Articles

The Economics of Pesticide Use and Regulation

DAVID ZILBERMAN, ANDREW SCHMITZ, GARY CASTERLINE, ERIK LICHTENBERG, JEROME B. SIEBERT

Pesticides enhance agricultural productivity, but the environmental and health side effects of their use justify government regulation, a subject of continuing societal debate. Bans on pesticide use are the principal regulatory device used in the United States. The economic impacts of such bans depend on the availability of substitutes, supply and trade conditions, and research and development. Without substitutes, pesticide bans result in reduced production levels and higher prices, a substantial loss of discretionary income to consumers, and a redistribution of income among agricultural producers. Most food safety concerns can be addressed by establishing standards and markets for pesticide-differentiated products, but worker safety and clean water concerns will require direct controls. Pesticide-use fees are shown to be more efficient than outright pesticide bans as a mechanism to obtain environmental goals.

THE USE OF SYNTHETIC ORGANIC PESTICIDES IN AGRICULTURE has expanded production possibilities and benefited farmers, processors, and consumers (*1*). Increasing concerns for environmental degradation, worker safety, and public health have spawned intense political debate over pesticide use. To examine this issue, we assess productivity and costs, trade-offs, and policy alternatives for U.S. agriculture, focusing primarily on California, the largest and most diverse agricultural state.

There has been explosive growth in pesticide use in the post–World War II period. The use of herbicides, insecticides, and fungicides in the United States during the last 25 years is charted in Fig. 1. Nearly 75% of herbicides are used on corn, soybeans, and cotton, sometimes as part of a low-tillage strategy. The recent decline in herbicide use is partly due to a reduction in farmed land and to an increase in herbicide cost. The decline in insecticide use during the 1980s is explained by the introduction of more potent materials (synthetic pyrethroids) and the adoption of integrated pest management (IPM) practices that use insecticides more selectively (*2*). Fungicide use has remained relatively stable during the 1970s and 1980s. Most fungicides, which affect quality, storability, and yield, are used on fruits and vegetables.

D. Zilberman, A. Schmitz, G. Casterline, and J. B. Siebert are in the Department of Agricultural and Resource Economics, University of California, Berkeley, CA 94720. E. Lichtenberg is in the Department of Agricultural and Resource Economics, University of Maryland, College Park, MD 20742.

Pesticide use varies by crop, pest, and location. Estimated pesticide cost is approximately 3% of the gross farm value in California, or $500 million. Cost revenue ratios vary from 1% (grapes and tomatoes) to 4% (oranges). Surveys suggest that California's agricultural pesticide-use levels for most crops are low relative to the rest of the United States and that California leads in the development and adoption of IPM.

Agricultural researchers have argued that pesticide-application strategies should take into account crop resistance and secondary pest problems. Economics would suggest the use of diversified pest management strategies such as monitoring pest populations, selective reliance on chemical pesticides, biological control, and cultural practices. Because of economic, health, and safety concerns, more than 50% of California farmers practice IPM in one form or another.

Productivity and Costs

Pesticide productivity has been estimated econometrically at different levels of aggregation (*3*). Although estimates vary widely, the incremental benefits of pesticide use far exceed the cost. A $1 increase in aggregate pesticide expenditures has been estimated to raise gross agricultural output from $3 to $6.50. A number of omitted factors, such as application and monitoring, resistance, and health and safety costs, might explain this difference.

Econometric studies have provided estimates of the productivity of broad pesticide categories for various crops. Such estimates usually measure the impact of a proportional incremental change for all pesticides within a category, whereas most policy analyses require impact estimates of specific chemical bans. Impact assessment should incorporate productivity estimates into market interaction models to show the effects of regulations on prices, land use, production, trade patterns, and the costs to society.

The partial budgeting approach is often used by government agencies to assess the impacts of banning pesticides. It relies on results of experimental studies to estimate cost and yield effects per unit of land. These effects are then summed across crops and regions to provide aggregate cost estimates. This approach tends to ignore possible price and land-use changes; it also tends to overestimate effects on growers, while underestimating consumer effects. An alternative approach obtains and aggregates the yield and cost effects of the regulations to estimate the effect on producer supply. These results are then incorporated into a system of supply and demand equations representing the forces that shape market outcomes. Solution of these equations approximates the impact of pesticide regulations.

