of host-plant resistance and almost none have explored the interactions between pesticides and host-plant resistance. The goal of this paper is to analyze the shortcomings of China's pesticide-intensive insect and disease control strategies by examining the relative productivity of pesticides and host-plant resistance, and the interactions between them. To meet this goal, the paper first describes the pest management strategies used by China's farmers and the incentives for input intensive rice production that lead to high pesticide use. The paper then examines the effectiveness of pest control strategies on rice production in eastern China, strategies based on high levels of insecticide and fungicide use as well as adoption of varieties which contain insect and disease resistance. Finally, the paper discusses the possible reasons why farmers apply high rates of pesticides and do not effectively utilize host-plant resistance, and the policy implications of such behavior.

To narrow the scope of the work, the paper addresses pest management practices in two provinces of eastern China, Zhejiang and Jiangsu. In order to collect the data necessary to carefully analyze pest

control productivity, the authors studied the production and management behavior of farmers in China's most important cropping sector during more than a year of field work, collecting a unique set of production, varietal, and pest infestation data at the township level.

2. Intensification of agriculture and infestation of pests in eastern China

Fertile soil and abundant water resources make China's greater Yangtse River Delta region one of the world's most productive rice growing regions. With low per-capita land availability (Table 1), farmers in the region have traditionally generated some of Asia's highest rice yields through intensive application of labor (Table 1). As the region's population growth has increased pressure on land, pressure has also risen to increase rice yields to address national concerns of rice self-sufficiency. Farmers are required to sell a substantial amount of rice production to state procurement agencies (Table 1). Although yield increases are a priority for government leaders, increasing off-farm labor opportunities have diminished labor availability and placed the burden for high yields on intensifying the use of purchased inputs (Table 1). These conditions have induced China's agricultural research system to generate, and pushed local leaders and farmers to adopt, modern agricultural technology, including pesticides (Lin, 1992; Huang and Rozelle, 1996). For example, farmers in both Zhejiang and Jiangsu increased their use of chemical fertilizers at about 5% per year (Widawsky, 1996) while increasing their adoption of high-yielding, input-intensive hybrid rice varieties.

2.1. Rising levels of pest infestations

Although pest infestations have always been a feature of China's rice production, they became a chronic problem with the adoption of fertilizer responsive varieties, a fallout from the technological revolution that began in the 1960s and has continued since then (Chengxiang, 1988). Averaging over the four major rice insect pests, the sample areas in Jiangsu and Zhejiang experienced outbreaks approximately 1.5 times in 1985 and nearly two times in 1991

Table 1
Production characteristics and pesticide use in eastern China, 1984–1991 county averages

	Jiangsu study counties				Zhejiang study counties				Overall average
	Gaoyou	Jingiang	Sihong	Xiangshui	Xinchang	Wenling	Pinghu	Tongxiang	
I. Production characteristics									
1. Cultivated area per capita (ha/capita)	0.10	0.04	0.11	0.08	0.05	0.04	0.10	0.07	0.07
2. Average rice yield (t/ha)	7.02	6.92	6.11	7.01	5.68	5.84	5.98	5.94	6.31
3. Grain selling obligation (% of grain production)	33	4	13	8	8	10	29	23	16
4. Value of agricultural to industrial output (1985 ratio)	2.88	0.24	63.99	9.45	1.49	1.62	1.18	1.00	
5. Value of agricultural to industrial output (1991 ratio)	2.12	0.24	12.81	4.13	0.72	1.05	0.76	0.50	
II. Pesticide use									
6. Average insecticide applications (number/year)	4.10	5.88	4.73	4.53	5.75	1.60	2.67	2.04	3.91
7. Average fungicide applications (number/year)	2.96	4.07	2.58	3.61	4.49	0.78	2.03	0.53	2.63
8. Total pesticide applications (number/year)	7.06	9.95	7.31	8.14	10.24	2.39	4.71	2.57	6.55
9. Amount of insecticide use (kg a.i./ha*year)	1.02	1.37	1.91	3.34	2.59	2.63	2.17	3.73	2.34
10. Amount of fungicide use (kg a.i./ha*year)	0.11	0.22	0.35	0.35	0.37	0.63	0.79	1.52	0.54
11. Total pesticide use (kg a.i./ha*year)	1.14	1.59	2.26	3.68	2.96	3.26	2.96	5.25	2.89

Note: The study sites include eight townships in each of the eight counties across two provinces in eastern China (Zhejiang and Jiangsu) for a total of 64 townships. Data were collected for 8 years from 1984–1991. The number of pesticide applications per year is an index of the number of times the entire sown area of a township was treated. The total area treated during each application is systematically recorded, and divided by sown area to create the index. Although some pesticides treat bacterial diseases, for ease of labelling, all disease control chemicals are here called fungicides.

Source: Authors' survey.

(Fig. 1, panel A)¹. Although disease generally affected rice fields somewhat less, each plot experienced an outbreak about one time per season (Panel B). If farmers had not responded with pest control treatments, meaning pesticide applications in the study area, local agricultural officials estimate that

¹Percent infested area is calculated by adding total infestation for all pests and dividing by sown area. When percent sown area is more than 100%, it indicates that on average more than one pest had infested the rice fields. Infestation figures, as well as potential and actual loss figures, are estimated by technicians (sometimes more than one) who are stationed in every township in the study area and also required to estimate crop losses from pests on an outbreak by outbreak basis. They report the level of loss they believed an untreated infestation would have caused in the absence of pesticide applications, as well as the actual loss incurred by farmers.

from 15% to 35% of the total crop would have been lost during the entire 8 year study period (Fig. 1, Panel C, light bars). After responding with pesticides, the actual losses fell (dark bars), but farmers still lost from 3% to 13%.

