PESTICIDES AND HOST-PLANT RESISTANCE IN CHINESE RICE PRODUCTION: PRODUCTIVITY AND TRADE-OFFS

David Widawsky and Scott Rozelle

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Food Research Institute
Stanford University
Stanford, California 94305

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Managing crop losses due to pests is a source of continuing concern to rice farmers in Asia, as crop losses due to pests threaten increases in agricultural output. Farmers commonly mitigate this threat through the use of two pest control practices: application of chemical pesticides and/or adoption of rice varieties resistant to locally occurring pests. Increased pesticide use in rice farming systems has generated concerns, both in terms of public health and farmer productivity (Rola and Pingali, 1993) and in terms of the rising expenditure (per land area) on pesticides. Concentrated efforts begun in the 1970's and early 1980's have resulted in rice varieties with host-plant resistance to several chronically damaging pests. With recent technological advances improving the speed and efficiency of rice breeding, it becomes relevant to analyze host-plant resistance in production systems both as an input and as a potential partial substitute for chemical pesticides.

Several empirical estimates of pesticide productivity appear in the economic literature along with some describing the relationship between high pesticide use and increasing pest virulence (Campbell, 1976; Carlson, 1977; Babcock et al., 1992). These previous studies, however, have not explicitly measured the productivity of host-plant resistance and its substitutability for chemical pesticides. The overall goal of this paper is to explore the relationship between pest control and agricultural productivity. Measurement of the yield contribution of pesticides and host-plant resistance is accomplished by estimating a rice production function for Eastern China, using the estimated elasticities of production and substitution to assess: a) the proportional yield-increase associated with greater use of these two forms of pest control ; and b) the opportunities for maintaining yields while reducing pesticide use through the development of host-plant pest resistance. Such estimates may be valuable to policy makers who need to assess the production-based contribution of research in varietal improvement or anticipate the production effect of pesticide regulation. This study produces the first estimates, based on field data from a developing country, of the substitutability between pesticides and host-plant resistance.

The paper contains four sections. The next section describes the role of pest control in rice production for Eastern China, and examines trends in pesticide use and host-plant resistance. The subsequent section specifies the empirical form of the model and discusses the sources of data. The final two sections examine the results and explore the study's broader policy implications.

Rice Production in Eastern China

Rice production in Eastern China is characterized by some of the highest yields in Asia (Table 1, Column 2). Farm size and land availability per capita are small in Eastern China and there is limited potential for expanding sown area. Traditionally, labor intensive methods of cultivation were used to meet yield requirements of the large rural population. But, in the last several decades, farmers in China have been under even more intense pressure to increase grain production, in large part to meet government procurement targets and in-kind taxation obligations (Column 4).[1] As incomes rise, rice demand is increasing for both direct consumption and indirectly as animal feed.[2] Rapid development of rural industries in recent years has also increased off-farm job availability and raised the opportunity cost of cropping-labor (Column 3). Farmers have responded to these conditions with dual efforts to increase yields and reduce agricultural labor, primarily through the intensification of applied inputs such as fertilizer and pesticides.

Table 1.Summary Statistics of Study Counties

County	Cultivated Area per capita (ha/cap)	Average Rice Yield (tons/ha)	Value of Industrial to Agricultural Output (ratio)	Grain Obligation: percent of grain production
Gao You	0.10	7.02	0.72	0.33
Jing Jiang	0.04	6.92	5.07	0.04
Si Hong	0.11	6.11	0.11	0.13
Xiang Shui	0.08	7.01	0.28	0.08
Xin Chang	0.05	5.68	2.41	0.08
Wenling	0.04	5.84	1.94	0.10
Pinghu	0.10	5.98	1.21	0.29
Tong Xiang	0.07	5.94	1.54	0.23
Average	0.07	6.31	1.66	0.16

Note: The study sites include 8 townships in each of 8 counties across 2 provinces in Eastern China (Zhejiang and Jiangsu) for a total of 64 townships. Data were collected for the 8 years from 1984-1991.