Lichtenberg, Parker, and Zilberman (*4*) used this approach to

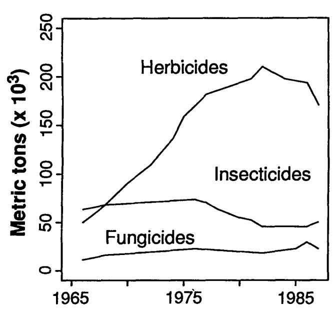

Fig. 1. Pesticide use in the United States (*18*).

study the impact of canceling ethyl parathion, one of the many pesticides used in California lettuce production. To account for seasonality, markets for lettuce in winter, spring, summer, and fall were modeled separately. Producer groups were categorized according to region, type of pest problem, and whether or not they used parathion. Areas treated with parathion and its substitutes were estimated from reported usage data. Estimates of the effect of canceling parathion at the field level were obtained from a study in California (*5*). Prices and consumption levels were taken from government statistics; supply and demand parameters were obtained from various available sources.

The anticipated effects of canceling parathion are shown in Table 1. Consumer and producer surpluses are used to calculate the consumer and producer effects. The consumer surplus approximates, in monetary terms, the difference between the benefits derived from a certain consumption level and the cost at the market. The producer surplus is a measure of profits (*6*). Parathion bans will result in higher prices and lower output, making consumers worse off. Because of higher prices, users of parathion (35% of farmers) suffer significant losses, whereas nonusers gain. Overall, lettuce producers lose.

Extrapolating from Table 1, the annual loss to consumers is about 3.8% of current spending on lettuce. The loss to producers is about 2.9% of their annual revenues. The per capita impact on each consumer is small (lettuce takes a minor share of their spending), whereas impacts on some producers may be significant because net income often does not exceed 10% of producers' revenues.

On the basis of this California study, we can suggest the following generalizations about factors affecting the impact of pesticide bans.

1) *Availability of substitutes.* The immediate effect of canceling a pesticide is a shift to chemicals that are usually more expensive or less effective, or both. When differences in cost and efficacy are small, the economic impacts are small. However, when effective substitutes are not available, the impacts may be large. Although more costly, substitutes were available for all parathion uses in lettuce except one—the control of lettuce root aphids in California's central coast, a major lettuce-producing region in summer and spring. Without parathion, yields in this region were estimated to drop by 25%. Were a substitute available, the impact of canceling parathion on output would be negligible and the annual average lettuce price would increase by only 0.10% as compared to a 3% increase without a substitute.

2) *Capacity for additional supply.* One major effect of banning a pesticide is to shift production to different regions in response to increased product prices. In spite of the 25% yield reduction in a major region, the aggregate impact on lettuce output is only 0.50%. Because of increased prices, nonusers increase lettuce production, almost compensating for lost output. The ban also redistributes income among producers—for each dollar users lose, nonusers gain 40 cents.

3) *Responsiveness of demand to prices.* As demand becomes inelastic, pesticide-use bans are likely to have a greater price effect. A ban on parathion is estimated to reduce annual lettuce production by 0.50%, but the estimated price effects are substantial. The average price of lettuce is estimated to rise by 3%, while the summer price increases 9%.

4) *Trade.* If exports account for a large share of demand, foreign consumers will bear a large share of the cost. International trade considerations play a minor role in the lettuce case because only 5% of production is exported. In a companion study (*4*) of the impacts of canceling parathion on almonds (55% of which are exported), the loss to foreign consumers was estimated to be substantially higher than that to domestic consumers.

In the long run, the increased cost of U.S. products may spur entry by foreign producers and erode the ability of the United States to shift the cost of environmental regulation abroad. Moreover, reduced exports would exacerbate the balance-of-trade problem.

