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Pesticide Use and Regulation: Making Economic Sense Out of an Externality and Regulation Nightmare

David Zilberman and Katti Millock

This article argues that the existing maze of pesticide policies reflects the multidimensionality of side effects of pesticide use that cannot be addressed by uniform policies. Pesticide policies will improve as (*a*) economic literacy among natural scientists and policymakers increases; (*b*) economic models of pesticide use and agricultural production in general better incorporate biological considerations; (*c*) benefit-cost criteria are introduced to determine regulations of pesticides; and (*d*) policies are enacted that take advantage of new information technologies and enable increased reporting of pesticide use. Moving from bans toward financial incentives and flexible policies that will allow chemical use where the benefit-cost ratios are high will improve resource allocation.

Key words: environment, externalities, monitoring, pesticides, precision agriculture

Introduction

The use of agricultural chemicals has long been the subject of controversy. In 1962 the publication of *Silent Spring* by Rachel Carson first sparked public concern over the negative side effects of such chemicals. More recently, controversy over the use of Alar heightened environmental consciousness in the United States and significantly affected the public policy agenda.[1] Hotly debated policies aimed at pesticide regulation include the banning of DDT, the Delaney Clause, California's Big Green initiative, and the proposed gradual removal of methyl bromide. Economists have been involved in much of this policy debate, and there is a growing body of economic literature on pesticides (Carlson and Wetzstein). Yet many of the existing policies regulating pesticide use do not reflect economic thinking and leave much to be desired from an economic perspective.

This article provides an explanation for this state of affairs and suggests some remedies to make future policies more economically sound. It suggests that the relevance and contribution of economics in the pesticide policy debate will increase as (*a*) economic literacy among natural scientists and policymakers increases; (*b*) economic models of pesticide use and agricultural production in general better incorporate biological considerations; (*c*) benefit-cost criteria are introduced to determine regulation of pesticides; and (*d*) policies are enacted that take advantage of new information technologies and enable

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[1] Uniroyal Chemical Company brand name for daminozide.

increased reporting of pesticide use. It further argues that the multidimensionality of pesticide problems and the heterogeneity of agriculture explain some of the complex and arcane policies aimed at regulating pesticides, and that institutional change and more information are crucial for reforms that will simplify policies and lead to more efficient outcomes.

Economic Education and Pesticide Policy

"Safety-first" has been the dominant paradigm for pesticide and environmental health regulations. Despite continuous attempts to reform regulations, most policies affecting pesticides and many other environmental health risks display lexicographic patterns, where investigation and regulations are triggered by discovery of risks. Once testing discovers that a chemical poses a carcinogenic or other significant environmental or health risk, regulators propose policies to ban or greatly reduce use of the chemical. Economic considerations and analysis are used to assess the cost of such regulations, thereby affecting the pace and extent of their introduction.

The Environmental Protection Agency (EPA) policy design and implementation divisions responsible for pesticides and other chemicals tend to have two units—one to assess the risks of particular materials and situations and the other to analyze the economic impacts of bans and other regulations. However, there are not many explicit mechanisms for conducting trade-off analyses. The current institutional framework for designing pesticide policies does not seem to pay much attention to assessing the trade-offs between economic costs and health risks in a consistent manner, and under current policies the implied valuation of life and limb varies drastically (Cropper et al.).

A major cause of the existing regulatory structure affecting pesticides is lack of economic literacy among many of the major players within this structure.[2] Society seems to view regulation of health risks or design of production practices as too important to be left in the hands of economists, and senior decision makers in the pesticide area generally have medical or biological degrees. Their lack of economic understanding is a major obstacle to a more economically sound regulatory framework.

Many biologists, public health specialists, and policy specialists who affect pesticide and environmental policy have had very little formal economic education. For example, undergraduate majors in biologic and environmental sciences at Berkeley are not required to take classes in economics. Furthermore, the introductory classes they do take do not impress upon them the relevance and usefulness of economics in addressing environmental policy problems.