Pesticides and Pest-Resistant Varieties. In Eastern China, chronic infestations of insects and diseases threaten recent rice yield increases and have led farmers to apply pesticides regularly and at high levels (Table

2).[3] The frequency of pesticide applications on rice in Eastern China is comparable to that of Japan (Row 10), where some of the most intensive input use in the world occurs.

Recently a number of studies have begun to question whether high level of pesticide use serve the interests of individual farmers. There is evidence that chronic high pesticide use erodes the productivity of other inputs, such as labor (Antle and Pingali, 1991). Field and laboratory studies in China show that increasing resistance of pest populations to high, systemic level of pesticide decreases the productivity of pesticides (Su et al. (1991), Bai et al. (1987)). This has led farmers to search for alternative forms of pest control.

Table 2.Insecticide Applications: Frequency and Amount

County	Average Insecticide applications (no. of times per year)	Average Fungicide applications (no. of times per year)	Total Pesticide Applications (no. of times per year)	Insecticide Use: Average Active Ingredient (kg/ha)	Fungicide Use: Average Active Ingredient (kg/ha)	Pesticide Total Use: Average Active Ingredient (kg/ha)
Gao You	4.10	2.96	7.06	1.025	0.114	1.14
Jing Jiang	5.88	4.07	9.95	1.369	0.224	1.59
Si Hong	4.73	2.58	7.31	1.907	0.352	2.26
Xiang Shui	4.53	3.61	8.14	3.338	0.346	3.68
Xin Chang	5.75	4.49	10.24	2.589	0.366	2.96
Wen Ling	1.60	0.78	2.39	2.633	0.631	3.26
Ping Hu	2.67	2.03	4.71	2.168	0.795	2.96
Tong Xiang	2.04	0.53	2.57	3.727	1.525	5.25
Average	3.91	2.63	6.55	2.34	0.54	2.89
Compared to:						
Japan	2.8[1]	3.5[1]	6.30[1]			10.8[1]

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[1] Source: Edwards(1986). Aggregate pesticide use on major crops, not solely rice, and includes herbicide. The average crop yield for Japan is 5.5.

One alternative response to chronic pest infestations has been the development of rice varieties with host-plant resistance to pests. China has an extensive agricultural research system capable of developing and extending rice varieties with resistance to pests in many different local conditions (Zhang and Ying, 1993). Indeed, after the initial yield gains of Green Revolution and hybrid rice varieties were realized, many rice breeders in China (and other centers of rice breeding in Asia) turned their attention to host-plant resistance (Khush [1987,1989]).[4] These efforts have led to widespread use of pest-resistant varieties. In many locations in Eastern China, one prerequisite for certification and extension of new varieties is a minimum resistance to locally endemic insects and/or diseases.

Rice breeders face a constant struggle to maintain resistance in extended varieties, and host-plant resistance to insects and diseases seems to be deteriorating in recent years. A metric for assessing this deterioration systematically is provided by standardized varietal resistance values developed for rice pests. One such scale measurement scheme for rice varieties grown in Eastern China, based on a 0-5 scale, illustrates declining host-plant resistance (Table 3).[5] Among those varieties having some level of disease resistance (and which were grown over the entire time period), resistance declined in up to 29% of varieties depending on the disease and time period.[6] For example, of varieties grown over the period 1988-91 which were resistant to neck blast, 27% of these varieties experienced some deterioration in neck blast resistance. For insect resistant varieties, up to 17% of varieties experienced deteriorating resistance. The average decline in disease resistance (on the 0-5 point scale) ranged from 0.13-0.31. The average for insects is -0.12-0.35.[7] This drop in resistance is likely related to changing pest populations. Given the potential for pest populations to change in response to high insecticide use, it may also be diminishing the influence of host-plant resistance. Such behavior could be estimated with an appropriate model of rice production.