5) *Research and development* (*R&D*). When pesticide bans are accompanied by extensive R&D efforts, substitute pest treatments may be developed to mitigate the initial effects of the ban. If a substitute is found for parathion in the treatment of the lettuce root aphid problem, the reduction in summer and spring outputs will become less than 45,000 metric tons for each season, and the overall cost of canceling parathion would be 10% of the current estimates (Table 1).

Impacts of Wholesale Pesticide Bans

There have been recent proposals to ban pesticide use in agricultural systems; Proposition 128 (popularly known as "Big Green"), a bond and initiative statute defeated on the California ballot in November 1990, was one such proposal. Proposition 128 would have phased out food-use pesticides known to cause cancer or reproductive damage. When a group of chemicals is banned, pesticide substitution possibilities and yields are reduced more than when just a single chemical is banned. A recent study (7) found that there were no substitutes for 30% of the pesticides that would have been

Table 1. Seasonal effects of banning parathion for lettuce. Costs are measured by the change in producer revenue for parathion users and nonusers in consumer expenditures on lettuce (*3*).

Season	Output (metric tons × 10^3)		Price (dollars/metric ton)		Cost (dollars × 10^6)			
	Pre-ban	Change	Pre-ban	Change	Users	Nonusers	Consumers	U.S. total
Winter	704	−0.1	244	0.2	−0.2	0.1	−0.2	−0.3
Spring	783	−5.4	248	13.0	−14.2	6.6	−9.7	−17.3
Summer	684	−7.1	252	22.0	−16.7	7.7	−14.3	−23.3
Fall	650	−1.3	299	5.1	−6.0	1.7	−3.2	−7.5
Year	2821	−13.9	256*	10.8*	−37.1	16.1	−27.4	−48.4

*Figures represent annual averages.

banned if Proposition 128 had passed.

Pesticide bans in fruits and vegetables. California is a major producer of fruits and vegetables that would be affected by Proposition 128. The five crops shown in Table 2 generate 46% of California fruit and vegetable revenue. We estimated the proposition's economic effect for these five crops, taking into account the uncertainty regarding key parameters. For each crop, there were five alternative estimates of the proposition's yield effects. These estimates were based on alternative interpretations of the law itself and on assumptions regarding California agriculture (*8*). Five demand and three supply price elasticities were used for each crop. The impact of the proposition on each crop's price, output, producer revenue, and consumer spending was computed under each possible scenario. We generated estimated distributions of the various outcomes. The means and high values of these distributions are presented in Table 2 (*9*).

Consumers bear most of the cost of the proposition. The expected value of consumer loss is about 25% of current expenditure on the five crops, and there is a 5% probability that this ratio will be above 52%. Estimated average impacts on producers vary among crops, but the aggregate expected loss is only 0.6% of crop revenue. However, there is a 5% probability that producer loss will be 12% of revenue; this may exceed net income. In spite of the modest impact of Proposition 128 on expected profits, the desire to avoid risking large losses may explain why many farm groups objected to it.

The large price effect for lettuce may be explained by its highly inelastic demand. The expected income of lettuce growers actually increases because the higher price more than compensates for the reduction in output. Tables 1 and 2 show that the consumer cost effect of a wholesale pesticide ban, relative to a selective ban, is of a much larger order of magnitude.

Pesticide bans in field crops. It is interesting to compare the estimated impacts of the California fruit and vegetable pesticide bans to those of large-scale pesticide bans for other crops. Assuming the prevailing economic and policy conditions, Knutson, Taylor, Penson, and Smith (*10*) estimated the economic impacts of complete pesticide bans on eight major U.S.–produced commodities. The estimated cost increases and yield decreases were substantial but, because of increased planting and land-use pattern shifts, the output reductions were smaller (Table 3). The aggregate net income of the agricultural sector is predicted to increase slightly; income distribution, however, is predicted to change drastically. Because of price effects, the income of the crop sector is predicted to increase by 18% but, due to higher feed costs, the income from the livestock and poultry-producing sectors will decline by 27%. Because of the ban, consumers are estimated to have an $18-billion annual loss; however, this translates to less than a $90 annual increase in food costs per consumer. This is a 6.5% increase in the food expenditures of the average consumer, but the relative impact on those with lower incomes will be much higher.

