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Issues in the Economics of Pesticide Use in Agriculture: A Review of the Empirical Evidence

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In this article, we review three perspectives used to place an economic value on pesticide use in agriculture and present associated empirical results. One approach is based on calculations of the marginal productivity; a second strategy considers the expected loss to pests relative to some current or maximum yield; and a third approach, related to the second, calculates the economic effect of banning pesticides, which is effectively the value that producers and consumers place on the chemicals used. We also review the economic effects of government policies to reduce or restrict pesticide use, including regulation and pesticide taxes as well as use of alternative technologies believed to reduce pesticide use, such as integrated pest management and genetically engineered plants.

Together with fertilizers and hybrid seeds, pesticides have enabled American farmers to achieve spectacular increases in land productivity over the second half of this century. For example, average corn yield rose from 37 to 134 bushels per acre over the last 40 years (Fahnestock). From an economic perspective, pesticide use generates significant benefits for society. Pesticides help producers achieve lower production costs, higher yields, and increased profits. Consumers are able to enjoy abundant and relatively inexpensive, unblemished foods. Despite their positive effects, evidenced by the willingness of U.S. farmers to spend $8.3 billion on pesticides in 1996 (USDA 1997), the potential hazard of these chemicals to human health and the environment have caused increased concern.[1] In 1993, the USDA, Food and Drug Administration, and Environmental Protection Agency (EPA) jointly pledged to work together to reduce the "risks to people and the environment associated with pesticides" (Kenworthy and Schwartz). Their overall goals are to

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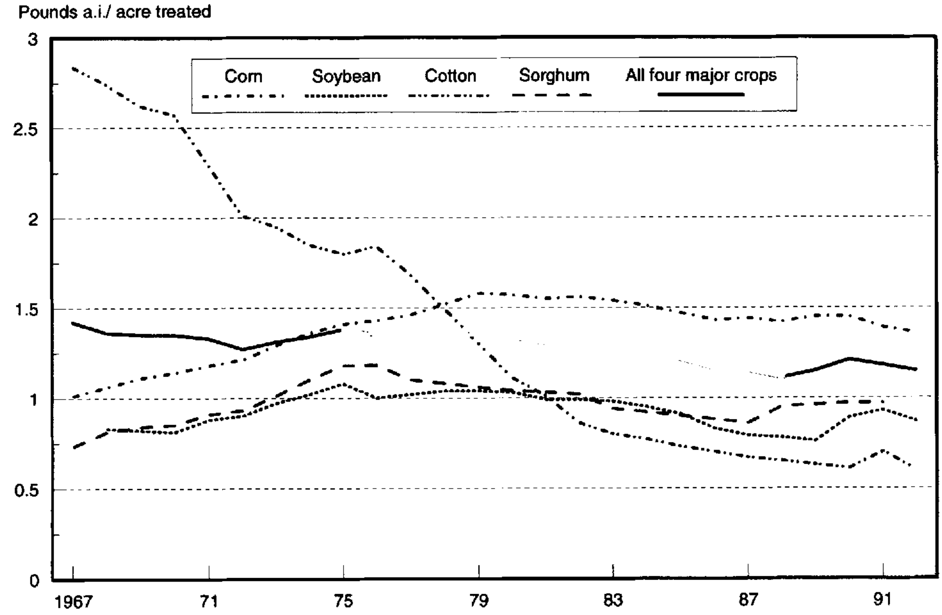
Figure 1. Average application rates (per crop year) of major pesticides used on major crops



reduce pesticide use, to promote alternative pest control methods (such as biological controls), and to change regulations to facilitate development and registration of safer pesticides.

The objective of this report is to summarize the empirical evidence related to the economics of pesticide use with an emphasis on the estimation of the value of pesticides in U.S. agriculture and the economic effects of reducing or restricting pesticide use or promoting alternative methods to manage pests to reduce the potential health and environmental effects associated with their use.

Background on Pesticides

The term "pesticide" refers to a large number of heterogeneous products. Thousands of formulations (commercial forms in which the pesticide is sold) are used. These formulations are mixtures of active ingredients (the active chemicals) and inert materials, used to improve safety and facilitate storage, handling, or application. Hundreds of active ingredients are used, and each has a different potency, spectrum of pest control, and impact on human health and the environment (Fernandez-Cornejo and Jans 1995).

Rapid technological change has characterized the pesticide industry. As new and better active ingredients have been introduced and other products banned by regulatory agencies or dropped by their manufacturers, per-acre pesticide rates have fallen. For example, one pound of active ingredient of a synthetic pyrethroid has about the same degree of pest control as several pounds of an older pesticide. Figure 1 shows that the weighted averages of pesticide application rates have declined slowly, driven by a sharp decline in insecticide application rates on cotton, which in recent years have been about one-quarter of the rates used two decades ago. Pesticide rates applied to other crops increased moderately during the late 1960s and early 1970s and declined thereafter. Despite the decline in rates, overall pesticide use on major crops in U.S. agriculture peaked in 1981–2 at a level less than twice the 1968 level (Fernandez-Cornejo and Jans 1995, Lin et al. 1995, Osteen and Szmedra).[2] However, as Fernandez-Cornejo and Jans (1995) showed using hedonic methods, if pesticide quality (potency, toxicity, and persistence) had not improved, pesticide use (at constant quality) would have peaked at a level more than three times that of 1968.

Expenditures on pesticides by U.S. farmers grew from $44 million in 1940 to $8.3 billion in 1996 (Lucier, Chesley, and Ahearn; USDA 1997), more than a sixteenfold increase in constant dollars. As a percentage of the value of the U.S. crops, pesticide expenditures were close to 8% in 1996 (USDA 1997). Corn and soybean production accounts for about half of U.S. agricultural pesticide expenditures because of the large acreage devoted to these crops (close to 140 million acres in 1992), whereas fruit and vegetable production (with less than 7 million acres in 1992) accounts for a small percentage of pesticide expenditures (USDA 1995).

Per-acre pesticide expenditures vary widely, increasing with the value of the crop. As seen in table 1, wheat farmers spent annually less than $6 per acre on pesticides, whereas corn and soybean growers spent about $22 per acre, cotton farmers spent $48 per acre, and expenditures by producers of high-value commodities such as strawberries approached $1,600 per acre. However, although per-acre pesticide expenditures vary widely, the average productivity of a dollar spent on pesticides is relatively constant across the selected crops, averaging about $12, which is similar to the average productivity of pesticides used on all U.S. crops in 1996 (table 1).[3]

Pesticides are regulated under the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) and the Federal Food, Drug, and Cosmetic Act (FFDCA) (Osteen 1994, Ollinger and Fernandez-Cornejo 1995). Both statutes were amended by the Food Quality Protection Act (FQPA) of 1996. Under FIFRA, the EPA regulates pesticide use through registration and labeling requirements. Before a pesticide is registered (and use thus permitted), the EPA must consider the potential adverse effects of the pesticide on humans and the environment, including acute and chronic toxicity, as well as the economic, social, and environmental costs and benefits of various pesticide uses (Schierow). Under the FFDCA, the EPA establishes maximum allowable levels (tolerances) for pesticide residues in foods sold in interstate commerce. Significantly, the FQPA eliminates the "distinction between raw and processed food (Delaney clause) tolerances" but requires that a pesticide tolerance be set to ensure "reasonable certainty that no harm will result from aggregate exposure to the pesticide chemical residues" (Schierow); that is, benefits can no longer be considered in setting new tolerances (Mintzer and Osteen).