2.2. Pesticide use

With the threat of crop losses from pests rising during the 1960s and 1970s, government officials assumed responsibility for pest control primarily by increasing the availability of chemical pesticides. By the 1980s, land-poor farmers in eastern China were applying pesticides regularly and at high levels (Table 1). The frequency of pesticide applications on rice in most of the counties studied, is among

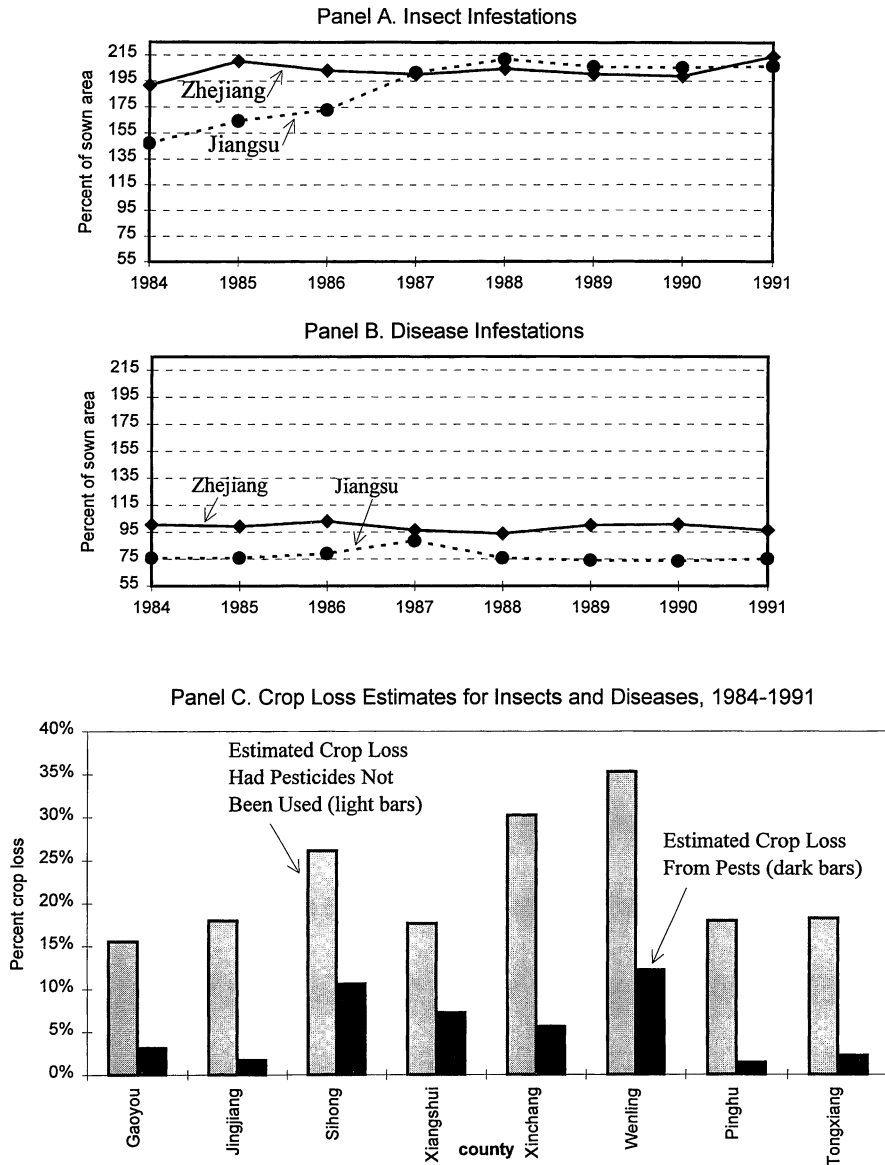


Fig. 1. Rice pest infestations and crop loss in eastern China, Sample Averages, 1984–1991.

the highest in rice producing Asia, comparable to that of Japan (Edwards, 1986). Among the survey locations in eastern China, five of the eight counties had average rates of insecticide use nearly twice that of lowland irrigated rice systems in the Philippines, where serious health and environmental effects have been linked to pesticide use (Rola and Pingali, 1993).

2.3. Drawbacks of intensive pesticide use

With high rates of pesticide use and the negative externalities associated with such levels, there is a concern about whether pesticide use has reached levels at which direct marginal contributions are minor, or perhaps even negative. Insecticide sprays early in a rice cropping season have been shown to

decimate populations of natural predators and induce infestations of damaging pests such as brown planthopper (Kenmore, 1980; Heinrichs and Mochida, 1984; Schoenly et al., 1996). The phenomenon of a 'pesticide spiral' may occur when heavy pesticide use in rice results in pest populations that are pesticide resistant (Chelliah and Heinrichs, 1980). Increasing pest resistance to pesticides creates a situation in which higher levels of pesticide are needed to achieve the same level of pest control (Litsinger, 1989). In China, field and laboratory studies have shown that increasing resistance in pest populations to high rates of pesticide use has decreased the effectiveness of pesticides (Chu et al., 1987; Su et al., 1991).