The estimates obtained in this study (*10*) were probably high. Inflated cost and yield impact estimates were used and extensive restrictions on imports were assumed (*11*). Another economic gain that must be considered is the reduction in government price-support expenditures due to price increases associated with the pesticide ban. Adjusting for this effect could reduce the cost of pesticide regulations by up to 30% (*12*). Also, for commodities such as rice and barley, where the United States is not an internationally dominant producer, price effects may have been overstated. In spite of these limitations, the study (*10*) demonstrates the importance and magnitude of structural and distributional changes resulting from pesticide bans. It provides a quantitative perspective on the value and role of pesticides used on major agricultural commodities grown in the United States.

The studies described above have generally reached similar conclusions regarding the short-run impacts of a hypothetical large-scale ban of pesticide use in the United States. The price of most commodities is expected to rise sharply, while consumers would have the largest total loss. However, the annual cost of pesticide bans on field crops, fruits, and vegetables to the average consumer would be above $100, but less than 10% of the total food expenditure. The aggregate effect on producers is not expected to be large, but the ban may lead to a substantial redistribution of income among producer groups; some groups may gain significantly but other groups could experience devastating losses.

The redistribution of income among producers partly reflects the reallocation of production capacities. Expansion and adjustment in land and other input uses cause the impact of bans on output to be smaller than the predicted yield effects. Redistribution of production by location is especially important for major agricultural commodities. For example, regulation of pesticide use in California cotton may lead to increased production in the southeastern United States; this would serve to moderate output and price effects. Similarly, short-run increases in fruit and vegetable prices would likely lead to increased production in Arizona, Texas, Florida, Mexico, and other regions—eventually causing prices to fall. In particular, lettuce production would tend to shift to other regions, causing California growers to lose. Thus, in the long run, consumer loss would be reduced, producer income outside California would rise, but Cali-

Table 2. Simulated impacts of a pesticide ban on five crops in California.

Crop	Impact	Output change (%)	Price change (%)	Producer revenue (dollars × 10^6)	Consumer spending (dollars × 10^6)	Total effect* (dollars × 10^6)	Initial revenue (dollars × 10^6)
Almonds	Mean	−15	21	−1	−94	−95	490
	High†	−34	59	−100	−256	−221	
Grapes	Mean	−19	29	−52	−358	−410	1508
	High†	−52	87	−365	−1031	−1123	
Lettuce	Mean	−9	57	130	−321	−191	832
	High†	−28	175	−81	−931	−607	
Oranges	Mean	−21	13	−52	−53	−105	458
	High†	−41	29	−115	−114	−204	
Strawberries	Mean	−25	18	−47	−57	−104	392
	High†	−53	37	−107	−114	−220	
Five crops	Mean			−22	−883	−905	3480
	High†			−422	−1809	−1753	

*The total effect is the sum of the change in producer revenue and consumer spending. This holds exactly in the mean but, because the high estimates for consumers and producers correspond to different situations, the sum is not exact for the high effect. †The high estimate is that value which may be exceeded with a 5% probability.

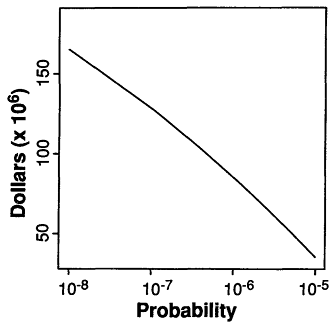

Fig. 2. The curve represents the estimated trade-off between the cost of producing pure water and incremental cancer risk for DBCP in well water, Fresno County, California. Risk is measured by the annual increase in the probability of a Fresno County resident contracting cancer. The curve depicts the lowest cost necessary to provide water at the given risk level (*1*).

Table 3. Percent change in performance measures due to pesticide bans on major commodities (*10*).

Measure	Wheat	Barley	Rice	Corn	Cotton	Soybean	Sorghum	Peanut
Yield	−25	−29	−57	−32	−39	−37	−20	−70
Production	−9	−12	−39	−18	−30	−26	4	−17
Price	6	23	83	38	34	100	13	146
Export	−15	−22	−64	−26	−46	−50	−35	−8

fornia agriculture would be the main loser.