Table 3.Changes in Host Plant Resistance Over Time

Varieties With Lower Resistance (% of varieties grown over the period)	Neck Blast	Bacterial Leaf Blight	Sheath Blight	Stem Borer	Brown Plant-Hopper	Whiteback Plant-Hopper	Leaf Folder
1984-1988	0.23	0.20	0.07	0.11	0.16	0.06	0.01
1988-1991	0.27	0.19	0.08	0.17	0.12	0.12	0.13
1984-1991	0.29	0.23	0.09	0.14	0.11	0.03	0.02
Average Change in Resistance (in scale units)							
1984-1988	0.25	0.14	0.13	0.19	0.24	0.35	-.04
1988-1991	0.31	0.13	0.14	0.17	0.15	-.12	0.26
1984-1991	0.22	0.20	0.18	0.39	0.22	.24	0.00

Modelling the Production Impact of Pesticides and Host-Plant Resistance

Given the importance of pest control measures on agricultural productivity, the impact of both pesticides and host-plant resistance can be measured with a yield function for rice:

rice yield = f(pesticides, resistance, pesticide-resistance interactions, fertilizer,
labor, location effects, state of technology, cropping system)

Estimating this model could lead to simultaneity bias due to the endogeneity of pesticide. Since pesticides are applied in response to pest pressure, high pesticide use is correlated to high infestation levels. However, high infestation levels decrease yields and when pesticide use is included directly in a yield model, estimated residuals will be correlated to pesticide use (via infestation). Consistent estimates of the yield function can be made with a two-stage least squares procedure by predicting pesticide use with a set of exogenous instruments, and using predicted values of pesticide use as exogenous variables in the yield function. Pesticide is explained with the general functional form:

pesticide use = g(infestation levels, locational dummies)

Empirical Model

Following Fan (1991), Lin (1992), and Huang and Rozelle (forthcoming) it is assumed that Chinese rice yields are Cobb-Douglas in their traditional inputs, fertilizer and labor. Since a Cobb-Douglas function is a special case of the translog (with a set of restrictions which limit the substitution possibilities among inputs) a restricted translog model is used. Including all interaction terms of a translog function results in severe multi-colinearity when estimating the yield function. Since we are interested in the interaction between pesticides and resistance, these interaction terms were included. The practical result is that the elasticity of substitution between pesticides and host-plant resistance is no longer restricted to being equal to one.

The empirical form of the yield equation is:

$$\begin{aligned}\ln(\mathit{yield}) &= \alpha_0 + \alpha_1 \ln(\mathit{resist}_I) + \alpha_2 \ln(\mathit{resist}_F) + \alpha_3 \ln(\mathit{insecticide}^*/\mathit{mu}) + \alpha_4 \ln(\mathit{fungicide}^*/\mathit{mu}) \\ &+ \beta_1 \ln(\mathit{resist}_I) * \ln(\mathit{insecticide}^*/\mathit{mu}) + \beta_2 \ln(\mathit{resist}_F) * \ln(\mathit{fungicide}^*/\mathit{mu}) \\ &+ \alpha_5 \ln(\mathit{nitrogen}/\mathit{mu}) + \alpha_6 \ln(\mathit{phosphorous}/\mathit{mu}) + \alpha_7 \ln(\mathit{labor}/\mathit{mu}) + \gamma_1(\mathit{time}) + \gamma_2(\mathit{doublecrop}) \\ &+ \sum_{i=3}^{9} \gamma_i(\mathit{county}_i) + \gamma_{10}(D_1) + \gamma_{11}(D_2) + e \quad ,\end{aligned}$$

where *doublecrop* is a measure of the proportion of total rice sown area cultivated in both the early and late season; *time* is a proxy for changes in technology; county_i is a set of dummy variables to account for the locational differences among the eight study counties; and D_1 and D_2 dummy variables to account for known disasters. One hectare is equal to 15 mu.

The terms, *insecticide** and *fungicide**, are predicted amounts of pesticide use, which are from a regression of insecticide (fungicide) on area infested by insects (diseases), the severity of the insect (disease) epidemic, and a set of locational dummy variables.