Economic education tends to take an inward-looking perspective, emphasizing rigor and precision in understanding economic concepts for the few who will become economists, while ignoring the many who will make economic decisions but who will not become professional economists. It is essential to develop instructional programs that will convey basic economic concepts to biologists, ecologists, etc. These concepts include trade-offs, cost-benefit analysis, discounting, public goods, externalities, market efficien-

[2] This statement reflects our personal perception. Economics may also be underutilized because of a rejection of its normative framework. Yet another explanation of the lack of cost-benefit considerations in the design of pesticide policies may be rent-seeking behavior on the part of individuals who benefit from standards (Buchanan and Tullock).

cy, and market limitations. Broader education in these concepts will make economic arguments more accessible for those involved in the pesticide policy debate.

Heterogeneity and Pesticide Regulations

We need not wait until future decision makers are more economically literate to improve the economic soundness of pesticide policy. First, we must improve our own capacity as economists to address pesticide issues effectively. Just as economic education should be introduced to biology and environmental science majors, basic concepts of ecology should be integrated into the curriculum of agricultural and resource economics.[3] Economic models of pesticide use already incorporate some features of biology, and this improves their performance in explaining important phenomena. For example, economists have developed important concepts such as the economic threshold of pesticide use, first introduced by Stern et al., and have developed quantitative principles to assess damage from pesticide resistance (Hueth and Regev). The works of Antle and Pingali in southeast Asia show that the benefits from pesticides may be quite negligible if both agronomic and health considerations are taken into account. Economic frameworks have been developed to assess the contribution of pesticides to important aspects of production, including reduction of risks, improvement of product quality, and reduction of storage losses.

However, the infrequent use of financial incentives to control pesticide use has baffled economists for a long time. A closer look at the productivity and damages associated with pesticides provides insight regarding the difficulties associated with establishing financial incentives to control their use. The textbook model of environmental economics assumes that a product provides social benefits. Gross benefits are captured by the area under the demand curve (D in fig. 1). Production entails both private costs (the area under the marginal private cost curve, MPC) and externality costs (the area under the marginal externality cost curve, MEC). The sum of private and externality costs leads to social costs (the area under the marginal social cost curve, MSC). Optimal pesticide use (denoted X^* in fig. 1) is determined at the intersection between marginal social costs and demand. The optimal externality tax is equal to the marginal externality cost associated with optimal quantity (AB in fig. 1).

To address political economic considerations, it has become quite popular to suggest issuing tradable externality rights at the level X^*. The market in these rights will result in equilibrium where the price of these rights is equal to the optimal tax.

A more realistic modeling of production and the externalities associated with pesticide use may be overwhelmed by multidimensionality and heterogeneity. Economic models tend to emphasize complex decisions and gaming frameworks but are compromised by assuming a high degree of homogeneity. However, when it comes to pesticide problems, heterogeneity presents most of the challenge.

There are three major side effects associated with pesticide use: negative impact on workers (worker safety problems); negative impact on consumers (food safety problems);

[3] Developing classes to provide an overview of the scientific methods of natural and health sciences relevant to agricultural and environmental policy, to be included as part of the education of economists, is as important as development of overview classes on economics as part of the education of biologists and scholars of other natural and health sciences.

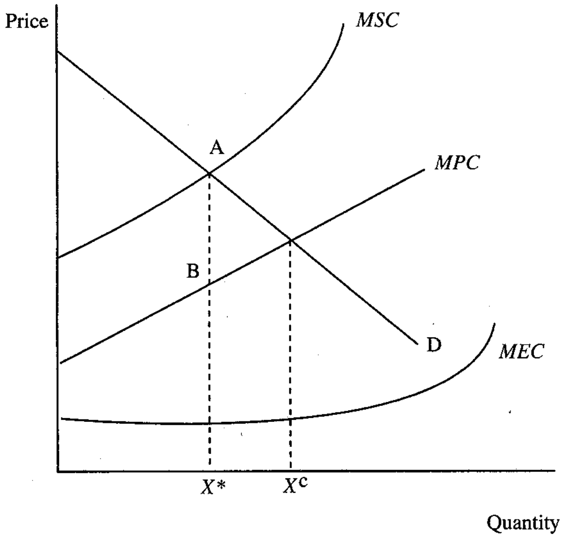

Figure 1. Intersection of demand with social marginal cost determines social optimum (X^*); and the intersection with marginal private costs determines competitive equilibrium (X^c), marginal private cost, and marginal externality cost