Marginal Pesticide Productivity

Pesticide productivity estimates are critical for informed pesticide policy debates as well as for microeconomic decision-making. Marginal productivity estimates provide an indirect measure of the cost "in terms of foregone agricultural output"

Table 1. Value of average product of pesticides for selected crops, 1991

Item	Corn	Sorghum	Barley	Wheat	Soybean	Rice	Peanut	Cotton	Strawberry[a]	Tomato[a]
Pesticide expenditures, $/planted acre	22.46	10.97	7.40	5.73	22.51	46.99	87.56	48.19	1,588	842
Yield, bushel/acre[b]	110.38	55.02	51.58	28.28	33.48	54.24	24.67	574.30	1,800	1,400
Price (harvest period average), $/bushel[c]	2.31	2.27	2.07	2.57	5.49	7.52	0.28	0.59	9.00	8.00
Total revenues, excluding government direct payments[d]	254.98	105.24	109.75	73.89	183.81	407.88	940.07	373.27	16,200	11,200
Value of average product, $/$ pesticide expenditure	11.35	9.59	14.83	12.90	8.17	8.68	10.74	7.75	10.20	13.30

Sources: Field crops, USDA (1994); fruits and vegetables, Smith and Taylor.

[a] For 1994.

[b] Except for peanuts and cotton (pounds/acre), tomatoes (25-pound boxes/acre), and strawberries (flats/acre).

[c] Except for peanuts and cotton ($/pound), tomatoes ($/25-pound box), and strawberries ($/flat).

[d] Yield × average price + value of byproducts (e.g., straw).

of reducing pesticide use to protect human health and the environment (Campbell). Conversely, the extent of pesticide reduction needed to "protect human health and the environment depends in part on the extent to which food and fiber production would fall" (Chambers and Lichtenberg). Under the usual assumptions, a farmer would maximize profits by increasing pesticide use up to the point where the expected marginal return [value of the marginal product (VMP)] equals the pesticide marginal cost. The marginal return is equal to the value of pest damage reduction, which is the potential yield savings times the crop price.

Most empirical studies typically report the value of the marginal product of pesticides aggregated over crops, pesticides, and/or regions (table 2). Headley (1968) calculated the marginal productivity of pesticides using state-level data aggregated over the 59 principal crops grown in the United States in 1963. As shown in table 2, Headley estimated that pesticides returned at the margin between $3.90 and $5.66 per dollar of pesticide expenditures. In addition, interpreting the marginal value as an average value, Headley calculated the economic benefits of pesticides at $1.8 billion, equivalent to 10.5% of the value of the crops. Campbell estimated a $12 return per dollar spent on insecticides applied in apple production, which is similar to the result obtained earlier by Fisher for Nova Scotia apples. Miranowski obtained marginal returns in corn production of $2.02 and $1.23 per dollar spent on insecticides and herbicides, respectively, and $1.82 for herbicides used in cotton in 1966. On the other hand, Lee and Langham obtained returns of less than $1 for pesticides used in citrus for 1964–8. More recently, Fernandez-Cornejo, Jans, and Smith (1996) estimated pesticide productivity for corn using 1991 farm-level cross-sectional survey data for 18 corn-producing states. They found that the marginal return of pesticides used on corn was $1.89 per dollar of pesticide expenditures.

The VMP of pesticides appears to be falling. Using farm-level cotton data, Carlson (1977) observed that the physical productivity of insecticides used in cotton was falling because of pest resistance to pesticides. Teague and Brorsen estimated a random coefficients regression model using state-level aggregate data for 1949–91 for the 10 largest agricultural states. Such a model allows estimation of how the value of the marginal product changed over time rather than making a point estimate. They found that the marginal return of pesticides averaged $7.96 per dollar of pesticide expenditures for the 1949–91 period and $4.16 for 1991. More importantly, they showed that marginal returns declined over that period for Iowa and Texas, although there was no such demonstrated tendency for California (figure 2). They noted that pesticide benefits exceeding (private) costs gives economic justification to the observed rising U.S. aggregate demand for pesticides over the past 40 years.

There is controversy surrounding the methodology used to measure the VMP. For example, Lichtenberg and Zilberman criticized some productivity studies for not reflecting the essential characteristic of pesticides as damage-control agents and proposed the use of the damage control model (Hall and Norgaard, Headley 1972, Talpaz and Borosh) to estimate marginal productivity. Lichtenberg and Zilberman also suggested that the use of certain functional specifications (such as the Cobb-Douglas specification) leads to overestimation of the productivity of damage-control inputs such as pesticides and underestimates the productivity of other inputs.

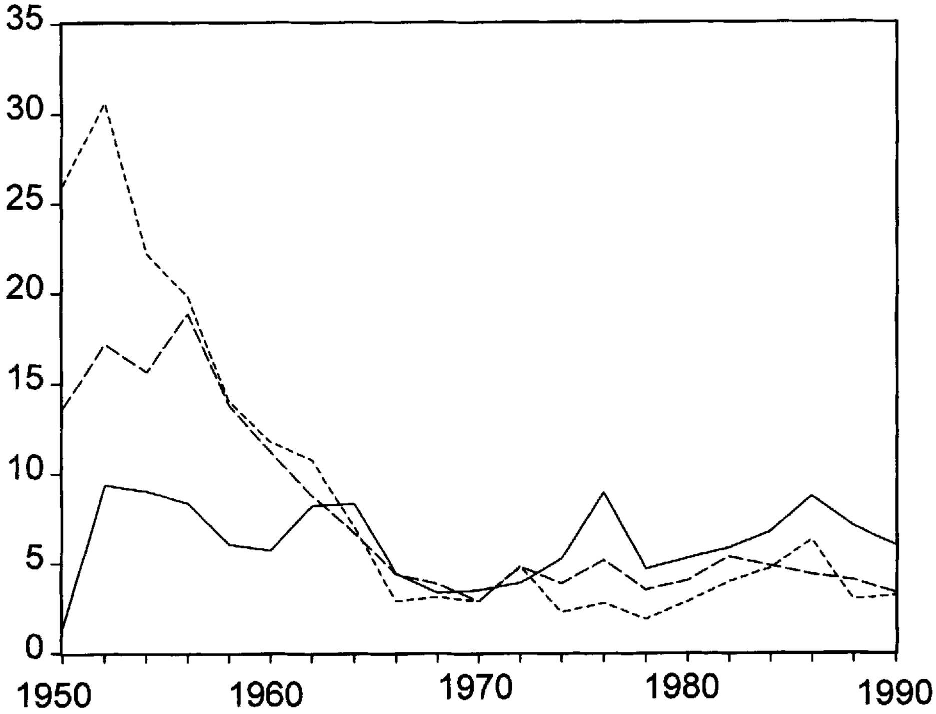
Although the damage-control models have proven their usefulness, Lichtenberg