2.4. Host-plant resistance in China

While breeding efforts to incorporate host-plant resistance in rice had started elsewhere, by the late 1970s a number of Chinese rice breeders were devel-

oping pest resistant rice varieties. In some areas the presence of resistance was mandated for seed certification. However, given the emphasis in agricultural planning to development and expansion of farm chemicals, host-plant resistance was assigned a secondary role, and adoption of varieties with host-plant resistance was rarely accompanied by decreases in pesticide use.

Despite this secondary status, local officials extended and farmers in eastern China adopted a wide array of rice varieties with host-plant resistance to insects and diseases during the period of the survey. On an average, most townships had between three and nine pest resistant varieties planted by farmers (Widawsky, 1996). Even with these resistant varieties, producers in the study area continued to use pesticides at rates high enough that they may have contributed to a deterioration of the resistance originally embodied in the newly released varieties. A substantial proportion of sown varieties grown during the 1984–1991 study

Table 2
Deterioration of host-plant resistance in eastern Chinese rice varieties, 1984–1991

	Neck blast	Bacterial leaf blight	Stem borer	Brown planthopper	Whitebacked planthopper	Leaf folder
% of varieties with lower resistance to specific pests over the period ^a						
1984–1988	0.23	0.20	0.11	0.16	0.06	0.01
1988–1991	0.27	0.19	0.17	0.12	0.12	0.13
1984–1991	0.29	0.23	0.14	0.11	0.03	0.02
% of resistance deterioration among varieties with lower resistance ^b						
1984–1988	0.353	0.308	0.283	0.107	0.319	0.333
1988–1991	0.300	0.315	0.247	0.273	0.329	0.333
1984–1991	0.350	0.307	0.286	0.271	0.25	0.387
% of resistance deterioration among all sown varieties over the period ^c						
1984–1988	0.102	0.040	0.068	0.006	0.080	0.049
1988–1991	0.059	0.070	0.030	0.036	0.039	0.052
1984–1991	0.110	0.126	0.089	0.060	0.033	0.069

^a For varieties that were grown over an entire period (e.g. 1984–1988) in a township, these figures reflect the % of incidences when host-plant resistance for a variety was lower at the end of the period than at the beginning. For example, 29% of varieties grown over the entire period 1984–1991 had declining resistance to neck blast.

^b For the above incidences, when varieties had declining resistance over a period, these figures represent the proportion of deterioration that occurred based on the 5-point resistance scale. For example, among the 29% of varieties grown over the period 1984–1991 that had declining neck blast resistance, the average rate of resistance deterioration was 35%.

^c For all varieties grown over an entire period, these figures represent the average rate of resistance deterioration. This includes varieties both with and without declining resistance. For example, among all varieties grown over the period 1984–1991, the average rate of deterioration in neck blast was 11%.

period, experienced deteriorating host-plant resistance (Table 2).² Among varieties with deteriorating host-plant resistance, the magnitude of resistance decline is substantial, averaging 25%–35% decline for all pests (Table 2). The average decline in resistance among all varieties, both those with and without deteriorating host-plant resistance, is still considerable and raises concerns about China's ability to maintain current levels of host-plant resistance in its rice cultivars (Table 2).

While host-plant resistance should aid in the struggle to maintain high yields by minimizing pest damage, the process of breeding for insect and disease resistance may be associated with lower yield potentials. A yield/resistance tradeoff may arise because host-plant resistance is commonly strongest in land-races or other cultivars with lower maximum-attainable yields (Khush, 1987), and their incorporation into modern rice cultivars adds genetic material from land races that may reduce yields. Back-crossing using high-yielding varieties can minimize this trade-off, but agricultural officials in eastern China indicated this had not always been completely successful.

3. Modelling pest control in China

The discussion above raises several important questions about the effectiveness of pest control practices in China. Does applying pesticides in rice justify their use at current rates, especially in the presence of improved varieties with host-plant resistance? Is host-plant resistance a productive input in rice production? Can host-plant resistance effectively substitute for pesticides as a form of pest control? Answering these questions requires measuring the productivity of both pesticides and host-plant resistance,

as well as measuring the tradeoff between the two. This section outlines the empirical framework for analyzing pest control in China, describes the data, and presents results from the analysis.

Modelling pest control presents a challenge for several reasons. To estimate their productivity, measures of both chemical pesticides and host-plant resistance need to be included in the analysis. To our knowledge, no previous study has tried to treat host-plant resistance as a directly measured input. There are complex interactions between pest infestations and crop yields, and model specification must be sufficiently flexible to include parameters for interactions and substitutability. The use of pesticides by farmers and their effectiveness may also depend on the level of pest infestation. For unbiased and efficient estimates of the impact of pesticide inputs on yields, the frequency and severity of pest outbreaks need to be taken into consideration.