Some of the negative impacts of the pesticide ban may be mitigated by new technologies. Increased commodity prices are likely to spur private R&D efforts and accelerate their adoption. Nevertheless, the capacity to develop such alternatives should not be overestimated (*13*); private R&D efforts are likely to be insufficient, especially for specialty crops that generate small volumes of pesticide sales. Massive publicly financed research would likely be necessary, and new discoveries could be long in coming. Wholesale restrictions, such as Proposition 128, would generate a need for new classes of pest control chemicals. Hence, the broader the imposed restrictions, the lengthier and more arduous the process of adjustment.

Trade-Offs

A full assessment of the economic impact of pesticide bans must consider indirect effects, such as problems of food safety, worker safety, and environmental quality.

Food safety. Recent reports by the Environmental Protection Agency (EPA) Science Advisory Board state that human health risks from pesticide exposure in food residues are relatively low. These reports suggest that food safety concerns are primarily problems of perception and preference. In addition, while consumers may be concerned about eating fresh produce sprayed with pesticides, their willingness to pay for such produce varies. In his survey of Atlanta shoppers, Ott (*14*) found 61.5% of consumers were ready to accept more cosmetic defects to ensure pesticide-free produce. Furthermore, only 10% of consumers were willing to pay more than 10% extra for pesticide-free produce. This can be contrasted to the 1990 weekly average price premium of 100% commanded by organic (chemical-free) romaine lettuce in Los Angeles (*15*).

In light of these findings, the government plays a valuable role in testing, assessing, and providing information regarding the health effects of consuming pesticide-treated foods. In most cases, the food safety problem can be best addressed by the marketplace, with the establishment of differentiated markets for organic or pesticide-free products. Government regulations may be used to monitor and establish standards for such products.

Pollutants and worker safety. The EPA Science Advisory Board found that worker occupational hazards and pollutants in drinking water were among the major risks to human health in the United States and that reduction of these risks justifies government policies that affect pesticide use and related activities. Such policies include bans on chemicals, use restrictions, pesticide fees, subsidies for nonchemical pest management practices, protective clothing, and application standards.

Lichtenberg and Zilberman (*16*) introduced and applied a framework constructing the trade-offs between costs and risks associated with pesticide-related policies. The estimated trade-off between the costs and risks resulting from alternative regulations to control 1,2-dibromo-3-chloropropane (DBCP) residue in drinking water in Fresno County, California, is shown by the curve in Fig. 2. Risk was assessed by measuring the average increase of a Fresno County resident's annual probability of contracting cancer. The negative slope of the curve indicates that reducing risk is more costly. The curve represents policies that attain certain risk levels at minimum cost or result in the lowest risk level for a given expenditure. The area above the trade-off curve represents inefficient policies, because other policies can attain the same risk level with lower costs, or can cost the same but result in lower risks.

Uniform regulations, imposing the same standard of performance at all locations, tend to be inefficient. In the case of the Fresno DBCP study, efficient policies varied the requirements for water providers according to their per capita costs of filtering or replacing existing water sources.

Lichtenberg, Spear, and Zilberman (*17*) analyzed the impacts of worker safety regulations that restricted reentry into apple orchards after treatment with organophosphate insecticides. Such treatment serves to protect apples from codling moth larvae infestations before harvest. Exposure to the insecticide residue may cause poisoning. Longer reentry restriction periods increase degradation of the residue to nontoxic by-products, but also reduce profits. Efficient reentry restriction schemes were found to be highly nonuniform. They required longer restricted reentry periods in California, which has drier summers, than in Washington and Michigan.