Table 2. Marginal productivity of pesticides in U.S. agriculture: comparison of selected results

	Year	Function	VMP ($/$)
General agriculture			
Headley (1968)	1963	Cobb-Douglas	4.16–5.66
Headley (1968)	1963	Third deg. polynomial	3.90
Carrasco-Tauber, Moffitt	1987	Cobb-Douglas	5.94
Carrasco-Tauber, Moffitt	1987	Weilbull	6.88
Carrasco-Tauber, Moffitt	1987	Logistic	7.53
Carrasco-Tauber, Moffitt	1987	Exponential	0.11
Teague, Brorsen	1949–91	Random coeff. regr.	7.96
Teague, Brorsen	1991	Random coeff. regr.	4.16
Specific crops[a]			
Miranowski (corn) for insecticides	1966	Quadratic	2.02
Miranowski (corn) for herbicides	1966	Quadratic	1.23
Miranowski (cotton) for herbicides[b]	1966	Quadratic	1.82
Shroder, Headley, Findley (soybeans) for herbicides	1965–79	Second deg. polynomial	2.30
Shroder, Headley, Findley (corn)	1964–79	Second deg. polynomial	2.50
Fisher (apples, Canada)			>1
Lee, Langham (citrus)	1964–88	Linear	<1
Campbell (apples)	1970	Cobb-Douglas	11.90
Hawkins, Slife, Swanson (corn, soybeans) for herbicides	1966–75	[c]	3.30–4.89
Hanthorn, Duffy (corn) for herbicides	1980	Linear	1.05
Hanthorn, Duffy (corn) for insecticides	1980	Linear	1.03
Lin et al. (1993) (potato)	1990	Logistic	6.28
Lin et al. (1993) (potato)	1990	Exponential	5.86
Lin et al. (1993) (potato)	1990	Weibull	0.58
Carpentier, Weaver (1995) (cereals, France)	1987–90	Cobb-Douglas	0.94
Fernandez-Cornejo, Jans, Smith (corn)	1991	Cobb-Douglas	1.89

[a] U.S. unless otherwise stated.
[b] Miranowski also reported the VMP of insecticides in cotton, but the underlying regression coefficient was statistically insignificant.
[c] Not available.

Figure 2. Value of the marginal product of pesticides



Source: Data from Teague and Brodsen.

and Zilberman's implication of overestimation of pesticide productivity has been questioned. Carrasco-Tauber and Moffitt used 1987 state-level aggregate data similar to Headley's to estimate marginal pesticide productivity using different specifications, including three damage-control specifications. Their estimates of the VMP of pesticides with and without the damage-control model yielded essentially the same result, leading them to conclude that the explanation of the (high) magnitude of the estimates of pesticide productivity "seems to lie somewhere other than with the functional specification of damage control." Moreover, research by Blackwell and Pagoulatos led them to conclude that Lichtenberg and Zilberman had failed to specify the correct form of the chemical damage-abatement function.

More recently, Carpentier and Weaver (1995) showed that empirical studies based on panel data may overestimate the marginal productivity of pesticides if the estimation excludes fixed (firm and time) effects. Accounting for fixed effects using an econometric technique known as generalized method of moments, they obtained a marginal value of $0.94 per dollar of pesticide expenditures using a panel data set of French farmers for 1987–90. Moreover, they showed that using the Lichtenberg and Zilberman specification instead of one in which pesticides play a symmetric role with respect to the other inputs "has little impact on the magnitude of the estimated marginal productivity of pesticides."[4]

Despite the significance of the contribution, the empirical ability of Carpentier and Weaver's model to explain the high pesticide productivity found for U.S. and Canadian agriculture in previous studies has yet to be examined, given that many of those studies were based on cross-sectional data (e.g., Campbell, Fernandez-Cornejo and Jans 1996, Lin et al. 1993, Miranowski). Moreover, given that French farmers use pesticides more intensely than U.S. producers (Brouwer, Terluin, and Godeschalk; Szmedra), the value of 0.94 found by Carpentier and Weaver for the marginal productivity of pesticides in French agriculture is not necessarily inconsistent with values higher than the one found in U.S. agriculture.

Marginal productivity studies have also been criticized for not considering the notion that some inputs, such as pesticides, may affect not only the amount but also the variability of output (Carpentier and Weaver, Just and Pope). However, there is no consensus on the overall role of pesticides regarding farm risk, and determining the effect of risk on the VMP of pesticides has proven to be even more elusive in aggregate productivity studies.

According to the conventional view, pesticides have been considered to be risk-reducing, leading to higher optimal use under risk aversion and are used as "insurance" (Mumford and Norton). The economic literature, however, reports mixed findings on the role of risk aversion. Moffit showed that when farmers manage pests according to a threshold, average pesticide use may or may not be greater because of the presence of risk aversion, depending on the frequency and rate of pesticide application. Pannell observed that uncertainty about output price and yield leads to lower optimal levels of pesticide use by individual farmers, whereas uncertainty about other variables, such as pest density, leads to higher optimal pesticide use under risk aversion. Horowitz and Lichtenberg noted that the theoretical analysis leading to the belief that pesticides reduce production risk is based on a limited view of production that assumes that pest damage is independent of other factors affecting output. They also demonstrated that pesticides may increase risk when crop growth is also random and pest populations are positively correlated with crop growth. Moreover, using a sample of cotton producers, Hurd (1994) found that yield variability was not significantly affected by pesticides; Archer and Shogren showed that the increased risk of an herbicide treatment failure (i.e., if the farmer fails to apply the herbicide or the applied herbicide fails to work because of the weather) will decrease application rates and result in the use of more flexible and persistent herbicides. Very recently, Gotsch and Regev found that fungicides for wheat producers in Switzerland have a risk-increasing effect on revenues under some conditions.

Other explanations have been advanced for the high empirical estimates of pesticide productivity in addition to the possibilities discussed. For example, it has been suggested that a disequilibrium could arise if there is a binding constraint in the system, such as an expenditure constraint (Campbell, Lee and Chambers). Another possibility is that risk attitudes of farmers (e.g., prudent use of credit) may be limiting their expenditures to suboptimal levels (Färe, Grosskopf, and Lee).

In summary, although there are controversies in the literature over methodologies and explanations, most empirical estimates of marginal pesticide productivity for U.S. agriculture generally indicate that the VMP is higher than the pesticide price. The implication of these studies is that pesticides appear to be more economically valuable than what could be concluded from pesticide expenditures. Consequently, Campbell's conclusion, that the marginal costs of reducing pesticide use for health and environmental considerations are relatively high, is still valid. However, some studies indicate that the VMP of pesticides is declining, suggesting that the marginal costs of reducing pesticide use may be declining as well.