3.1. Functional forms and empirical specifications

The Cobb–Douglas production function has often been used to estimate pesticide productivity, but has two shortcomings. The elasticity of substitution between host-plant resistance and pesticide (and among all other inputs) is constrained to be identically equal to one, and a standard Cobb–Douglas model does not account for the potential endogeneity of pesticides. If pesticides are applied in response to pest pressure, and high levels of infestations are correlated to lower yields, then a relationship between pesticides and negative residuals in a production function might bias productivity estimates for pesticide and host-plant resistance.

To empirically account for these factors, the initial modelling approach used in this analysis can be specified as a two-stage Cobb–Douglas models with interaction terms. The first stage to be estimated is a log-linearized exponential function for pesticide use:

$$z_p = a_0 + \sum_{i=1}^r a_i A_i + \sum_{j=1}^r d_j D_j + \sum_{h=1}^7 b_h L_h + \sum_{g=1}^w c_g S_g \quad p = 1, 2 \quad (1)$$

²A metric of pest resistance for rice varieties grown in eastern China is based on internationally recognized methods of assessing pest resistance in rice (International Rice Research Institute, 1979). Varieties that show some level of resistance are assigned a standardized resistance index based on their susceptibility (or lack of it). In the study area in eastern China, the resistance scale ranged from 0 to 5 and was based on criteria in government published handbooks. Resistance data were collected from seed company and plant protection departments at each location for varieties grown in that location, and the status of resistant varieties was tracked over time for each of six major pests.

where z_p is the logarithm of insecticides and fungicides, and is modelled as a function of scope (A_i) and severity (D_j) of pest infestations and shifter variables (L_n and S_g). The coefficients to be estimated are a_0 , a_i , d_j , b_h , and c_g . Pesticides appear as an exponential function since pesticides are applied in eastern China according to certain conditions (e.g. pest infestations), but pesticide use levels off rather quickly.³

Using predicted values of z_p from Eq. (1) and allowing for interactions between chemical pesticides and host-plant resistance by including the terms z_1z_3 , and z_2z_4 , pest control productivity can be estimated from the log-linear production function in the second stage:

$$y = \alpha_0 + \sum_{i=1}^n \alpha_i x_i + \sum_{j=1}^4 \beta_j z_j + \beta_5 z_1 z_3 + \beta_6 z_2 z_4 + \sum_{k=1}^m \gamma_k S_k + \sum_{h=1}^7 \delta_h L_h \quad (2)$$

where z_1 is insecticide, z_2 is fungicide, z_3 is host-plant resistance against insects, and z_4 is host-plant resistance against diseases (log-terms are in lower case). The coefficients to be estimated are α_i , β_j , γ_k , and δ_h . The vector of ‘normal’ inputs, x , includes factors such as fertilizer and labor, S accounts for yield differences due to cropping patterns and major weather events. Locational shifters, L , account for fixed differences in regional elements such as water control, soil, and land fertility. Including pest control interaction terms in the production function relaxes the constraint on fixed substitutability between pesticides and host-plant resistance that is typical of the Cobb–Douglas function, but retains the parsimony of the form. If yields and inputs are scaled by their geometric means, then the elasticity of substitution can be expressed from the estimated coefficients of Eq. (2) as (Boisvert, 1982):

$$\epsilon_{1,3} = \frac{-(\beta_1 + \beta_3)}{-(\beta_1 + \beta_3) - (2\beta_5\beta_1\beta_3)/\beta_1\beta_3} \quad (3)$$

Alternatively, a two-stage translog specification (where pesticides are predicted from Eq. (1)) allows for even more flexible marginal products and substitution elasticities than the modified Cobb–Douglas one. In this case, the log-linearized production function is given by:

$$y = \alpha_0 + \sum_{i=1}^n \alpha_i x_i + \frac{1}{2} \sum_{i=1}^n \sum_{i2=1}^n \alpha_{i1,i2} x_{i1} x_{i2} + \sum_{j=1}^4 \beta_j z_j + \frac{1}{2} \sum_{j1=1}^4 \sum_{j2=1}^4 \beta_{j1,j2} z_{j1} z_{j2} + \sum_{i=1}^n \sum_{j=1}^4 \theta_{ij} x_i z_j + \sum_{k=1}^m \gamma_k S_k + \sum_{h=1}^7 \delta_h L_h \quad (4)$$

Using data scaled by their geometric means in the translog production function, the elasticity of substitution of host-plant resistance for insecticides is given by:

$$\epsilon_{1,3} = \frac{-(\beta_1 + \beta_3)}{-(\beta_1 + \beta_3) + (\beta_1^2\beta_3,3 - 2\beta_{1,3}\beta_1\beta_3 + \beta_{1,1}\beta_3^2)/\beta_1\beta_3} \quad (5)$$

3.2. Data

The data come from a variety of sources in rural China, and were collected by the authors during nearly one year of fieldwork in 1993. Township-level data come from eight randomly selected townships in each of the eight counties (for a total of 64 townships) in Jiangsu and Zhejiang provinces and were available for eight years, 1984–1991. While most information came from standard data reporting and statistical collection sources, the written records of pest control technicians from the 64 townships provided information for unique measures of pesticide inputs, pest infestations, pest damage, and the level of pest-resistance for each variety. Rice yield was measured in kg ha^{-1} and explanatory variables were specified as follows.

