eterization of diapycnal mixing continues to be a major uncertainty in assessing the ocean's ability to sequester heat, pollutants, and carbon dioxide.

References and Notes

1. M. E. Stern, *Tellus* **12**, 172 (1960).
2. R. B. Lambert, W. Sturges, *Deep-Sea Res.* **24**, 211 (1977).
3. R. W. Schmitt, *J. Phys. Oceanogr.* **11**, 1015 (1981).
4. B. Ruddick, *J. Phys. Oceanogr.* **22**, 1274 (1992).
5. R. W. Schmitt, H. Perkins, J. D. Boyd, M. C. Stalcup, *Deep-Sea Res.* **34**, 1697 (1987).
6. M. Tsuchiya, L. D. Talley, *J. Geophys. Res.* **103**, 12,899 (1998).
7. A. P. S. Wong, G. C. Johnson, *J. Phys. Oceanogr.* **33**, 1493 (2003).
8. J. R. Ledwell, A. J. Watson, C. S. Law, *Nature* **364**, 701 (1993).
9. J. R. Ledwell, A. J. Watson, C. S. Law, *J. Geophys. Res.* **103**, 21,499 (1998).
10. K. L. Polzin, J. M. Toole, J. R. Ledwell, R. W. Schmitt, *Science* **276**, 93 (1997).
11. J. R. Ledwell, E. T. Montgomery, K. L. Polzin, R. W. Schmitt, J. M. Toole, *Nature* **403**, 179 (2000).
12. J. D. Boyd, H. Perkins, *Deep-Sea Res.* **34**, 337 (1987).
13. R. W. Schmitt, *Annu. Rev. Fluid Mech.* **26**, 255 (1994).
14. R. W. Schmitt, J. M. Toole, R. L. Koehler, E. C. Mellinger, K. W. Doherty, *J. Atmos. Ocean. Tech.* **5**, 484 (1988).
15. R. W. Schmitt, *Deep-Sea Res.* **26A**, 23 (1979).
16. R. Lueck, *Deep-Sea Res.* **34**, 1677 (1987).
17. G. Marmorino, W. K. Brown, W. D. Morris, *Deep-Sea Res.* **34**, 1667 (1987).
18. A. E. Gargett, R. W. Schmitt, *J. Geophys. Res.* **87**, 8017 (1982).
19. T. J. McDougall, *Deep-Sea Res.* **38**, 367 (1991).
20. T. R. Osborn, *J. Phys. Oceanogr.* **10**, 83 (1980).
21. T. Osborn, C. Cox, *Geophys. Fluid Dyn.* **3**, 321 (1972).
22. T. J. McDougall, in *Small-Scale Turbulence and Mixing in the Ocean*, J. N. a. B. Jamart, Ed. (Elsevier Oceanography Ser., vol. 46, Elsevier, New York, 1988), pp. 21–36.
23. L. St. Laurent, R. W. Schmitt, *J. Phys. Oceanogr.* **29**, 1404 (1999).
24. The 95% confidence limits for the diffusivities were calculated using a "bootstrap" method with the statistics of 1000 random subsamples of half of the 165 stations for each of the measured variables. This treats each station as independent but does not account for possible systematic errors in the flux ratio or flux Richardson number.
25. M. C. Gregg, T. Sanford, *Deep-Sea Res.* **34**, 1689 (1987).
26. M. E. Stern, *Deep-Sea Res.* **14**, 747 (1967).
27. J. M. Toole, D. T. Georgi, *Prog. Oceanogr.* **10**, 123 (1981).
28. C. J. Garrett, *J. Phys. Oceanogr.* **12**, 952 (1982).
29. W. J. Merryfield, *J. Phys. Oceanogr.* **30**, 1046 (2000).
30. T. M. Joyce, *J. Phys. Oceanogr.* **7**, 626 (1977).
31. R. Ferrari, K. Polzin, *J. Phys. Oceanogr.* (in press).
32. M. C. Gregg, *J. Geophys. Res.* **94**, 9686 (1989).
33. K. Polzin, J. M. Toole, R. W. Schmitt, *J. Phys. Oceanogr.* **25**, 306 (1995).
34. E. Kunze, in *Double-Diffusive Convection*, A. Brandt and J. Fernando, Ed. *Geophys. Monogr.* 94, 313 (1995).
35. R. W. Schmitt, in *Small-Scale Turbulence and Mixing in the Ocean*, J. N. a. B. Jamart, Ed. (Elsevier Oceanography Ser., vol. **46**, Elsevier, New York, 1988), pp. 435–452.
36. W. J. Schmitz, J. R. Luyten, R. W. Schmitt, *Bull. Mar. Sci.* **53**, 1048 (1993).
37. We wish to thank the captains and crews of the R/Vs *Oceanus* and *Seward Johnson* for consistently fine work throughout our cruises. We also thank D. Wellwood, T. Bolmer, T. Farrar, T. Donoghue, B. Guest, C. Sellers, S. Birdwhistell, S. Sutherland, A. deBoer, L. Houghton, S. Ledwell, A. Benitez, G. Hernandez, and R. Brathwaite for scientific assistance during the cruises. This work was supported by the National Science Foundation under grants OCE-0081502 and OCE-0350743. This is Contribution Number 11284 of the Woods Hole Oceanographic Institution.