Expected Losses Relative to a Current or Potential Yield

A perspective favored by physical scientists estimates the value of pesticide use in agriculture considering the expected yield losses to pests relative to some current practice baseline yield or potential maximum yield. Estimates of crop yield losses that might result without the availability of pesticides are difficult to obtain because these losses vary by crop, soil, and weather (which affect fertility and pest populations). In addition, yields may vary yearly because of technological developments (e.g., new plant varieties and new pesticides), changes in cropping practices (e.g., destruction of crop residues), appearance of new pests, development of pesticide resistance by certain pests, and weather. As a result, estimates are highly variable. Few empirical estimates are available in the literature, and most of these are based on judgments of experts in different natural science fields. Alternatively, field-trial data could be obtained using an experimental approach, but given the factors involved, the tests would be time-consuming and expensive and would have debatable relevance to actual farm conditions (Taylor et al.). Recently, Liu and Carlson proposed a method using a "relative efficacy index" to estimate substitute herbicides and their use levels based on field studies of herbicide efficacy and farm survey data. The method does not depend on expert opinion but has yet to be applied to actual herbicide cancellation decision studies.

A summary of estimated yield losses for several major U.S. crops is presented in table 3. In general, relative to yields prevailing at the time, the expected losses from insects and diseases without the use of insecticides and fungicides range between about 2% and 26% of the yield, except for peanuts, fruits, and vegetables, which have higher yield losses. Crop losses from weeds not treated with herbicides are estimated to be between 0% and 53% for the crops studied. We compared the yield losses reported by different sources for a given crop (table 3) and believe the results are fairly consistent, given the difficulty in making the estimates of yield losses and considering the difficulty in assigning losses to particular pest categories because of the interrelationships among insects, nematodes, diseases, and weather in causing losses (USDA 1965).

For comparison, older estimates reported to have been made by FAO indicated that "cessation of use of all pesticides in the United States would reduce agricultural output by 30%" (Bradburry and Green, pp. 377–99). To put this into the context of marginal productivity studies, and considering that the major impact of pesticide use reduction on the livestock sector is through feed (Knutson et al. 1990b, p. 25), a 30% reduction in agricultural output resulting from not using pesticides would imply a pesticide productivity, at current prices (USDA 1997), ranging between $3 and $4 per dollar of pesticide expenditures.

Economic Effect of Banning or Reducing Pesticides

The economic significance of pesticides has been indirectly examined in several studies that consider the effect of banning pesticides in general or banning specific pesticides. Two methods are generally used. Partial budgeting is a simple method used to estimate the value of the production lost without pesticides assuming that output prices remain constant. Large-scale econometric models are used to account for market interactions and to allow for input and output substitution.

Total Bans

Knutson et al. (1990b) used expert-judgment estimates of potential changes in yield and production costs and a large econometric model to conclude that the total elimination of pesticides would increase annual consumer expenditures by $228 per household (in 1989 dollars), which amounts to about $30 billion per year. Knutson et al. (1994) estimated sharp yield losses and cost increases in the production of selected fruits and vegetables after a 50% and a 100% reduction of pesticides. In a similar study, Taylor studied the economic effect of a complete elimination of pesticides in the production of fruits and vegetables. He concluded that the acreage required for production would increase by 2.5 million acres (44%), unit production costs would increase by 75%, wholesale prices of fruits and vegetables would increase by 45%, returns to producers would decrease by 30%, retail prices would increase by 27%, and domestic consumption would fall by 11%.

These studies have generated controversy (Ayer and Conklin, Gianessi 1991, Smith). Critics argue that considering the extreme case of total elimination of chemicals is unrealistic, that the studies do not allow for the impact of induced research in the long run, and other relatively less important technical issues, leading to an overestimate of the economic impacts. The authors of the studies accept the first criticism but claim that considering an extreme case has provided considerable insights into why such a case is unrealistic. They agree that further research is needed to determine intermediate points between current practices and a total ban in specific groups of chemicals (Knutson et al. 1990a). Regarding the second major criticism, Knutson et al. (1990a) argue that there was no point in speculating about future scientific developments, particularly within the current regulatory framework, because those discoveries would likely occur beyond the ten-year horizon of their studies.

Partial Bans

Pimentel et al. (1991b) examined the case of reducing pesticide use in the United States by approximately 50% and concluded that it could be achieved at a cost of $1 billion per year. They also concluded that their results were consistent with plans drafted by the Danish and Swedish governments to reduce pesticide use by 50%. It should be noted, however, that it is difficult to estimate the impact of a 50% reduction because of the many ways in which such reduction could be implemented. In addition, Pimentel's parallel of the European and U.S. cases is inappropriate, given the different conditions and more intense pesticide use prevailing in Europe compared to those of the United States (Szmedra, pp. 6–7). Gianessi (1991) provided a detailed critique of many of the problematic assumptions and conclusions of the Pimentel study.

A study of cancellation of specific pesticides to evaluate of the impact of the Delaney clause of the Federal Food Drug and Cosmetic Act was carried out by the National Center for Food and Agricultural Policy (NCFAP) (Gianessi and Ander-

Table 3. Estimated yield losses from pests without using pesticides

Crop	Without Insecticides (%)	Without Fungicides (%)	Without Herbicides (%)	Without Pesticides (%)	Source
Corn	1	5	18–43[1]	na	NAPIAP (USDA, 1985a), pp. 7, 11, 14; corn belt
Corn	8	11	8–18[1]	na	NAPIAP (USDA, 1985a), pp. 8, 11, 14; northern plains
Corn	2–15[2]	na	19	na	Taylor and Frohberg, for the corn belt
Corn	5[3]	5[3]	30	32	Knutson et al., 1990b, p. 15
Corn	na	0	na	na	Palm, p. 112
Soybean	1	2	32–49[1]	na	NAPIAP (USDA, 1985b), pp. 18, 22, 26 for corn belt
Soybean	0	2	13–24[1]	na	NAPIAP (USDA, 1985a), pp. 18, 21 for northern plains
Soybean	na	na	22	na	Taylor and Frohberg, for the corn belt
Soybean	3[3]	3[3]	35	37	Knutson et al., 1990b, p. 15
Soybean	na	1		na	Palm, p. 112
Wheat	4[3]	4[3]	23	24	Knutson et al., 1990b, p. 15
Wheat	na	0	na	na	Palm, p. 112
Cotton	26[3]	26[3]	17	39	Knutson et al., 1990b, p. 16
Cotton	na	1	na	na	Palm, p. 112
Rice	16[3]	16[3]	53	57	Knutson et al., 1990b, p. 16
Rice	na	0	na	na	Palm, p. 112
Peanuts	66[3]	66[3]	29	78	Knutson et al., 1990b, p. 16
Peanuts	na	45	na	na	Palm, p. 112
Sorghum	20[3]	20[3]	0	20	Knutson et al., 1990b, p. 17
Sorghum	na	0	na	na	Palm, p. 112