and negative impact on the environment.[4] There are no simple links between input use and/or pesticide use and the damages associated with each of these impacts. In both environmental and worker safety, damage depends on the residue of applied pesticides (not on the volume applied, but on the amount that misses the target pest and instead drifts to damage other species or workers). Since residues depend both on level of pesticide use and method of pesticide application, it is clear that taxing pesticide use without considering application technology may lead to inefficient outcomes. To illustrate the point, consider a situation where pesticides can be applied by two technologies. In figure 2, the curve VMP_1 represents the value of marginal product of the more accurate technology. The curve VMP_0 represents the value of marginal product in production of the less accurate technology. The two curves intersect because application beyond a certain level has negative marginal productivity. It is also reasonable to assume that the more accurate technology has an added fixed cost, which is defined by F_1. Suppose the price of pesticides is very low, defined as W. Without any externality considerations, the optimal application under the more accurate technology will be X_1^0, and under the less accurate technology will be X_0^0. And, $X_1^0 < X_0^0$.

The more accurate technology will be used if

$$\int_0^{X_1^0} VMP_1(z)\,dz - WX_1^0 - F_1 > \int_0^{X_0^0} VMP_0(z)\,dz - WX_0^0.$$

Namely, the more accurate technology will be used if the yield and input-use savings associated with it are greater than its fixed costs. In most cases, when pesticide prices are low and the fixed costs are significant, precision technologies are not viable.

[4] Pimentel et al. estimate that about 73% of the overall costs of pesticide use in the U.S. are through the impact on the environment. Public health impacts, including both worker and food safety problems, account for 10% and pesticide resistance for about 17%. Most of the public health effects are due to pesticide-related cancers (about 10,000 cases a year), which are mostly related to food safety problems.

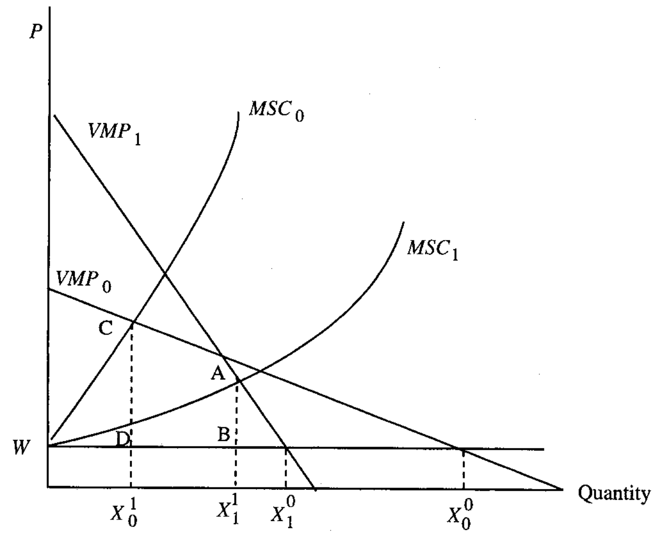

Figure 2. Competitive and optimal choices of pesticides under traditional technology (X_0^0 and X_0^1), respectively, and competitive and optimal choices of pesticides under precision technology (X_1^0 and X_1^1), respectively

Now, let us incorporate environmental costs. The more precise technology has lower residues per unit of applied input than the more traditional technology. Thus, the marginal social costs (sum of marginal externality costs and input price) under the more precise technology, MSC_1, are much smaller than the marginal social costs of pesticide use under the traditional technology, MSC_0. Therefore, under the more precise technology, optimal chemical use when you take into account the externality costs is X_1^1 and, under the traditional technology, it is X_0^1. Note that more pesticide may actually be used with the more precise technology because it generates fewer externalities. Second, if only the more precise technology is used, the optimal tax should be equal to AB in figure 2. If the traditional technology is still used, the optimal tax would be much higher and would be equal to CD in figure 2. Obviously, a technology-dependent pesticide tax is needed to obtain optimal resource allocation.[5]