Data. The data used to estimate the yield function come from an extensive township-level survey conducted by one of the authors in Eastern China in 1993. Annual data were collected for the period 1984-1991 in 8 townships in each of 8 counties in two coastal provinces, Zhejiang and Jiangsu (for a total of 64 townships).[8] Agricultural data in China have been systematically recorded in townships by local agricultural technicians trained at agricultural colleges. This study collected these township-level records for pesticide use, sown area for each variety in each season, pest infestations, rice output, and information on standard inputs; such as fertilizer (*nitrogen* and *phosphorous*--measured in nutrient weight) and labor (measured as number of workers in the agricultural sector).

Many different chemicals are used in Eastern China to control insects and diseases that infest rice. The physical amount and concentration for each pesticide used are recorded by township agricultural officials on an annual basis. However, since physical amounts of each pesticide cannot be directly compared (different chemicals are sold at different concentrations), pest control chemicals must be aggregated.[9] In this case, two methods of aggregation are tried. Price is one method of weighting the amount used, since price can be used as an indicator of quality when markets are functioning effectively. Relative efficacy is the second method used, where efficacy is the ratio of the recommended dose of a chemical to the recommended dose of the strongest pesticide. If one insecticide is applied at twice the rate of another under similar circumstances, it is reasonable to assume it is half as potent and its "effective weight" is adjusted accordingly. The result is a set of annual observations for each township on insecticide and fungicide total value and "effective amount."

The sown area affected by each of the seven pests in each rice season (used to instrument pesticide use) is recorded annually by the townships.[10] The infestation data for each insect (disease) are used both individually and aggregated across insects (diseases) and season to generate two sets of instruments for predicting pesticide use.

Indices of insect and disease resistance are derived from two sources. Detailed records are kept of the sown area for each rice variety grown in a township in a given year. Additionally, the resistance index (0-5 scale described earlier) of each variety in different time periods is known for the most common rice pests.[11] The resistance scale of each variety to each pest is weighted by the proportion of sown area in that variety, and these are aggregated across insects and diseases. Thus, if a variety has strong insect resistance, but represents a small proportion of sown area, it contributes a small amount to the overall insect resistance of the township in that year. Since each location in each year has a different mix of varieties (with different levels of pest resistance) indices of resistance are calculated for both insects and diseases for each observation in the data sample (resist_I and resist_F).

Results

The yield equation is estimated with ordinary least squares. Continuous variables are scaled by their geometric means. Six specifications of the model are estimated: two yield models using actual, not predicted, value and effective amount of pesticide (models 1a and 1b), two using predicted effective pesticide amount (one with a full set of pesticide prediction variables and one with an aggregated set; models 2a and 2b), and two using predicted pesticide in value terms (with full and aggregated sets of predictors; models 3a and 3b). Models 1a and 1b are used to test the endogeneity of pesticide use.

To determine the endogeneity of insecticide and fungicide use, a test suggested by Hausman (1978) and Doran (1989) is used to compare the results of Model 1 (where actual values of pesticide are used) versus those of Models 2 and 3, which used instrumented measures.[12] Insecticide and pesticide variables in two of the models with predicted values of pesticide are found to be endogenous. Thus, it may be that the estimated coefficients from Model 1, which does not correct for endogeneity, are inconsistent and biased. Testing the validity of the instruments (Hausman, 1983), infested area, infestation severity, and location effects are found to be exogenous and therefore reasonable predictors of pesticide use.

Table 4.Regression Results

	Model 1a: Predicted Effective Pesticide (full set of instr.)	Model 1b: Predicted Effective Pesticide (aggregated instr.)	Model 2a: Predicted Pesticide Value (full set of instr.)	Model 2b: Predicted Pesticide Value (aggregated instr.)
Production Elasticity:				
Insect Resistance	0.03512	0.02578	0.02608	0.02109
	(3.173)	(2.546)	(2.436)	(1.938)
Insecticide	0.00132	0.00592	0.00017	0.00023
	(0.632)	(2.159)	(0.077)	(0.089)
Disease Resistance	-.00238	0.00017	0.00089	0.00888
	(-.164)	(0.012)	(0.059)	(0.590)
Fungicide	0.00061	-.00191	-.00003	-.00533
	(0.486)	(-.572)	(-.016)	(-2.055)
Nitrogen	0.01848	0.01385	0.01482	0.01981
	(1.214)	(0.907)	(0.956)	(1.29)
Phosphorous	0.00035	0.00197	0.00146	0.00023
	(0.067)	(0.376)	(0.277)	(0.044)
Labor	0.00142	0.00457	0.00002	0.0097
	(0.143)	(0.451)	(0.002)	(0.098)
Interaction Term:				
Insecticide*Insect Resistance	-.01112	-.00656	-.00376	-.00007
	(-1.933)	(-0.991)	(-0.824)	(-0.015)
Fungicide*Disease Resistance	0.00471	0.00372	0.00836	0.00100
	(2.211)	(0.741)	(1.606)	(0.284)
Substitution Elasticity:				
Insecticide/Insect Resistance	2.5681	1.7065	1.4015	1.0075
Fungicide/Disease Resistance	-.2312	-.1410	0.0485	0.6393