Policy Alternatives

A complete ban of a chemical (or group of chemicals) is a uniform policy. Such a ban does not discriminate between situations where the elimination of a chemical would result in major or minor cost increases. In many cases, a substantial share of the environmental and health benefits associated with a complete ban can be preserved by introducing a partial ban or a restrictive-use policy. In such cases, pesticide use is allowed only in situations where substitutes are poor or nonexistent. For example, when parathion use in lettuce is permitted only for growers in California's central coast region, parathion use in the United States is reduced annually by more than 80%. The total economic cost of a partial ban drops below \$0.5 million for the spring, summer, and fall seasons, compared to \$17, \$23, and \$7 million (Table 1) for each of these seasons under complete bans. The price effect of this partial parathion ban is insignificant for all seasons, unlike a complete ban which leads to 5% and 9% price increases in the spring and summer.

Pesticide fees or taxes can have effects similar to those of partial-ban, limited-use policies. Fees increase pesticide prices, encouraging farmers to become more selective in their chemical choices and to switch to other options as they become relatively more cost-effective. For lettuce, fees that raise the cost of parathion use by \$30 per hectare are likely to have the same effect on the profit-conscious grower as the partial ban policy suggested earlier.

Fees can restrict environmental and health risks below target levels at the least cost. Uniform pesticide regulation may be much more costly than fees in attaining policy targets. Furthermore, when the health costs of risk can be enumerated, the most efficient fee or tax policies are those that equate the incremental benefits of risk reduction to the incremental costs of reduced economic activities. It is advisable to use the proceeds of pesticide-use fees or taxes to finance R&D efforts when developing alternative pest-management practices, subsidizing their adoption, and addressing negative side effects from pesticide use.

Establishing mechanisms for monitoring and enforcing environmental regulations has always been an administrative challenge. The organizations established to implement pesticide registration requirements in some states (most notably, California) provide the base to administer pesticide taxation policies. The derivation and assessment of policy parameters will require much more "policy-relevant" research and more interdisciplinary cooperation among managerial, agricultural, and environmental health scientists.

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Numerical Models of Extragalactic Radio Sources

JACK O. BURNS, MICHAEL L. NORMAN, DAVID A. CLARKE

Numerical simulations with supercomputers allow analysis of the wide range of nonlinear physics inherent in the hydrodynamic and magnetohydrodynamic equations. When applied to extragalactic radio sources, these numerical models have begun to reproduce many of the complex structures observed on telescopic images. This combination of telescopic and numerical observations provides powerful probes of the physics of radio galaxies. In this review, some of the recent results from both two-dimensional and three-dimensional numerical simulations of the formation and evolution of extended radio morphologies are described. These numerical models have allowed the exploration of important physical phenomena including the role of magnetic fields in the dynamics and emissivity of extended radio galaxies, intermittent outflow from the cores of active galaxies, instabilities and disruption of fluid jets, and the bending of collimated outflows by motion through the intergalactic medium.

DURING THE LAST DECADE, REMARKABLE PROGRESS HAS been made in imaging extragalactic radio sources by means of aperture synthesis telescopes such as the Very Large Array (VLA) (*1*). High-fidelity radio maps reveal a wealth of complex structures (*2*), including twin lobes of emission on opposite sides of an active galactic nucleus (AGN), collimated jets stretching between the galaxy core and the lobes, and knots (or hot spots) and filaments within the lobes and jets.

During this same decade, significant progress was also made in the theoretical interpretation of these radio morphologies. Much of this advance resulted from the increased accessibility of large-scale supercomputer-class machines and the advent of hydrodynamic and magnetohydrodynamic (MHD) algorithms of advanced design. These coupled with the National Science Foundation computer network and powerful yet affordable computer workstations permit a broad cross section of the astronomical community to participate in numerical simulations and interpretations of extragalactic radio sources. For many years, the national observatories provided an infrastructure that resulted in high-quality data for both the expert and the novice. In much this same way, the national supercomputer centers now permit observers as well as theorists to participate in sophisticated modeling of astronomical phenomena.

J. O. Burns is head of the Astronomy Department, Box 30001, Department 4500, New Mexico State University, Las Cruces, NM 88003. M. L. Norman and D. A. Clarke are with the National Center for Supercomputing Applications, University of Illinois at Urbana-Champaign, Urbana, IL 61801.

Observed Radio Source Characteristics

The typical structures associated with powerful extragalactic radio sources are illustrated in Fig. 1, A and B. The frequency spectrum