Table 3. Continued

Crop	Without Insecticides (%)	Without Fungicides (%)	Without Herbicides (%)	Without Pesticides (%)	Source
F. vegetables[4]	62	48	24	76	Knutson et al., 1993
P. vegetables[5]	24	15	28	45	Knutson et al., 1993
All vegetables	na	0–44[6]	na	na	Palm, p. 113
F. fruits[7]	61	29	23	79	Knutson et al., 1993
P. fruits[8]	27	54	7	68	Knutson et al., 1993
All fruits	na	10–60[9]	na	na	Palm, p. 113

[1] Higher value with current cultivation, lower value with extra cultivation.
[2] For continuous corn; range depends on the region.
[3] Without insecticides and fungicides.
[4] Fresh vegetables: weighted average of fresh potatoes, tomatoes, lettuce, onions, and sweet corn.
[5] Processed vegetables: weighted average of processed potatoes, tomatoes, and sweet corn.
[6] Upper limit is for tomatoes.
[7] Fresh fruits: weighted average of fresh apples, oranges, and peaches.
[8] Processed fruits: weighted average of processed apples, grapes, oranges, and peaches.
[9] Upper limit is for apples.

son). The NCFAP study estimated that the aggregate economic loss for 28 crop–pesticide class combinations, selected from a list of 85 crops and 38 pesticide active ingredients that could have been affected by enforcement of the Delaney settlement agreement, would be $387 million per year. Considering that these results apply to a relatively few pesticide–crop combinations, they appear to be consistent with those of Knutson et al. (1990b, 1994) and Taylor.

The USDA's National Pesticide Impact Assessment Program (NAPIAP) has conducted a variety of biological and economic studies of pesticide use for specific crops to estimate the cost to producers and consumers of banning specific pesticides. Numerous assessments have been conducted since 1977, but because market and pest conditions often change, we focus on those conducted in recent years. Table 4 presents the estimated impact of the loss of certain herbicides, insecticides, and fungicides used on corn, cotton, and other crops to producers and consumers. The results are calculated for a single year or represent the annual average of several years.

The value of a pesticide's use to agricultural producers and consumers is influenced in part by the availability and characteristics of alternative means of pest control (Osteen and Szmedra). Because many individual pesticides have alternatives of about the same cost and efficacy (at least to treat major crops), the value of a single chemical is relatively low because another chemical may be readily substituted for it. The value of a family of chemicals is likely to be higher because the likelihood of having suitable substitutes is lower. For example, the loss of an individual pyrethroid insecticide would cost cotton producers less than $3 million, but the loss of the entire class of pyrethroids would cost producers more than $170 million (USDA 1993b).[5] Certain chemicals, such as the fungicide captan (used to treat corn seed) and the fumigant methyl bromide (used for a variety of crops), have few, if any, substitutes. The loss of such chemicals has high costs.[6] A chemical's benefit may also increase over time, not because of an increase in efficacy but by elimination of its substitutes from the market (either through a government ban or pest resistance). Depending on the order in which pesticides are banned, a chemical on the market may have a high economic value to society simply because its substitutes have been banned, even though it may pose a greater health risk than its substitutes (Osteen 1993).

The value of a pesticide also varies geographically and among users and nonusers. Producers in areas of heavy pest infestation will place a higher value on chemical use than those in areas free of the pest. As implied by Knutson et al. (1990a,b, 1994) and Taylor, if a chemical becomes unavailable, production may shift geographically as growers in pest-free areas or those with lesser pest pressure may expand production, whereas growers in more heavily infested regions may exit the sector. Some producers (users of a pesticide) may suffer losses from cancellation of its use while others (nonusers) may gain (Osteen and Szmedra). For example, Lichtenberg et al. found that users of ethyl-parathion on almonds, plums, and prunes would lose about $2 million in producers' surplus, whereas nonusers would gain about $0.5 million if the pesticide became no longer available.[7]

Reducing Potential Health and Environmental Effects of Pesticide Use

Although pesticide use yields important economic benefits, it also has potential health and environmental effects. Because agricultural producers do not bear the full cost of those effects, government policies (or proposals for policies) attempt to restrict pesticide use, impose those external costs on users, or encourage alternative agricultural practices. The following sections discuss some economic issues of pesticide regulation, market incentives to reduce pesticide use, and alternative pest-management approaches to reduce the external effects of pesticides.

Costs and Benefits of Pesticide Regulation

New and existing pesticides must meet strict health and environmental standards. Requirements for pesticide registration with the EPA involve field testing involving up to 70 different types of tests that can take several years to complete. As a consequence, overall research and development costs are high: Recent estimates suggest that research and development of a new chemical pesticide (including testing) takes 11 years and costs between $50 and $70 million (Ollinger and Fernandez-Cornejo 1995).

An empirical study by the Council for Agricultural Science and Technology found that EPA regulation encouraged an increase in research expenditures; a delay in the time required to register and reregister pesticides; a decline in the number of new pesticides registered per year; and a shift in the allocation of research expenditure from synthesis, screening, and field testing to administration, environmental testing, and residue analysis. Hatch found that increased regulatory stringency led to a 7% to 9% decline in pesticide registrations.

More recently, Ollinger and Fernandez-Cornejo (1995, 1998) showed that regulation discouraged new chemical registrations: The number of new pesticides registered by the EPA during 1987–91 was half that of 1972–6. Moreover, using firm-level data and considering three alternative measures of regulation (the change in EPA-estimated costs of regulation, industry-reported testing costs, and employment at the EPA), Ollinger and Fernandez-Cornejo (1998) found that a 10% increases in regulatory costs led to a 15% to 20% decline in the number of new pesticide registrations. Moreover, pesticide regulation contributed to an industrywide increase in research spending, which encouraged some small firms to leave the pesticide industry. In addition, regulation encouraged firms to focus their research on pesticides used in large crop markets such as corn and soybeans, abandoning minor markets such as horticultural crops.

On the other hand, Ollinger and Fernandez-Cornejo (1995, 1998) concluded that pesticide regulation in the United States has encouraged the introduction of "less toxic" pesticides. They considered acute and chronic human toxicity and fish and wildlife toxicity. Because regulation requirements, pesticide firms refocused their research away from persistent and toxic pesticides, and the proportion of lower-toxicity pesticides registered increased. A 10% increase in testing costs to meet EPA standards was found to lead to a 5% increase in the proportion of less toxic pesticides registered.

Historically, FIFRA allowed regulators to weigh the anticipated benefits of pesticide use against potential risks. Although the FQPA does not allow benefits consideration in setting new tolerances, an important question regarding pesticide regulation is the trade-off between health risks and economic benefits implicit in past regulation decisions. Cropper et al. (1992a) examined the EPA's special review process for pesticides between 1975 and 1989 and concluded that the agency "appears

Table 4. Economic impact of the loss of selected pesticide uses for selected crops—summary of NAPIAP studies

Crop/Chemical	TYPE (H, I, F)	Producer Loss	Consumer Loss	Total Loss
		$ million per year		
Corn				
Captan	F	1465	na	na
Triazines	H	911	na	na
Atrazine	H	679	na	na
Acetamides	H	76	na	na
Cotton				
Pyrethroids	I	172	na	na
Desiccants/defoliants		146	na	na
Dinitroanilines	H	139	na	na
Cranberries				
Groups of herbicides	H	34	31	65
Groups of fungicides	F	20	19	39
Groups of insecticides	I	11	10	21
Lettuce	F	127	160	287
Grain sorghum[1]				
Atrazine	H	(4)–(22)	54–87	58–65
Glyphosate	H	(1)–(1)	5–8	6–7
Soybeans				
Carboxin	F	67	na	na
Pendimethalin	H	50	na	na
Metribuzin	H	35	na	na
Bentazon	H	32	na	na
Various fruits, vegetables, and non-food crops				
Methyl bromide[2]	Fu			
With imports		na	na	1300–1488
Without imports		na	na	1317–1531

Sources: Mahr and Moffitt; Morrison et al.; Pike et al.; USDA (1993a, b, 1994).
Type: H = Herbicide, I = Insecticide, F = Fungicide, Fu = Fumigant.