Pesticides: This study uses three common techniques for measuring pesticide use: real monetary value (yuan/ha), pure active ingredient (kg a.i./ha), and

³The pesticide equations were also estimated as simple linear functions and there was very little difference in coefficient estimates or regression coefficients. The exponential form was therefore employed because it facilitates testing of pesticide endogeneity in a Cobb–Douglas production function using Hausman’s (1978) method.

potency-adjusted or 'effective' amounts where active ingredient was standardized by a recommended dose for each pesticide. Measures of all the three are utilized for both insecticides and disease-control pesticides using detailed pesticide data collected in each township;

Host-plant resistance: Each variety grown in each location is assigned resistance scores (for 3 year intervals) to each of the four insects and two diseases using a five-point scale (with higher scores being associated with higher resistance). Variety-specific resistance data are weighted in two ways. First, since high resistance to a certain insect does not insure resistance to all insects, pest-specific resistance is weighted by the incidence of that pest in the township, giving more weight to resistance against the most chronic pests. Second, since widely sown varieties exert greater influence on township-level yield than sparsely sown varieties, proportion of sown area in each variety is used to weigh variety-specific insect and disease resistance, giving more weight to cultivars that dominate a township's varietal mix.

Pest pressure: The proportion of total sown area infested by a given insect or disease is an indicator of the extent of pest pressure. Incidence of multiple pesticide treatments is included as a measure of the severity of a pest infestation.

Other factors: Chemical fertilizer is included as a pure nutrient amount of both nitrogen and phosphorous (i.e. kg pure N/ha). Labor is measured as the ratio of available laborers to total cultivated area (and exhibited strong positive correlation with provincial estimates of per hectare labor use, as enumerated in the state price bureau's cost of production data). Machinery input is the proportion of cultivated area plowed by mechanical tractor. Time is a proxy for technical change. The proportion of double-cropping represents the influence of a shorter growing season compared to single-season rice production. A dummy variable for climatic disasters (e.g. a major flood in Gaoyou in 1991) accounts for major production shocks. Procurement obligations quotas (in kg ha⁻¹) in pesticide prediction equations measure policy pressure to generate high yields through the use of pesticides. Fixed-effects, or county-specific dummy variables, account for spatial differences. The data are summarized by

their mean and standard deviation in Widawsky (1996).

4. Results

Eqs. (1) and (2) were estimated as specified. The two-stage translog model (Eqs. (1) and (4)) produced alternative estimates, where some interaction terms were restricted to reduce multicollinearity.⁴ For each model, three estimates are obtained corresponding to the different methods for measuring pesticides.⁵

The general performance of the yield function estimates is fairly robust with regard to pesticide specification and yield function (Table 3). The R²-values of the estimated yield functions vary from 0.53 to 0.59. Because conditions in eastern China emphasize high yields and input use, one might expect that the high rate at which the traditional inputs are used leads to low marginal productivities. The productivity of fertilizer, labor, and machinery are generally quite low, but are similar to those found in other studies of intensive rice cultivation in Asia, in general (Pingali et al., 1995b), and China in particular (Putterman and Chiacu, 1994).⁶

Parameter estimates from the pesticide prediction equations demonstrate that pesticide use is correlated to rate of infestation of both insects and diseases (Table 4). Regression coefficients ranged from 0.42 to 0.57 for the insecticide equations and from 0.30 to 0.35 for the fungicide equations. Tests of endogeneity

⁴Since there are four pest control inputs and four normal inputs, there are potentially 36 interaction terms alone which makes estimation unfeasible. Therefore, the interaction which were not restricted to be equal to zero were: squared pest control terms, squared normal-input terms, insecticide* (insect resistance), fungicide* (disease resistance), and all nitrogen* (pest control input) interactions.

⁵Full regression summaries are given in Widawsky, 1996.

⁶The other explanatory variables in the yield equations all had expected impacts on yield. The positive coefficient on the time variable supports the notion that technological progress took place during the survey period, and is consistent with other studies of rice yields in China (Huang and Rozelle, 1996). Double-cropping is associated with lower yields, the result of shorter growing seasons. The coefficient on the variables representing inclement weather years is predictably negative in all cases.

reject the simple Cobb–Douglas model in which pesticides are assumed to be exogenous.⁷ Models of rice yield that do not account for the relationship between pesticides, pest infestations, and rice yields may generate biased estimates of pest control productivity. Therefore, while some coefficient estimates from the simple Cobb–Douglas functions are similar to those of the other yield functions, we will concentrate the rest of our attention on estimates derived from the models where pesticides are endogenous.

4.1. Estimates of pesticide productivity

Productivity of pesticides as measured by elasticity of production, and allocative efficiency as measured by the ratio of value marginal product of pesticide to the price of pesticides suggest that farmers in China are overusing chemical pest control methods