The performance of the model is fairly stable over the different specifications. The R^2 value varies between 0.61 and 0.63. The explanatory variables have the expected signs, and in many cases estimated coefficients are significant at the 0.05% level. The production elasticities also generally have the expected positive signs (Table 4). Given the conditions in Eastern China which emphasize high yields, it is expected that farmers are applying traditional inputs at a very high rate such that marginal products are low. From Table 4, this appears to be the case. These results are similar to those described in a survey by Putterman (1994), which compared the estimated production elasticities from several studies of agricultural production in China. Putterman(1993), Kim(1990), and Weimer (1990) conducted studies using production team data from the early 1980's and estimated production elasticities of current inputs between 0.05 and 0.11.

Positive output elasticities (with statistical significance) for insect resistance are indicative of higher yields associated with insect resistance (Table 4, row 1). Although incorporating insect resistance is complicated from a breeding point of view, China's program in Jiangsu and Zhejiang province's appear to be successful. Host-plant resistance increases yields at all levels of insecticide use.

The estimated elasticity of disease resistance, however, is not stable across models. In fact, it is close to zero, indicating little return to increased disease resistance. This may be because measures of disease resistance are generated with less precision than their insect counterparts. However, disease resistance scales have been used for many years and there is no reason to doubt their validity. It may also be that China's varieties are less effective because diseases are evolving and beginning to overcome host-plant resistance, a problem that does affect this region (as discussed above). The positive (and significant in two of the models) interaction term between disease resistance and fungicide demonstrates that the resistant varieties in these regions only positively affect rice yields after fungicides have been applied at moderately high levels. If fungicides are only applied at high levels of infestation, the effectiveness of Chinese disease-resistant varieties are not appearing until high levels of disease occurrence.

The negative term on the insecticide/resistance interaction term shows that the effectiveness of host-plant insect resistance decreases as the level of insecticide rises. One possible explanation of this result is that as farmers use more insecticide, they not only kill pests, they also destroy a number of beneficial predators, an observation that has become increasingly well-known to rice scientists (Rola and Pingali, 1993). When many of the natural enemies of insects are destroyed, ceteris paribus, there are more harmful insects around which inflict greater crop damage at a given level of host-plant insect resistance. It also has been shown that continued heavy use of pesticides favors the selection of less susceptible insects, so high insecticide use could tend to diminish the effectiveness of insect resistance (in the cases where the propensity of insects to overcome resistance to insecticide is correlated with the its ability to overcome host-plant resistance).

The elasticity of substitution describes the how pest control inputs can be traded off while maintaining yields. Intuitively, we would expect that higher resistance could compensate for lower pesticide use, which would generate a positive elasticity of substitution. The estimated elasticities of substitution of insect resistance for insecticides are all positive and range between 1.01 and 2.57. With a 1 percent increase in the resistance scale, insecticide can be reduced by 1 to 2 percent and still maintain the same level of yields. The elasticity of substitution between disease resistance and fungicides estimates are not as robust.

These measures of substitutions demonstrate the potential advantage of breeding for higher insect resistance, in that insecticide use can be reduced without sacrificing yields. From a farmer's standpoint, this could mean large potential cost savings if the seed prices of varieties with host-plant resistance are kept low. Policy makers may also take advantage of this tradeoff by supporting research on insect resistant varieties in order to meet environmental and health objectives.