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Insect-Resistant GM Rice in Farmers' Fields: Assessing Productivity and Health Effects in China

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Although no country to date has released a major genetically modified (GM) food grain crop, China is on the threshold of commercializing GM rice. This paper studies two of the four GM varieties that are now in farm-level preproduction trials, the last step before commercialization. Farm surveys of randomly selected farm households that are cultivating the insect-resistant GM rice varieties, without the aid of experimental station technicians, demonstrate that when compared with households cultivating non-GM rice, small and poor farm households benefit from adopting GM rice by both higher crop yields and reduced use of pesticides, which also contribute to improved health.

Despite promises that GM crops could make a contribution to the reduction of hunger throughout the world, GM varieties are primarily used for industrial crops, such as cotton, and feed crops for animals (*1–3*). The difficulties of commercializing GM rice (and other food crops) appear to be causing declines in the amount and direction of public and private biotechnology research (*4*). Consequently, GM rice has not been commercialized anywhere in the world, and little is in the pipeline in most countries. Even China, a country that aggressively commercialized Bt cotton and invested heavily into research on GM food crops, has not commercialized any major food crops.

One reason that commercialization may not have proceeded is that there has been little independent evidence on whether GM food crops would really improve farmer welfare. This study's objective is to report on the results of an economic analysis that uses data from eight rice preproduction trial sites in China. We attempt to answer three questions: Does GM rice help reduce pesticide use in the fields of farmers? Do the new varieties of GM rice increase the yields for farmers? Are there any identifiable health effects on the farmers that adopt GM rice strains?

China's biotechnology research program has generated a wide array of new technologies, including several GM rice varieties (*5*). A number of GM rice varieties have entered and passed field and environmental release trials, and four varieties are in preproduction trials in farmers' fields. Two of the varieties—the two in which the scientists that developed the varieties gave our study team permission to undertake economic analysis—are the focus of this study (*5*). One variety, GM Xianyou 63, was created to be resistant to rice stem borer and leaf roller by insertion of a Chinese-created *Bacillus thuringiensis* (Bt) gene (*5*, *6*). The other variety, GM II–Youming 86, also was created to be resistant to rice stem borers, but in this case, the resistance was created by introducing a modifed cowpea trypsin inhibitor (CpTI) gene into rice (*5–8*). The insect-resistant GM varieties entered preproduction trials in 2001.

The nature of China's preproduction trial system has facilitated the analysis of the effect of insect-resistant GM rice on farm households before commercialization. The preproduction trials of GM Xianyou 63 are being conducted by farmers in seven villages in five counties in Hubei province. The trials for GM II–Youming 86 are being conducted in one village in Fujian province. In the preproduction villages, households were randomly selected to participate in the study. All of the farmers that were randomly selected did participate (i.e., there were no drop-outs), and so all farmers in the sample villages can be divided into two groups—adopters and nonadopters. Each adopter was provided with a fixed amount of insect-resistant GM rice seed. For households with limited land size, the seed was enough to cover all of their plots (henceforth, full adopters). Others received only enough to cover part of their plots (partial adopters). Except for being provided insect-resistant GM rice seed (at the same price as they would have paid for non-GM varieties), there were no subsidies, and adopters cultivated the insect-resistant GM rice without the assistance of technicians. Because farmers use their own periodic, in-field

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observations on the severity of pest infestation to decide whether or not to apply pesticides on both the insect-resistant GM and non-GM rice (that is, they are not following a prescribed dosage), the study can provide an estimate of the amount of farm-level pesticide reduction that can come from the adoption of the insect-resistant GM rice.