[1] Under some scenarios, producers who do not use the chemical gain more than users lose. Lower bound estimates are reported.

[2] Including quarantine uses for imports.

to have balanced the risks of pesticide use against the benefits in reaching a final decision to cancel or continue a pesticide." They also estimated that the final decision to cancel or continue the registration of pesticides implied a trade-off of $72 million in producer benefits per cancer case avoided among pesticide applicators and $9 million per cancer case avoided among consumers (in 1986 dollars). In comparison, the value that individuals place on an avoided statistical death has been estimated between $0.5 million and $9 million in 1986 dollars (Congressional Budget Office). Abler argued that the figures estimated by Cropper et al. are too high because the benefits were calculated at existing prices and did not consider the effect of pesticide restrictions on producer prices, because producers could even gain from pesticide restrictions if output prices increased enough. However, higher output prices also imply consumer losses, which would also have to be included. Moreover, higher output prices due to restricted pesticide use have not been empirically documented, although they have been predicted in some simulation studies (e.g., Knutsen et al., 1990b).

Few studies have tied pesticide cancellations with actual improvement in the environment. Liu, Carlson, and Hoag evaluated ten potential herbicide cancellations in southern states. They examined not only the producer and consumer surplus associated with the cancellations but also the environmental impact on groundwater. They concluded that even though the effect of the cancellations on groundwater quality can be very significant, a cancellation does not guarantee improvements in groundwater quality because it depends on the "initial shares of the product to be canceled and its substitutes, as well as on the relative leaching potential of each related pesticide." This interaction also implies that the effects of multiple cancellations are different from the summation of the effects of independent cancellations.

Reducing Pesticide Use with Market Incentives

Instead of using direct controls (registration, bans, and other quantity restrictions), pesticide use could be reduced with price incentives, such as taxes and subsidies. A relatively simple economic strategy is the imposition of ad valorem taxes on these chemicals. The effectiveness of such a strategy depends in part on the responsiveness of the pesticide demand to increases in pesticide prices, which is measured by the demand elasticity.

Published empirical estimates of pesticide demand elasticities in U.S. agriculture vary widely (table 5). To a large extent, the differences among elasticity estimates are due to differences in model specification, including levels of aggregation of inputs and outputs and firms, functional form, price expectations, and introduction of exogenous variables, such as weather or government policies (Fernandez-Cornejo 1992, 1993). Elasticity estimates may also differ because of differences in behavioral assumptions, such as profit maximization or cost minimization. Finally, many reported elasticities may be unreliable because they were often derived from models that are inconsistent with economic theory. Table 5 presents selected estimates of price elasticity of demand for pesticides derived from consistent models. In general, farmers' responsiveness to price changes for pesticides is small in the short run and small to moderate in the long run. This means that substantial taxes would be needed to achieve moderate reductions in pesticide use, particularly in the short run.

However, the effect of a pesticide tax is not uniform across regions, and large differences have been predicted in some cases. For example, Chen, McIntosh, and Epperson estimated that a 1% tax on pesticides in Alabama would decrease pesticide use by 2.4%, and Shumway and Chesser found that the effect of a pesticide tax would have a large impact on selected pesticides in some regions of Texas.

The effect of a chemical tax may be influenced by risk and government policy considerations. Leathers and Quiggin suggested that farmers' response to a pesti-

Table 5. Own-price elasticities of pesticide demand: selected estimates in U.S. agriculture

Author/location	Elasticity	Type of Elasticity
Antle, USA	−0.194	Long run[2]
Brown and Christensen, USA	−0.188	Short Run[1]
Capalbo M2, 1988, USA[3]	−0.688	Long run[1]
Capalbo M4, USA[3]	−0.876	Long run[1]
Capalbo M7, USA[3]	−0.606	Short run[2]
Chen et al., AL	−2.4184	Short run[2]
McIntosh and Williams, GA	−0.112	Sort run[2]
Fernandez-Cornejo, IL/IN	−0.104/−0.082	Short run[2]
Fernandez-Cornejo, IL/IN	−0.382/−0.604	Long run[2]
Fernandez-Cornejo, IL/IN	−0.101/−0.081	Short run[1]
Fernandez-Cornejo, IL/IN	−0.119/−0.086	Long run[1]
Villezca-Becerra and Shumway, CA/IO	−0.091/−0.040	Short run[2]
Villezca-Becerra and Shumway, TX/FL	−0.210/−0.165	Short run[2]

[1] Hicksian (cost minimizing) demand elasticities.
[2] Marshallian (profit maximizing) demand elasticities.
[3] The numbers refer to models 2, 4, and 7 (M2, M4, M7) appearing in Capalbo (1988).

cide tax depends on the risk effect of pesticides. Hrubovcak, LeBlanc, and Miranowski found that government price supports could alter the effectiveness of a chemical tax; for example, a tax on pesticides would have a smaller effect if price support was increased. More recently, Shortle and Laughland examined taxes on chemical inputs used in corn production and showed that the tax is less effective when the output subsidy is increased to compensate farmers for the tax, as opposed to when it is held constant.[8]

Just as government commodity price supports combined with supply control policies in the past may have led to more intensive use of pesticides (Miranowski; Miranowski, Hrubovcak, and Sutton), their removal is expected to reduce pesticide use. In fact, analyzing the effect of a reduction in government agricultural support programs before the Federal Agriculture Improvement and Reform Act of 1996 (FAIR), Fernandez-Cornejo (1993) found that the long-term impact of reducing price supports on pesticide use for corn producers was larger than that of a similar percentage increase in the pesticide price. These findings support the argument that market-oriented agricultural policies, such as the FAIR act, may be environmentally beneficial in the long run.

Alternative Pest Management Methods

Two major ways to manage pests while reducing the potential health and environmental effects of pesticides are the use of integrated pest management (IPM) techniques and new pesticide products.