Moreover, the marginal externality costs may be dependent on the location of pesticide applications. This adds another dimension and suggests that the optimal pesticide tax should be dependent on location in addition to technology. As Nichols shows, the degree of correlation between control costs and location determines the relative advantage of standards compared with uniform taxes. The impact of pesticide use on both worker and environmental safety depends on when and where chemicals are applied. Pesticide applications may cause more severe damage in riparian zones, where contaminated runoff reaches the water more easily than in areas farther from streams and wildlife. This is the rationale for the provision of buffer zones where spraying is not allowed. For example, the European Union introduced subsidies to farmers who created unsprayed buffer zones under its 1992 reform of the Common Agricultural Policy. Legislation in Germany, Sweden, and Switzerland prohibits aerial spraying of pesticides in sensitive areas such as forests (OECD). The damage to workers' health from pesticide applications is likely

[5] See arguments reviewed and developed in Khanna and Zilberman to show the superiority of technology-dependent taxes to alternative second-best policies.

to be much smaller as the time lapse between the application of the chemical and entry to the field increases. Thus, the marginal damage externality costs associated with pesticide application may be dependent on application technology, location, and time of application. Thus, establishing an across-the-board uniform and efficient pesticide tax is unrealistic in many cases.

Several textbooks emphasize the ease and uniformity of externality taxes in systems with heterogeneous producers as a major advantage over the nonuniform policy regulations that may be associated with obtaining optimality through direct control of outputs or inputs. But when externality costs vary across location, time, and application technology, this advantage of taxation over direct control disappears.

Current U.S. regulation is governed by the Food Quality Protection Act of 3 August 1996. It amends the two major pesticide laws: the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) and the Federal Food, Drug, and Cosmetic Act (FFDCA). A main element of regulation is the requirement of registration of a pesticide with the Environmental Protection Agency (EPA) and subsequent requirements of labels specifying active ingredients, dosage, and concentration. The EPA classifies pesticides into two categories: general or restricted use. Restricted use pesticides can only be applied by or under the direct supervision of a certified applicator. Whereas FIFRA regulates use of pesticides, food safety concerns are particularly addressed in FFDCA, which authorizes the EPA to set maximum residue concentration levels for food. The so-called Delaney Clause (Section 409 of FFDCA) precluded the use of cost-benefit considerations for any cancer-causing additive. The Food Quality Protection Act of 3 August 1996 changed the Delaney Clause, and the use of cost-benefit considerations is now prohibited for any reproductive effects. Nor can benefit assessment be used to override health-based standards for children. Worker safety is regulated by the Worker Protection Standard (WPS), a regulation revised by the EPA in 1992. It gives detailed requirements for who can apply pesticides, stipulates protective measures for workers handling crops treated with pesticides, and sets minimum time of reentry after application of a pesticide. Water quality concerns from pesticide use are addressed in the Safe Drinking Water Act, which establishes maximum containment levels for polluting chemicals.

This wide array of pesticide regulations reflects the heterogeneity and multiplicity of the impacts of pesticide use. Reentry regulations are designed to address situations where the severity of impacts is dependent on timing. Spatial restrictions on pesticide use are enacted to address situations where impacts depend on spatial variability. The state of California has special regulations requiring site-specific permits to apply restricted pesticides. Computational costs, enforcement, and implementation costs have led to the selection of these types of regulations, and in many cases they present the best available regulatory approach.

Economic research can be very valuable in assessing and improving various regulations. Lichtenberg, Spear, and Zilberman present a framework to assess reentry regulations and demonstrate empirically the gains from varying reentry period by regions. While economists should play an active role in assessing and improving various pesticide regulations, economic research can provide insights that may motivate research into technological and institutional innovations that will lead to improved policy tools and better management solutions. For example, since the health risks associated with entry to a field shortly after chemical spraying depend on pesticide residue levels, economists can estimate the economic gains from residue monitoring devices and establishing an upper-bound residue limitation above which entry is disallowed.