Our analysis presented here is based on surveys of a randomly selected subsample of households in the preproduction villages. During the first year of the study (2002), in six of the eight sample villages, there were only a limited number of adopters, and so all of them were chosen (some were full; the rest were partial adopters). A similar number were randomly chosen from all adopters in the other two villages. In total, 40 adopters (28 partial and 12 full) were chosen in 2002. In addition, 37 nonadopters (about one for each adopter) were chosen randomly from the pool of nonadopters in each village. In total, 77 households were surveyed in 2002. During 2003, a similar strategy was used, but because more insect-resistant GM seed was distributed, more adopters were added to the survey. Overall, 101 were interviewed in 2003 (32 nonadopters, 53 partial adopters, and 16 full adopters). There were 69 households that were interviewed in both years.

The enumerators, using producer-recall interviewing techniques, collected information on inputs and outputs for all of the plots on which the farmers produced rice, including detailed information on pesticide use and the variety of rice grown. Farmers also recounted the prices paid for pesticides and whether or not the plot was adversely affected by a weather shock. In total, the survey obtained data from 347 rice production plots: 123 plots planted with the insect-resistant GM rice varieties and 224 plots planted with non-GM rice.

Data from the surveys demonstrate that the characteristics of rice producers using the insect-resistant GM rice and non-GM rice are nearly identical and that the main difference between the households is in the level of pesticide use (*9*). For example, there is no statistical difference between the size of the farm or the plot or plots, the share of rice in the household's cropping pattern, or the household head's age or education. In contrast, there is a large difference in the use of pesticides (Table 1) (*10*). GM rice farmers apply the same types of pesticides but apply them less than once per season (0.5 times) compared with 3.7 times per season by non-GM rice farmers. The difference in the levels of pesticide use on insect-resistant GM and non-GM rice is statistically significant. On a per hectare basis, the quantity of and expenditure on pesticides of non-GM rice production is 8 to 10 times as high, respectively, as those for insect-resistant GM rice. Insect-resistant GM rice adopters spend only 31 yuan per season per hectare on only 2.0 kg of pesticide for spraying for pests, whereas nonadopters spend 243 yuan for 21.2 kg.

Because other factors might affect pesticide use when comparing insect-resistant GM rice and non-GM rice, multiple regression can determine the net impact of the adoption of insect-resistant GM varieties on pesticide use. To estimate a use function for pesticide by China's rice farmers in the sample areas, the following model is used:

$$\text{Pesticide use} = f(\text{GM rice varieties, pesticide price, weather effects, year effects, producer and farm characteristics}) \quad (1)$$

Equation (1) is similar to models that have been used elsewhere in the literature (*11*, *12*). To empirically estimate Eq. (1), the data from the survey are used to create variables that are based on standard definitions (*13*). The dependent variable for the analysis is the quantity of pesticides used per season (although substantively identical results are generated from either the number of sprayings per season or the value of pesticide use). The independent variable of interest, the use of the insect-resistant GM rice varieties, is measured by including a single dummy variable (GM rice, both varieties) which equals 1 if the farmer used either GM Xianyou 63 or GM II–Youming 86. In an alternative specification, 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. A set of household 0 to 1 indicator variables (108 of them—one for each sample household minus 1) is included to isolate the effect of GM varieties on pesticide use from observed and unobserved producer characteristics.

The regression analysis illustrates the importance of insect-resistant GM rice varieties in reducing pesticide use (Table 2, rows 2 to 6). The significant, negative coefficient on the "GM rice, both variety" variable means that GM rice use allows farmers to reduce pesticide use by 16.77 kg/ha, a reduction of nearly 80% (when compared with pesticide use of farmers using non-GM varieties—Table 1, row 3). The negative and significant coefficients on the GM Xianyou 63 and GM II–Youming 86 variables also demonstrate that each variety significantly reduces pesticides. Although the magnitudes of the coefficients differ, tests show that there is no statistical difference between the actual effects of the two insect-resistant GM varieties on pesticide use (Table 2, rows 3 and 4) (*14*).

The data also show that there is a difference, albeit narrower, between yields of insect-resistant GM and non-GM varieties. According to the descriptive data in Table 1, the mean of insect-resistant GM rice yields (6364 kg/ha) is higher than those of non-GM varieties (6151), although only by 3.5%. A box plot also shows that the median of insect-resistant GM rice yields is marginally higher than those of non-GM rice (fig. S1). ANOVA tests that differentiate among year, village, and GM versus non-GM effects demonstrate that the effect is statistically significant (*15*).