Integrated pest management

IPM includes a number of techniques to maintain pest infestation at the most economically sensible level rather than attempting to completely eradicate all pests

(Vandeman et al.). Because IPM techniques were designed to address some of the health and environmental concerns of pesticides as well as the problem of pest resistance to pesticides, the USDA has set a goal for the use of IPM on 75% of U.S. farmland by the year 2000. One important IPM technique is scouting, the primary method of monitoring pest populations by regular and systematic sampling of the fields to estimate pest infestation levels and subsequently to determine whether an economic threshold is reached (Vandeman et al.). Other monitoring methods include soil testing for pests (e.g., nematodes), use of pheromones and visual stimuli to attract target pests to traps, and recording environmental data (e.g., temperature and rainfall) associated with the development of certain pests. Pest-management practices used in IPM include cultural controls, such as hand hoeing, mulching, and crop rotation; strategic controls, such as planting dates and location; use of plant varieties resistant to some pests; and biological controls. Biological controls are believed to pose few health and environmental hazards and have proven to be effective as an alternative to complete reliance on pesticides (Ollinger and Fernandez-Cornejo 1995). They include natural enemies of pests, such as predators (e.g., wasps and lady beetles), parasites, pathogens (including bacteria, fungi, and viruses), competitors, antagonistic microorganisms, and semiochemicals (including pheromones and feeding attractants) (Hokkanen, p. 185; Vandeman et al.).

Assessing and comparing the effects of IPM programs is difficult because of the heterogeneity across regions, time, and types of crops grown. For example, it is difficult to compare adoption of IPM programs in hot, humid climates, which are more favorable to the development of pests, to adoption in more moderate climates. In addition, IPM involves an assortment of techniques that have developed to different degrees for different crops, and different farmers may adopt IPM practices to various degrees. Moreover, the methodologies used to assess the effects of IPM on pesticide use, yields, and profits vary widely from simple comparisons of sample averages of adopters and nonadopters to advanced econometric techniques.

Although IPM is sometimes defined as an attempt to reduce pesticide use while maintaining current production levels (Hall), the empirical evidence on the effect of IPM on pesticide use is mixed, even for a given crop. Table 6 presents a summary of empirical studies on the effect of IPM on pesticide use, yields, and profits. The table summarizes the cases examined by Norton and Mullen, which are supplemented by more recent studies. The evidence to date appears to indicate that, on average, IPM reduces pesticide use while maintaining or increasing profits. An unweighted average of 44 studies reported by Norton and Mullen shows that IPM adoption is associated with a reduction in pesticide use by 15% and an increase in net returns (National Foundation for IPM Education). Results are not uniform, however, particularly because scouting alone tends to increase pesticide use in many cases.

Cotton is the commodity most studied in relation to the effects of IPM, with about twenty studies having been published over the past twenty-five years. Regarding the effect of IPM on pesticide use, the findings are mixed. When the effect of scouting is examined separately, pesticide use is found to increase in many cases, but when scouting is considered in combination with other IPM techniques, it decreases pesticide use in most of the cases. Yields and profits generally increase. A similar effect is shown for corn, although only three studies have reported IPM impacts for this commodity (table 6).

Table 6. The impact of IPM on pesticide use, yields, and profits—summary of empirical results

			Pesticide Use			
Commodity	IPM Techniques	Total Number of Studies	Most common effect	Range (Percent)	Yield	Profits (Net Returns Per Acre)
Cotton	Scouting only	10	Increase	−64 to +92	Increase[2]	Increase[2]
Cotton	Scouting/others[1]	9	Decrease	−98 to +34	Increase[2]	Increase[3]
Soybeans	Scouting only	5	Decrease	−21 to +83	Increase[4]	Increase[4]
Soybeans	Scouting/others[1]	2	Decrease	−100 to −85	na	Increase
Corn	Scouting	1	Increase	+15 to +47	Increase	Increase
Corn	Scouting/others[1]	2	Decrease	−50 to +67	Increase[5]	na
Peanuts	Scouting only	5	Decrease	−81 to +177	Increase[6]	Increase[5]
Fruits/nuts	Scouting only	6	Decrease	−43 to +24	Increase[7]	Increase[7]
Fruits/nuts	Scouting/others[8]	4	Decrease	−41 to −12	same[5]	same[5]
Vegetable	Scouting/others[8]	7	Decrease	−67 to +13	same	Increase[5]

Sources: Norton and Mullen; Greene and Cuperus; Fernandez-Cornejo and Jans (1996); Yee and Ferguson, Fernandez-Cornejo (1996, 1997).

[1] Scouting plus other techniques or other techniques alone.

[2] Only 6 studies reported results.

[3] Only 8 studies reported results.

[4] Only 4 studies reported results.

[5] Only 1 study reported results.

[6] Only 3 studies reported results.

[7] Only 2 studies reported results.

[8] All studies but one considered insect IPM only.

Most IPM studies for vegetable production were carried out in the 1980s and do not use econometric techniques but rather compare sample averages for adopters and nonadopters. The results of those studies, summarized by Greene and Cuperus and by Norton and Mullen, show that IPM adopters were able to reduce the number of applications and pesticide expenditures in the majority of the cases. Most studies on IPM for fruits focused on apples and pears (Norton and Mullen). Like the case of vegetables, the majority of those fruit studies report a reduction in pesticide use by IPM adopters, particularly when IPM is defined more broadly than just scouting for pests.

Econometric studies show mixed results for the impact of adoption of IPM techniques. Burrows found that IPM adoption leads to a significant reduction in pesticide expenditures for a sample of cotton growers in California collected in 1970–4. Yee and Ferguson found that scouting increases pesticide use among cotton farmers in 14 major producing states, whereas Carlson (1980) cites evidence of "both complementary and substitute relationships between scouting and pesticide use" among cotton producers in North Carolina. Wetzstein et al. found that "IPM has no effect on pesticide expenditures" among a sample of Georgia cotton farmers. Fernandez-Cornejo (1996, 1998) evaluated the impact of IPM using a model that accounts for self-selection and simultaneity and that is consistent with profit maximization. His results showed that IPM adopters used fewer insecticide and fungicide applications for tomatoes and grapes. However, using a similar model, Fernandez-Cornejo and Jans (1995, 1996) showed that IPM had no significant effect on pesticide use for orange growers in Florida and California.

Although important, the total amount of pesticide use is just one element in determining the potential risk of pesticide use. Another element, neglected by most studies focusing on the effect of IPM on pesticide use, is pesticide quality, notably toxicity and persistence. In particular, there has been little empirical examination of claims that pesticides used in IPM differ from those used on a preventive or routine schedule and that IPM uses pesticides that target specific pests and are less toxic to beneficial organisms (Allen et al.). In a recent study of grape producers in six states, Fernandez-Cornejo (1998) showed that IPM adopters applied significantly less insecticides and fungicides than nonadopters. He also showed that the average toxicity (Fernandez-Cornejo and Jans, 1995) and the index of potential environmental impact of insecticides (Kovach et al.) decreased slightly with adoption of insect IPM. However, toxicity and the potential environmental impact index of fungicides remained about the same for adopters and nonadopters of IPM for diseases.