Economic Analysis and Pesticide Regulations

Despite the advantage of some existing policies, the direct controls used today to regulate pesticides leave much to be desired. A major challenge facing our profession is to expose the inefficiency and waste associated with some existing regulations and propose alternatives. Not all of the alternatives would involve financial incentives and market mechanisms, but these might prove to be less costly and more efficient regulations. The Delaney Clause, for example, was inefficient because it did not allow considering several forms of risk. Unfortunately, we do not know of any widely accepted study that estimated even the order of magnitude of the costs associated with the Delaney Clause and compared it with plausible alternatives. A study of this nature would have to provide comparisons in terms of monetary costs of statistical lives saved.

It may be a role of agencies such as the U. S. Department of Agriculture Economic Research Service (USDA/ERS) to initiate studies along these lines, recruit collaboration of researchers from the land grant system, and provide useful input for the policy process. Addressing such a major policy issue rigorously would also allow assessing weaknesses in modeling the economic and environmental aspects associated with chemical use as well as set direction and priorities for future research. For example, in the case of the Delaney Clause, estimates of the health benefits may be much less accurate than estimates of the economic costs, and as economists we can provide some direction for methodological development in other disciplines that will lead to more useful policy results.

Despite the suspension of the Delaney Clause, the recently passed Food Quality Protection Act still delimits benefit-cost trade-offs when additives have a threshold effect. The lack of explicit mechanisms for cost-benefit analyses in the legislation may partly reflect resistance to the normative foundation of economics. However, political economy shows how interest groups can influence regulation, and benefit-cost trade-offs are implicitly done in policy. Cropper et al. show that intervention by grower groups or environmental organizations affects the probability of a pesticide being canceled or reregistered.

The role of the economist in pesticide policy assessment is to incorporate knowledge from a variety of natural sciences and perform a balancing act to evaluate policy proposals and determine the trade-offs between policies. In the process, economists may affect the research agendas of these other disciplines by determining what type of information is needed to better assess health or economic impact of pesticide regulations. In some cases, economic research may induce development of new technology, as it will indicate what type of extra knowledge can lead to less costly regulations. Monitoring devices to enable farmers to assess reentry time based on residue levels rather than relying upon standardized uniform reentry regulations is one type of technological development that could improve the efficiency of current policy. As Lichtenberg, Spear, and Zilberman show, weather information, such as that provided by the computerized Californian network CIMIS, could be used to decentralize and adapt regulations to local conditions.

The needs of the policy process may affect the outcomes of economic analysis. Estimates of the equity and efficiency effects of various policies on goods traded in markets seem to be quite useful and understandable to educated noneconomists. For instance, studies by Yarkin et al. (1994a, b) assess the distributional impact of the proposed phase-out of methyl bromide in California and show how a given reduction could be achieved at lowest economic cost. Because of the uncertainty of these impact-assessment estimates, they should be accompanied by some measure of reliability (see Zilberman et al. 1991). Estimating nonmarket impacts on health and the environment requires inputs from other disciplines (public health), and their translation to monetary terms is subject to controversy. It may be useful to provide two sets of impact estimates—market impacts in monetary terms and health impacts in physical terms (e.g., number of disease days or probability of death).

In most studies the health risk estimates only consider the direct effects of use of chemicals on workers or consumers. But eliminating pesticides may affect the diet of certain consumers by reducing the supply of certain products (fruits and vegetables). These dietary changes may also have health effects which should be incorporated into the analysis. Research on the link between pesticide regulations and dietary intake and health may be quite useful and may provide insightful information to the pesticide policy debate (Ames, Profet, and Gold).