Multiple regression analysis largely supports the descriptive results (Table 2). Holding all household-level effects, plot-specific inputs, and certain other plot characteristics constant, the yields of insect-resistant GM varieties are 6% higher than those of non-GM varieties. When examining the effects of specific varieties (compared with other conventional varieties—the base category), the yields of GM Xianyou 63 are shown to be 9% higher (at the 10% level of significance) than other conventional varieties. Although the yields of GM II–Youming 86 are not found to be significantly different from conventional non-GM varieties, this result in part may be due to the fact that there are relatively few observations (because preproduction trials of GM II–Youming 86 are from one village only, and there are relatively few farm households that were partial adopters). Therefore, according to the descriptive and multiple regression analyses, although the evidence on effect of the insect-resistant GM rice varieties on increasing yields is not as overwhelming as that which examines the relationship between the GM rice varieties and pesticides, the GM Xianyou 63 rice variety does appear to increase yields (between 6 and 9%) (*16*).

The high incidence of pesticide-related illness in households in developing countries, including China, created an interest in tracking the health effects of insect-resistant GM rice adoption (*11*, *12*, *17*). To assess the effects in this study's sample, enumerators asked

Table 1. Pesticide use and yields of insect-resistant GM rice adopters and nonadopters in preproduction trials in China, 2002–2003 (means ± SD). Insect-resistant GM rice includes two varieties, GM Xianyou 63 and GM II–Youming 86. Data are from the authors' survey.

Parameter	Adopters	Nonadopters
Pesticide spray (times)	0.50 ± 0.81	3.70 ± 1.91
Expenditure on pesticide (yuan/ha)	31 ± 49	243 ± 185
Pesticide use (kg/ha)	2.0 ± 2.8	21.2 ± 15.6
Pesticide spray labor (days/ha)	0.73 ± 1.50	9.10 ± 7.73
Rice yield (kg/ha)	6364 ± 1294	6151 ± 1517
No. of observations (plots)	123	224

households about how the use of pesticides affected their health during, or immediately after, the time that they applied pesticides (*18*). Specifically, the questionnaire asked the farmers, "During or after spraying for pesticides on your farm, did you suffer from any of the following symptoms: headaches, nausea, skin irritation, digestive discomfort, or other problems?" If the respondent answered "yes," a follow-up question was asked: "After beginning to feel poorly, did you take any one of the following actions: 1) visit a doctor; 2) go home and recover at home; 3) take some other explicit action to mitigate the symptoms?" If the respondent answered "yes" to both of the questions, it was recorded as a case of pesticide-induced illness.

In the same way that research on Bt cotton adoption showed that the productivity effects of Bt cotton were supplemented by positive health effects (*3*), according to the analysis based on the survey data, similar effects occur within the sample rice-growing households. Among the sample farmers, there were no full adopters that reported being affected adversely by pesticide use in either 2002 or 2003 (Table 3). Of those that cultivated both insect-resistant GM and non-GM plots, 7.7% of households in 2002 and 10.9% of households in 2003 reported that their health was affected adversely by pesticide use; none, however, reported being affected after working on the sample GM plot. Of those that used only non-GM varieties, the health of 8.3% of households in 2002 and 3% in 2003 was affected adversely.

This study provides evidence that there are positive impacts of the insect-resistant GM rice on productivity and farmer health. Insect-resistant GM rice yields were 6 to 9% higher than conventional varieties, with an 80% reduction in pesticide usage and a reduction in their adverse health effects. Such high potential benefits suggest that products from China's plant biotechnology industry could be an effective way to increase both competitiveness internationally and rural incomes domestically. The benefits are only magnified if the health effects are added. The implications of the commercialization of GM rice in China also could far exceed the productivity and health effects on its own producers. Paarlberg suggests that if China were to commercialize a major crop, such as rice, it is possible that it would influence the decisions about the commercialization of GM crops in the rest of the world (*4*).

Table 2. Estimated parameters using a household fixed-effects model for estimating the effect of insect-resistant GM rice varieties on farmers' pesticide application and the yields of households in preproduction trials in China. The coefficients from the multiple regression model represent the net effect of insect-resistant GM rice varieties on pesticide use and yield, with the other plot-varying variables in the model held constant. For rice variety dummies, the base value is other non-GM varieties. Model 1 has both varieties as one variable; model 2 has treated the two varieties separately. The use of household fixed effects is accomplished by including 108 household dummy variables (equals 1 for the household and 0 otherwise), which allows for the control for all unobserved non–time-varying producer and farm characteristics. Values are means ± SD. The symbols *, †, and ‡ denote significance at 1, 5, and 10%, respectively. Data are from the authors' survey.