Conclusions

The estimated production and substitution elasticities for pesticides and host-plant pest resistance indicate that efforts to increase insect resistance in rice could have a substantial impact in increasing yield and reducing the amount of insecticide required to maintain yields in Eastern China. This could have an immediate impact on the profitability of rice production for farmers. The results are less suggestive for disease resistance. It is easier to incorporate disease resistance into rice varieties, and rice breeders in China tend to focus on disease resistance in order realize success in their breeding programs. Thus, the estimated elasticities of production and substitution for resistance may suggest that the gains from increasing disease resistance are largely played-out, while there are still considerable gains to be realized from increasing insect resistance in rice.

This paper has presented estimates which can be useful in assessing the benefits of programs aimed at improving host-plant pest resistance in rice. Future research efforts to combine these results with estimates of the cost of developing pest resistance would provide policy planners with a powerful tool to evaluate the costs and benefits of rice improvement programs.

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Endnotes

1. Social and economic institutions in rural areas give local leaders great influence in farmers' input decisions (Rozelle, 1994), and for these leaders, job-performance and advancement are often based on meeting grain production targets for their area. In addition, a history of poorly functioning markets create an incentive for local leaders to promote local self-sufficiency in grain production. Thus, they often try to induce farmers to intensify input use and adopt improved varieties in order to meet these targets.

2. Huang and David (1993) have shown that rice in Asia is not an inferior good. Positive income elasticities for direct rice consumption in China are reported in Huang and Rozelle (1994a,1994b) and Halbrandt et al. (1994).

3. Number of pesticide applications per year is an index of the number of times the entire sown rice area of a township was treated. Records are kept for the total area treated during each application of pesticide and is divided by sown area to create the index. Although some pesticides treat bacterial diseases, for ease of labelling we adopt the convention of referring to all disease control chemicals as fungicides.

4. So called Green Revolution high yielding varieties (HYV's) are widely grown throughout Asia and were bred into many Chinese varieties. On the other hand, hybrid rice varieties have only been extensively developed and grown in China.

5. Data were collected in the study sites describing the resistance (over time) of varieties to each of 3 diseases and 4 insects on a standard 0-5 scale, where 0 connotes no resistance and 5 connotes strongest resistance.

6. Individual varieties can suffer precipitous declines in resistance, resulting in discontinued use. Many varieties were, in fact, discontinued due to extremely poor resistance and were not included since observations on resistance are not always available at the point when they were discontinued. Including such varieties would greatly increase incidence of resistance breakdown.

7. Negative values indicate an improvement in resistance. While improvements in resistance for a given variety in the field are not expected, farmers occasionally replenish seed stocks from government seed companies, and seed may maintain the same name but have greater purity, and hence better resistance.

8. Townships are the lowest level of aggregation at which data are commonly available for agricultural input use, area sown to specific varieties, and pest infestation. Townships in China usually comprise about 2000 families and 1,000 hectares of riceland, and typically contain 10-20 villages. Counties are made up of 10-20 townships.

9. Rola and Pingali (1993) weighted pesticides by concentration to arrive at a measure of active ingredient. In China, pesticide technology has changed so rapidly that it is necessary to also include a weight for the inherent toxicity of different pesticides, an index of efficacy.

10. In Zhejiang and Jiangsu, there are basically three seasons: early and late seasons (double rice crops), and middle season (single rice crop).

11. The most common insects pests on rice in the study area: striped stemborer, brown planthopper, white-backed planthopper, and leaffolder. The most common rice diseases are neck blast, bacterial leaf blight, and sheath blight.

12. Testing the endogeneity of a regressor is done by testing the residuals of the instrumental regressions. The residuals from regressions of the endogenous variables on a set of instruments are inserted as variables into the original equation which includes current (not-predicted) values of the suspected endogenous variables. An F-test is conducted on the coefficients of the inserted residuals. The null hypothesis (there is no endogeneity) is that they are jointly equal to zero. Rejecting the null hypothesis implies endogeneity.

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