Precision Technologies, Information, and Pesticide Selection

As we have argued, the responses to pesticide regulation depend on technologies available to farmers. Thus, optimal resource allocation and pesticide management policies should change over time as new technologies are introduced. This suggests that, in spite of the desirability of stable and constant regulations, it is optimal to modify regulations as new technologies are developed. Actually, the relationship between regulations and technology is more complex since changes in policy may induce the development of new technologies. Policy should consider not only current technological options but also the capacity to introduce new innovations and the potential of policies to encourage innovations. This suggests that policies based on the concept of adaptive management will become increasingly important. Millock, Zilberman, and Sunding analyze a taxation scheme which leads to increased information on emissions from nonpoint sources through voluntary adoption of monitoring equipment by polluters. The information gained under such regulations would provide valuable information for the regulator on pollution-intensity of various application technologies.

The impact of technologies on the capacity to regulate pesticides and to improve environmental quality and health should also be considered as government research and development policies are determined. As regulations adjust to changes in technology, the market potential of new innovations should be evaluated not only under current regimes that may not make them very appealing economically, but also under future regimes that take into account their existence and impose more restrictive regulations that will lead to their adoption. Obviously, more research in this area is needed. But it is particularly pertinent now, as the emergence of biotechnology suggests new opportunities to address some of the more difficult pest management problems (Zilberman, Sunding, and Khanna).

Technological considerations are especially important in selecting pesticide policies. The introduction of precision technologies suggests new opportunities for pesticide regulation. We view precision technologies as a broad class of technologies that increases input use efficiency. Efficiency of input use is the ratio of the input effectively utilized in production (or converted into output) to the input that is applied to the production process. Some precision technologies involve monitoring field conditions and adjusting input use accordingly (IPM), others use expensive application equipment that reduces residues (low pressure, high precision pesticide applicators).[6] Farmers can then adjust their input applications according to spatial variability and take advantage of reductions in the cost of information technologies to document their activities; this will provide a foundation for learning and future performance improvement. Precision technologies reduce aggregate pollution through the reduction of input use as well as increase in input use efficiency. Adopting precision technologies puts high demands on the computational skills of the farm operator. These technologies could be supported by a collectively run information program through, for instance, land grant universities' extension services. Obviously, large-scale adoption of precision technologies may take one or two decades. The policy design process is very slow, and as economists interested in regulation, we have to take a long-run view. As the cost of information gathering declines and the likelihood of recording and preserving production information by farmers and consultants increases, the prospects of introducing more efficient policies are increasing.

Thus, governments first must be aware of the adoption and spread of information-intensive technologies. They have to follow the patterns of use of pesticide consultants and recognize alternative opportunities for efficient ways to obtain agricultural production data. The reduction in information-gathering costs will make it less costly to require farmers to record and report pesticide applications. This reporting, which will also specify location and time, can be used as input for policy action. In the long run, it may be technically feasible to have computerized systems that will specify taxes required to be paid when certain inputs are applied at certain times. Alternatively, such a system may be used to provide subsidies for environmentally friendly pest control choices. In some cases, information-intensive systems that will record pesticide applications may also be expanded to develop local markets in pesticide use permits.

While these ideas may seem farfetched, some current developments make them look feasible. California has introduced pesticide-use reporting requirements and, while the system may be costly and underused, it is functioning. A computerized water market using the Internet to facilitate transactions between farmers has been introduced in the Westlands Water District in California and now other major water districts are joining. Independent pesticide consultants throughout the United States have developed private databases on pesticide use, production yields, and other pertinent inputs for their activities; they use these data to modify their recommendations. A significant number of farmers have already adopted precision technologies. The National Resource Inventory is a Geographic Information System that provides information on environmental conditions for a large number of locations in the United States. Thus, we are developing the information base to assess input use over different locations.