⁷Endogeneity of pesticides was tested using Hausman (1978) method. The test is run by estimating the two-stage Cobb–Douglas yield function with both predicted and actual pesticide levels and testing whether the coefficients on both predicted insecticide and fungicide are jointly zero (an F -test). For value-based measures of pesticides the F -value was 4.18, for active ingredient based measures it was 6.02, and for effective or potency-based measures the F -value was 1.91. The first two tests comfortably reject the null hypothesis that pesticides are exogenous, and the last test is somewhat less convincing. Exogeneity of instruments was tested with Hausman (1983) method which simplifies to regressing the residuals from Eq. (2) on the instruments. A low R^2 -value implies that the error is not correlated to the explanatory instruments. A high R^2 -value rejects the null hypothesis of no correlation (e.g. exogeneity). The test statistic is N^*R^2 , where N is the number of observations. The test-statistic is distributed chi as (chi-squared with 2 degrees of freedom, and had values of 11.46, 11.41, and 18.13 for the value-based, pure, and effective specifications of pesticide, respectively). The second nested (null) hypothesis is that there is no difference between the two-stage Cobb–Douglas and translog models. Testing the null hypothesis that there is no difference between the models is carried out by jointly testing whether all the interaction terms are equal to zero, a standard F -test. In the estimates using value-based and active-ingredient based pesticides, the test statistics reject, with 99% confidence, the hypothesis that the two-stage Cobb–Douglas and translog specifications are the same ($F=2.102$ and 2.2716 , respectively). For the model using potency-adjusted active ingredient, the test-statistic is $F=1.354$ and rejects the null hypothesis less convincingly at 83% confidence. In spite of this, there is not too much difference between the two specifications in estimates of pesticide productivity, host-plant resistance productivity, or elasticities of substitution, as the next section shows.

(Table 5).⁸ Small and significant production elasticity for insecticide (and even negative in the case of fungicides) indicate that producers receive low returns at the margin. Pesticide use is allocatively inefficient in so far as additional pesticide use generates costs greater than the returns from higher yields. If pesticides have negative net returns in production, and the externalities of pesticide use (which are not included) have been shown to increase costs even further (as shown in Rola and Pingali, 1993), then these results may aid in formulating future policies that reduce the use of chemical pesticides.

4.2. Estimates of host-plant resistance productivity

Productivity of host-plant resistance to insects, as measured by its production elasticity, is positive for all specifications of the production models (Table 5). These results show that host-plant resistance is effective at the margin in controlling insects. Moreover, economic returns to improving host-plant resistance may be substantial. One rough way to calculate the value of host-plant resistance to insects in the two study provinces is to suppose a modest 1% increase in host-plant resistance and use production elasticities to calculate the value of the increase in rice production that would result. The value of the increase in Zhejiang and Jiangsu would range from \$ 281 000 to \$ 1.49 million.⁹ These calculations do not take into account supply responses and price effects from increased production. Rather, they are a heuristic device to broadly define the magnitudes of direct benefits from small improvements in host-plant resistance. In fact, these benefits are substantial when compared to the approximately \$ 1.5 million per year that is spent on all rice research in four provinces in eastern China, including Zhejiang and Jiangsu (Rozelle et al., 1996). Resistance to diseases had negative estimated impacts (a somewhat counter-intuitive result that may be related to both the rapid deterioration of the effective-

⁸These measures were calculated from estimated pest control coefficients in yield equations (see Appendix A).

⁹These figures are based on province-wide rice production in 1993 of 17.13 million t in Jiangsu and 12.99 million t in Zhejiang (ZGNYNJ, 1995), a rice price of 417 yuan/t, and an exchange rate of Y 8.3/\$. All prices in the analysis are deflated using the rural price index.

Table 3
Summary of general regression results (not including pest control variables)

	Dependent variable: rice yield		
	Model using expenditure	Model using pesticide active ingredient	Model using effective amount of pesticides
I. Production elasticity			
Nitrogen:			
Cobb–Douglas	0.013 (0.017)	0.017 (0.017)	0.017 (0.017)
Two-stage Cobb–Douglas	0.002 (0.015)	0.001 (0.015)	0.003 (0.016)
Two-stage translog	–0.009 (0.017)	–0.014 (0.017)	–0.009 (0.017)
Phosphorous:			
Cobb–Douglas	0.003 (0.006)	0.001 (0.006)	0.001 (0.006)
Two-stage Cobb–Douglas	0.0001 (0.006)	0.001 (0.006)	0.001 (0.006)
Two-stage translog	–0.007 (0.008)	–0.004 (0.008)	–0.007 (0.008)
Labor:			
Cobb–Douglas	0.041 (0.013)	0.036 (0.013)	0.036 (0.013)
Two-stage Cobb–Douglas	0.026 (0.012)	0.027 (0.012)	0.031 (0.013)
Two-stage translog	0.043 (0.016)	0.042 (0.016)	0.046 (0.016)
Machinery:			
Cobb–Douglas	0.016 (0.008)	0.016 (0.009)	0.016 (0.009)
Two-stage Cobb–Douglas	0.018 (0.008)	0.018 (0.008)	0.018 (0.008)
Two-stage translog	0.003 (0.011)	0.0004 (0.011)	0.003 (0.011)
II. Slope shifts			
Time:			
Cobb–Douglas	0.002 (0.002)	0.002 (0.002)	0.002 (0.002)
Two-stage Cobb–Douglas	0.005 (0.002)	0.005 (0.002)	0.006 (0.002)
Two-stage translog	0.005 (0.002)	0.006 (0.002)	0.008 (0.002)
Double-cropping:			
Cobb–Douglas	–0.302 (0.029)	–0.291 (0.029)	–0.292 (0.029)
Two-stage Cobb–Douglas	–0.276 (0.027)	–0.282 (0.027)	–0.287 (0.028)
Two-stage translog	–0.289 (0.034)	–0.308 (0.033)	–0.304 (0.035)
Disaster:			
Cobb–Douglas	–0.205 (0.023)	–0.206 (0.023)	–0.205 (0.023)
Two-stage Cobb–Douglas	–0.152 (0.020)	–0.153 (0.020)	–0.153 (0.020)
Two-stage translog	–0.155 (0.020)	–0.153 (0.020)	–0.156 (0.020)
III. Regression coefficients (adjusted R^2)			
Cobb–Douglas	0.54	0.53	0.53
Two-stage Cobb–Douglas	0.57	0.57	0.57
Two-stage translog	0.59	0.59	0.57

Note: Figures in parentheses are standard errors.

ness of disease resistant varieties and a yield/resistance trade-off).