Variables	Pesticide use (kg/ha)		Yields (kg/ha) in log	
	Model 1	Model 2	Model 1	Model 2
Intercept	19.93 ± 1.17*	19.78 ± 1.32*	7.55 ± 0.50*	7.61 ± 0.51*
Variety dummies				
GM rice, both varieties	–16.77 ± 1.28*		0.06 ± 0.03‡	
Variety-specific dummy variables				
GM Xianyou 63		–17.15 ± 2.60*		0.09 ± 0.05‡
GM II–Youming 86		–25.33 ± 5.48*		0.02 ± 0.10
Non-GM Xianyou 63		1.04 ± 2.61		–0.03 ± 0.05
Non–GM II–Youming 86		–1.25 ± 3.82		0.07 ± 0.07
Control variables				
Pesticide price (yuan/kg)	–0.02 ± 0.03	–0.02 ± 0.03		
Natural disaster dummy (affected = 1)	8.56 ± 2.65*	8.65 ± 2.65*	–0.51 ± 0.05*	–0.51 ± 0.05*
2003 year dummy	–0.17 ± 1.20	–0.01 ± 1.24	–0.05 ± 0.02†	–0.05 ± 0.02†
Labor (log)			0.17 ± 0.07†	0.17 ± 0.07†
Fertilizer (log)			0.04 ± 0.06	0.03 ± 0.06
Machine (log)			0.00 ± 0.01	0.00 ± 0.01
Other inputs (log)			0.03 ± 0.04	0.02 ± 0.04
Pesticides (log)			0.00 ± 0.00	0.00 ± 0.00
Household dummy variables		Included but not reported		
No. of observations	347	347	347	347

Table 3. The effect of insect-resistant GM rice use on the health effects of farmers in sample preproduction village sites in China, 2002–2003. Full adopters planted insect-resistant GM rice only; partial adopters planted both GM and non-GM rice; and nonadopters planted non-GM rice only. The numbers are the percentage of sample households that were adversely affected by pesticides. Data are from the authors' survey.

Adverse health effects reported and year	Full adopters	Partial adopters		Nonadopters
		GM plot	Non-GM plot	
2002	0.0	0.0	7.7	8.3
2003	0.0	0.0	10.9	3.0

References and Notes

1. M. Qaim, D. Zilberman, *Science* **299**, 900 (2001).
2. It should be noted that despite there being no genetically modified major food grains being used anywhere in the world, there are more minor food crops, such as papaya and squash.
3. J. Huang, S. D. Rozelle, C. E. Pray, Q. Wang, *Science* **295**, 674 (2002).
4. R. Paarlberg, *Issues Sci. Technol. Online* (Spring 2003); available at www.issues.org/issues/19.3/paarlberg.htm.
5. See Supporting Online Material (SOM), section 1 on *Science* Online.
6. J. Tu *et al.*, *Nat. Biotechnol.* **18**, 1101 (2000).
7. C. Deng, G. Song, J. Xu, Z. Zhu, *Acta Bot. Sin.* **45**, 1084 (2003).
8. This paper discusses the line and the gene construct for CpTI and transfer of the gene into tobacco. Information on the transfer of the gene into rice is in preparation for publication (J. Huang, R. Hu, S. Rozelle, C. Pray).
9. See SOM, section 2. Insect-resistant GM rice strains are produced only to deal with pests and not to increase flavor or alter nutrition. As a consequence, there is no difference in prices between the insect-resistant GM rice and non-GM rice.
10. See SOM, section 7.
11. J. M. Antle, P. L. Pingali, *Am. J. Agric. Econ.* **76**, 418 (1994).
12. J. Huang, F. Qiao, L. Zhang, S. Rozelle, "Farm pesticide, rice production, and the environment" [Economy and Environment Program for Southeast Asia (EEPSEA) Res, Rep. 2001-RR3, International Development Research Center (IDRC), Singapore, 2001].
13. See SOM, section 3.
14. See SOM, section 4.
15. See SOM, section 5.
16. See SOM, section 6.
17. J. Huang, R. Hu, C. Pray, F. Qiao, S. Rozelle, *Agric. Econ.* **29**, 55 (2003).
18. See SOM, Section 8, for original and translation of questions.
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Supporting Online Material
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References and Notes

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