One possible objection to using farm-level micro economic data for regulatory purposes, stemming from models of the economics of information, is that it may give farmers incentives to manipulate these data. However, in spite of the critical role of individual

[6] Highly touted precision technologies that rely on remote sensing and sophisticated monitoring equipment are a subset of a larger group of technologies that have the same properties, namely, improving input use efficiency while incurring extra capital costs (Khanna and Zilberman).

and corporate financial records in determining income and sales taxes, we perceive a high degree of honesty in bookkeeping throughout the United States, which is encouraging. The quality of policymaking will depend on government capacity to design procedures that will ensure accuracy of information on production choices and pesticide-use levels as well as preserve confidentiality. Requiring farm-level data reporting (e.g., on pesticide use, production decisions, and environmental conditions) will gradually become more demanding as the cost of information gathering and transfer declines, will reduce the information asymmetry between regulators and farmers, and will help establish more efficient policies. Such regulation must consider farmers' resistance to revealing such information and create incentives for voluntary participation in self-reporting programs. Innes analyzes self-reporting and argues that there are additional benefits to that form of monitoring environmental quality when there are ex post benefits of remediation. Farmers would have incentives to report pesticide use and health effects voluntarily if fines were higher for detected violations that had not been reported.

The proliferation of input use consultants throughout the United States (Wolf; Zilberman et al. 1994) may make it easier to affect pesticide use patterns to reflect social benefits and costs. For example, such consultants could be certified to prescribe certain pesticide treatments and be held liable for their choices.[7] Regulatory agencies could influence the choices through direct regulations or financial incentives. These certified consultants would serve the role of "plant and environmental doctors" and would work with certified applicators who would apply chemicals, report the applications, and pay the appropriate fees. Some large-scale farms would have certified consultants and applicators on staff; smaller farmers would hire these professionals (who might be independent business people or employees of input dealers) or obtain the credentials themselves.

Conclusions

The design of effective pest management strategies and pesticide regulation is very challenging due to the multidimensionality of side effects from pesticide use, heterogeneity of agricultural production systems and the environment, randomness of weather and markets, and lack of knowledge and information. The textbook regulatory solution to externality problems is of limited use under these conditions, and policymakers may need to rely on second- or third-best solutions to address pesticide side effects.

Current pesticide regulations are significantly inefficient, even acknowledging the difficulties associated with determining pesticide policies. They can be greatly improved by incorporating economic considerations into the policy process. Moving from bans toward financial incentives and flexible policies that will allow chemical use where the benefit-cost ratios are high will improve resource allocation. Economically sound incentives to increase precision of chemical application and reduce chemical residues may also reduce environmental side effects of pesticide use in a cost-effective manner.

New and upcoming technologies that improve monitoring of side effects and precision of pesticide use will improve the efficiency of pesticide regulations. However, the development of these technologies presents a unique challenge and opportunity for agricultural economists. Satellites and monitoring equipment may provide farmers with num-

[7] Pesticide control advisors partially play this role in California and some other states.

bers, but economic principles have to be applied to put these data to efficient use. Economics has a crucial role to play in taking advantage of the new technologies at the farm level and in the policy arena, and agricultural economists should be major players in developing the models and software required.

It is sometimes assumed that private companies will be able to develop all of the algorithms needed to successfully implement precision agriculture. However, econometrics and computational challenges are very significant, and much applied research will still be needed to develop the software for precision agriculture. Farm management has been underemphasized in agricultural economics in recent years; in the near future it will be challenged to develop new methodologies and algorithms to estimate response functions and compute optimal input-use levels, taking advantage of real-time information and recognizing heterogeneity.

Even with new monitoring technology, there will be asymmetry between the information available to pesticide users and regulators. The development of new pesticide regulations will provide the challenge of applying and extending the most recent concepts in public economics to the particular problems associated with pesticide use and its side effects. Designing effective measures to solve both micro and macro problems associated with pesticides requires economic skills in addition to sound knowledge of agronomic and environmental systems.

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References

Ames, B. N., M. Profet, and L. S. Gold. "Nature's Chemicals and Synthetic Chemicals: Comparative Toxicology." *Proc. Natl. Acad. Sci. USA* 87(1990):7782–786.

Antle, J. M., and P. L. Pingali. "Pesticides, Productivity, and Farmer Health: A Philippine Case Study." *Amer. J. Agr. Econ.* 56(1994):418–30.

Buchanan, J. M., and G. Tullock. "Polluters' Profits and Political Response: Direct Control versus Taxes." *Amer. Econ. Rev.* 65(1975):139–47.