4.3. Elasticity of substitution of host-plant resistance for pesticides

Another striking result of the model estimates is that in all cases, there is substantial potential for

substituting host-plant resistance for insecticides. Based on the elasticities of substitution, improvements in host-plant resistance can be accompanied by decreases in insecticides, with no loss in production (Table 5). Approximate estimates of the value of pesticide savings from a 10% increase in the index of host-plant resistance show that the savings from

Table 4
Results from pesticide prediction equations

Variable	Dependent variable: pesticide amount		
	Model using pesticide expenditure	Model using pesticide active ingredient	Model using effective amount of pesticides
I. Insecticide			
Intercept	-1.11(0.10) ^a	-1.27 (0.10)	-1.43 (0.10)
Infested area:			
Stemborer	3.03 (1.10)	3.61 (1.06)	2.60 (1.05)
Brown planthopper	2.13 (1.31)	1.02 (1.26)	2.08 (1.25)
Whitebacked planthopper	6.43 (1.12)	5.50 (1.08)	5.63 (1.07)
Leaffolder	5.80 (1.18)	6.07 (1.14)	6.23 (1.13)
Severity of infestation:			
Stemborer severity	0.02 (0.05)	0.06 (0.05)	0.05 (0.05)
BPH severity	0.21 (0.05)	0.26 (0.05)	0.20 (0.05)
WBPH severity	-0.21 (0.06)	-0.13 (0.06)	-0.11 (0.06)
Leaffolder severity	0.05 (0.05)	-0.04 (0.05)	-0.03 (0.05)
Other variables:			
Time	-0.001 (0.01)	0.0001 (0.01)	0.03 (0.01)
Grain quota	-0.001(0.001)	-0.0007 (0.001)	-0.001 (0.001)
Adjusted R^2	0.42	0.49	0.57
II. Fungicide			
Intercept	-0.99 (0.14)	-1.25 (0.15)	-1.16 (0.13)
Infested Area:			
Neck blast	7.38 (2.98)	13.81 (3.36)	5.25 (2.83)
Bacterial leaf blight (BLB)	3.58 (3.06)	-0.76 (3.45)	0.67 (2.90)
Sheath blight	6.49 (1.84)	5.87 (2.07)	7.18 (1.74)
Severity of Infestation:			
Neck blast severity	-0.10 (0.06)	-0.05 (0.07)	-0.06 (0.06)
BLB Severity	-0.06 (0.07)	-0.11 (0.08)	-0.15 (0.07)
Sheath blight severity	0.30 (0.06)	0.34 (0.06)	0.33 (0.05)
Other Variables:			
Time	-0.02 (0.01)	-0.01 (0.01)	0.04 (0.01)
Grain quota	0.002 (0.001)	0.002 (0.001)	0.002 (0.001)
Adjusted R^2	0.30	0.35	0.35

^a Figures in parentheses are standard errors of coefficient estimates. Due to limitations of space, coefficients on locational dummy variable are not included in the table.

substituting host-plant resistance for insecticides could be substantial.¹⁰

¹⁰Calculations can be made similar to the ones for approximating the productivity gain from improvements in host-plant resistance. They show that the savings in insecticide ranges from US\$ 305 000 per year to US\$ 7.55 million per year. Once again, these results are based on current prices that do not take into account price changes from a shrinking insecticide market. However, as before, the example shows that in just the two study provinces, the benefits from an improvement in host-plant resistance may well outweigh the costs, and at the same time substantially reduce negative externalities from pesticide use.

5. Discussion and conclusions

Pesticide use is high in eastern China, a consequence of economic and policy pressures to raise yields by intensifying input use. The difference between potential and actual crop loss might lead one to conclude that China's pesticide-first policy has been successful, a statistic often cited by government leaders as the basis for continuing pro-pesticide policies. This paper has shown, however, that although pesticides may reduce crop losses on average, they are probably being overused in Chinese rice production while host-plant resistance is being under-utilized. All

Table 5
Summary of pest-control productivity estimates

	Model using value-based pesticide	Model using pure amt. of pesticides	Model using effective amt. of pesticides
Production elasticity of insecticides ^a			
Two-stage Cobb–Douglas	0.006	0.007	0.003
Two-stage translog	0.003	0.007	0.002
Allocative efficiency of insecticides ^b			
Two-stage Cobb–Douglas	0.640	0.779	0.357
Two-stage translog	0.416	0.823	0.292
Production elasticity of fungicides ^a			
Two-stage Cobb–Douglas	−0.035	−0.038	−0.031
Two-stage translog	−0.048	−0.047	−0.045
Allocative efficiency of fungicides ^b			
Two-stage Cobb–Douglas	neg.	neg.	neg.
Two-stage Translog	neg.	neg.	neg.
Production elasticity of host-plant resistance to insects ^a			
Two-stage Cobb–Douglas	0.0343	0.0331	0.0333
Two-stage translog	0.037	0.040	0.037
Production elasticity of host-plant resistance to diseases ^a			
Two-stage Cobb–Douglas	−0.037	−0.042	−0.035
Two-stage translog	−0.013	−0.025	−0.018
Elasticity of substitution, host-plant resistance for insecticides ^a			
Two-stage Cobb–Douglas	0.327	0.719	0.526
Two-stage translog	0.229	0.365	1.738
Elasticity of Substitution, host-plant resistance for fungicides ^a :			
Two-stage Cobb–Douglas	0.279	0.432	0.390
Two-stage translog	0.106	0.201	0.228

^a Elasticity of production is evaluated at the geometric mean.

^b Allocative efficiency is the ratio of value marginal product of pesticide to pesticide price. Value marginal product is evaluated at the geometric mean.

estimates show that current rates of pesticide use are allocatively inefficient at the margin, connoting inefficiency even in the absence of other issues such as negative externalities.

Why are farmers overusing pesticides? One reason may be that farmers lack good information about the productivity of pesticides. Studies in the Philippines (Pingali et al., 1995a), Vietnam (Heong et al., 1994), and elsewhere in Asia have shown that after farmers received information about the true productivity of pesticides in rice production, they decreased their use of pesticide, often dramatically so. Another argument raised in trying to reconcile negative returns to producers is that since farmers may be risk averse, and

pesticides may help reduce the risk of catastrophic pest loss, the apparent economic inefficiency is, in fact, merely a rational risk premium and not economic inefficiency at all. Some of the studies cited above, however, have shown that curtailment of pesticide use has occurred with no precipitous increase in yield variability. Even if farmers are risk averse, reducing pesticide use may not increase uncertainty.

The results also show that host-plant resistance, especially insect resistance, is a productive, underutilized input. Benefits from improvements in host-plant resistance may be quite large. As a substitute for pesticides, improvements in host-plant resistance could lead to substantial savings in pesticides without

Table 6
Summary of coefficient estimates for pest control variables in the yield functions

Pest control parameter	Cobb–Douglas			Two-stage modified Cobb–Douglas			Two-stage translog		
	Model I	Model II	Model III	Model I	Model II	Model III	Model I	Model II	Model III
Insecticide (β_1)	–0.015 (0.008)	–0.001 (0.009)	–0.003 (0.008)	0.006 (0.015)	0.007 (0.015)	0.003 (0.016)	0.004 (0.015)	0.008 (0.016)	0.003 (0.016)
Fungicide (β_2)	0.016 (0.007)	–0.001 (0.005)	–0.0003 (0.006)	–0.035 (0.017)	–0.038 (0.015)	–0.031 (0.018)	–0.048 (0.018)	–0.047 (0.016)	–0.045 (0.019)
Insect resistance (β_3)	0.008 (0.025)	0.0139 (0.025)	0.014 (0.025)	0.034 (0.023)	0.033 (0.024)	0.033 (0.024)	0.037 (0.027)	0.041 (0.027)	0.037 (0.028)
Disease resistance (β_4)	–0.018 (0.028)	–0.023 (0.028)	–0.023 (0.028)	–0.037 (0.025)	–0.042 (0.026)	–0.035 (0.026)	–0.013 (0.029)	–0.025 (0.029)	–0.018 (0.030)
Insecticide*insect resistance (β_5 or β_{13})				0.041 (0.037)	0.018 (0.034)	0.011 (0.031)	0.055 (0.039)	0.021 (0.035)	0.021 (0.033)
Fungicide*disease resistance (β_6 or β_{24})				–0.093 (0.037)	–0.063 (0.033)	–0.028 (0.038)	–0.125 (0.039)	–0.080 (0.034)	–0.047 (0.040)
Insecticide ² (β_{11})							–0.003(0.020)	–0.008 (0.017)	0.004 (0.015)
Fungicide ² (β_{22})							0.023 (0.021)	0.029 (0.014)	–0.002 (0.017)
Insect resistance ² (β_{33})							–0.017 (0.034)	–0.003 (0.034)	–0.021 (0.035)
Disease resistance ² (β_{44})							0.068 (0.037)	0.057 (0.037)	0.050 (0.038)

Note: Figures in parentheses are standard errors. Model I represents estimates where pesticides are expressed in real value terms, Model II represents pesticides in terms of kilograms of pure active ingredient, Model III represents potency adjusted active ingredient.

reducing rice yields. Part of the under-utilization of host-plant resistance may be grounded in a lack of information. In spite of the fact that varieties with host-plant resistance are widely available, there is scant evidence that producers take into account available host-plant resistance in choosing how much pesticide to use.

All these results strongly suggest that China might do well to reconsider its commitment to increasing pesticide use in rice and consider increasing investments in improving host-plant resistance. More importantly, it is critical to appreciate that the relationship between the two is complex, and additional detailed research on the dynamic nature of pest control, infestation, and productivity is needed.

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Appendix A

See Table 6.

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