Carlson, G. A., and M. E. Wetzstein. "Pesticides and Pest Management." In *Agricultural and Environmental Resource Economics,* eds., G. A. Carlson, D. Zilberman, and J. A. Miranowski, pp. 268–318. New York and Oxford: Oxford University Press, 1993.

Carson, R. *Silent Spring.* Boston: Houghton Mifflin Co., 1962.

Cropper, M., W. N. Evans, S. J. Berard, M. M. Ducla-Soares, and P. R. Portney. "The Determinants of Pesticide Regulation: A Statistical Analysis of EPA Decision Making." *J. Polit. Econ.* 100(1992):175–97.

Hueth, D., and U. Regev. "Optimal Agricultural Pest Management with Increasing Pest Resistance." *Amer. J. Agr. Econ.* 56(1974):543–52.

Innes, R. "Self-Reporting and the Optimal Enforcement of Environmental Laws When There Are Remediation Benefits, Penalty Assessment Costs, and Heterogeneity in the Likelihood of Violators' Apprehension." Paper presented at the 1996 AAEA annual meeting, San Antonio TX, 28–31 July 1996.

Khanna, M., and D. Zilberman. "Incentives, Precision Technology and Environmental Quality." *Ecological Econ.,* forthcoming, 1997.

Lichtenberg, E., R. C. Spear, and D. Zilberman. "The Economics of Reentry Regulation of Pesticides." *Amer. J. Agr. Econ.* 75(1993):946–58.

Millock, K., D. Zilberman, and D. Sunding. "Incentives for Monitoring Nonpoint Source Pollution." Work. Pap., Dept. Agr. and Resour. Econ, University of California, Berkeley CA, 1996.

Nichols, A. L. *Targeting Economic Incentives for Environmental Protection.* Cambridge MA: The MIT Press, 1984.

Organisation for Economic Co-operation and Development (OECD). *Activities to Reduce Pesticide Risks in OECD and Selected FAO Member Countries: Results of a Survey.* Paris: OECD, July 1995.

Pimentel, D., H. Acquay, M. Biltonen, P. Rice, M. Silva, J. Nelson, V. Lipner, S. Giordano, A. Horowitz, and M. D'Amore. "Assessment of Environmental and Economic Impacts of Pesticide Use." In *The Pesticide Question: Environment, Economics, and Ethics,* eds., D. Pimentel and H. Lehman, pp. 47–84. New York and London: Chapman and Hall, 1993.

Stern, V. M., R. F. Smith, R. van den Bosch, and K. S. Hagen. "The Integration of Chemical and Biological Control of the Spotted Alfalfa Alphid, Part I: The Integrated Control Concept." *Hilgardia* 29(1959):81–101.

Wolf, S. A. "Privatization of Crop Production Information Service Markets: Spatial Variation and Policy Implications." Unpub. Ph.D. diss., University of Wisconsin-Madison, 1996.

Yarkin, C., D. Sunding, D. Zilberman, and J. B. Siebert. "Methyl Bromide Regulation: All Crops Should Not Be Treated Equally." *California Agr.* 48(1994a):10–15.

———. "Cancelling Methyl Bromide for Postharvest Use to Trigger Mixed Economic Results." *California Agr.* 48(1994b):16–21.

Zilberman, D., A. Schmitz, G. Casterline, E. Lichtenberg, and J. B. Siebert. "The Economics of Pesticide Use and Regulation." *Science* 253(1991):518–22.

Zilberman, D., D. Sunding, M. Dobler, M. Campbell, and A. Manale. "Who Makes Pesticide Use Decisions: Implications for Policymakers." In *Pesticide Use and Produce Quality,* ed., W. Armbruster, pp. 23–39, Oak Brook IL: Farm Foundation, 1994.

Zilberman, D., D. Sunding, and M. Khanna. "The Changing Nature of Agricultural Markets: Implications for Privatization of Technology, Information Transfer, and the Role of Land-Grant Research and Extension." In *Privatization of Information and Agricultural Industrialization,* ed., S. Wolf, pp. 265–93. Boca Raton FL: CRC Press, 1997.