New Products

During the past decade, research has focused on the development of biological pesticides, or biopesticides, including bacteria, viruses, and fungi. These "reduced-risk" pesticide products, whose development has been facilitated by the EPA through simplification of registration, differ significantly from chemical pesticides in that they help to manage rather than eliminate pests, have a delayed impact, and are more selective (Ollinger and Fernandez-Cornejo 1995). Among biological pesticides, the most successful is the soil bacterium *Bacillus thuringensis,* which kills lepidorean insects by lethal infection. The use of *B. thuringensis* (called the nation's most valuable natural pesticide) is increasing, particularly in IPM programs, because of its environmental safety, improved performance, cost competitiveness, selectivity, and activity on insects that are resistant to chemical pesticides (Marrone).

Furthermore, because it is becoming increasingly costly for firms to develop chemical pesticides that are harmless to crops, sufficiently toxic to kill target pests, and meet human health and environmental regulations, firms have been turning to genetic engineering (Ollinger and Fernandez-Cornejo 1995). Compared with traditional genetic plant breeding, genetic engineering reduces the time required to identify desirable traits. In addition, by inserting into the plant a gene (DNA from a different organism) that imparts some desirable properties, genetic engineering allows a precise alteration of a plant's traits, facilitating the development of plant characteristics not possible through traditional plant-breeding techniques. This allows targeting of a single plant trait, which decreases the number of unintended characteristics that may occur with traditional breeding techniques. The development of genetically engineered plants takes about six years and costs about $10 million, almost half the time and one-sixth of the expense for chemical pesticides (Ollinger and Fernandez-Cornejo 1995).

It is believed that genetic engineering can help reduce use of chemical pesticides in agriculture. For example, genetically engineered corn that contains a gene derived from *B. thuringensis* (called Bt-corn) is expected to reduce the need for conventional chemical pesticides (to protect corn from the corn borer) by about 10 million pounds per year (*Pesticide and Toxic Chemical News*). The sale of Bt-corn was approved by the EPA in August 1995, and commercial use began on a small scale in 1996 (only 1–2% of corn-planted acreage), increased to 3% in 1997, and adoption is expected to exceed to more than 10% of corn acreage in 1998.

Despite its benefits, some scientists are concerned that the new Bt-corn will hasten pest immunity to *B. thuringensis* because these new corn varieties contain genes from the bacterium. This has led the EPA to require producers to develop resistance management plans (including a high dose of *B. thuringensis,* to ensure that few resistant biotypes survive to mate, and "refugia," or sanctuaries set aside to ensure that susceptible biotypes are more numerous than resistant ones.) Still, some consumer groups and environmental organizations are demanding that transgenic foods be labeled and kept separate from other foods. Furthermore, retailers in Europe are supporting labeling, and Austria and Luxemburg have banned genetically engineered food.

Genetically engineered plant varieties resistant to particular herbicides are also believed to reduce herbicide use. For example, it has been estimated that by converting 30% of cotton acreage to cotton varieties tolerant to bromoxynil (which is used effectively at lower rates than traditional products), herbicide use could be reduced by 10 million pounds, and farmers would realize annual savings of $40 million (Salquist).[9] In the same vein, Monsanto has developed a soybean variety that is not damaged by its popular glyphosate (Roundup) herbicide, and similar glyphosate-tolerant varieties are being developed for canola, cotton, corn, sugar beets, and oilseed rape. Despite concerns about the possibility of accelerated weed resistance with the use of herbicide-tolerant varieties, their use is growing rapidly. For example, use of Roundup-resistant varieties increased from close to 2% of soybean-planted acreage in 1996 to about 13% in 1997 and is expected to increase to 28% in 1998.

Concluding Comments

We reviewed several perspectives used to place a value on pesticide use in agriculture. One viewpoint, generally favored by economists, is based on calculations of the marginal productivity of pesticides. Another perspective, favored by physical scientists, considers the expected loss to pests (insects, weeds, and pathogens) relative to the current or maximum yield. An example of this approach is the estimation of the percentage of a crop that would be lost to insects without insecticides. A third viewpoint, related to the second, has been used by interdisciplinary teams to calculate the economic effect of banning pesticides, which is effectively the value that producers and consumers place on those chemicals.

U.S. farmers spent about $8.3 billion on pesticides to protect their crops in 1996, and most of the empirical results for U.S. agriculture indicate that, at the margin, pesticide returns more than $1 per dollar spent on pesticides. Thus, the marginal costs of reducing pesticide use for health and environmental considerations are relatively high. However, the value of the marginal product of pesticide use is declining, suggesting that the marginal costs of reducing pesticide use may be declining as well.

Estimates for expected crop losses from disease, weeds, or insects without using pesticides are generally based on expert judgment and show a broad variation with the crop. Economic losses from banning pesticides vary widely from banning some individual pesticides ($2–3 million), to banning pesticide families, classes, and pesticides in general (several billion dollars). Pesticides with few or no substitutes (e.g., methyl bromide) are valued highly.

Some important issues related to the impact of government policies to restrict pesticide use have also been reviewed. Past pesticide regulation decisions have been estimated to imply a trade-off of $9 million in producer benefits per cancer avoided among consumers and $70 million for pesticide applicators. Pesticide regulation has been found to encourage the introduction of less toxic pesticides but to discourage innovation and induce abandonment of minor crop markets. Because farmers' responsiveness to price changes for pesticides is small, particularly in the short run, pesticide taxes do not appear to be an effective tool to reduce pesticide use in the United States, but the effect of taxes varies with region and government policies.

Potential ways to reduce the health and environmental hazards associated with pesticide use are the application of IPM techniques and the use of improved pesticide products, such as biopesticides. The success of any policy aimed at reducing the health and environmental risks associated with pesticide use will ultimately depend on the availability of profitable alternatives which, in turn, depends on the development of those alternatives. As Gianessi (1993) observed, "the success of the regulatory program depends on the success of the research program." If the goal of reducing the health and environmental risks associated with pesticide use is to be reached, public and private funding of studies to investigate alternatives to the riskier chemical pesticides must be a priority.

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Disclaimer

The views expressed are those of the authors and do not necessarily correspond to the views or policies of the U.S. Department of Agriculture.

Endnotes

[1] However, human health and environmental costs associated with pesticides are not well documented. A controversial estimate, placing the external (to farmers) economic costs of pesticide use in U.S. agriculture at $839 million per year in 1980 dollars (Pimentel et al. 1991a), was modified by the same senior author to $955 million per year (Pimentel et al. 1991b) and subsequently revised to $8 billion per year (Pimentel et al. 1992).

[2] The period considered was 1967–92. Total pesticide use increased further in 1994.

[3] The average pesticide productivity is a partial factor productivity measure equal to the ratio of total output to pesticide input. This measure is analogous to labor and land productivity. These partial measures focus on a particular input, ignoring the contribution of other inputs to output, but they are commonly used because they are easy to interpret and are useful for comparisons across time, crop, etc.

[4] See additional updated discussion in their recent article (Carpentier and Weaver 1997).

[5] Atrazine is an exception. It accounts for a large percentage of triazine use in corn, and its value is close to that of the entire family of triazines.

[6] For example, the USDA estimates that producer and consumer losses of banning agricultural uses of methyl bromide are approximately $1.3–$1.5 billion annually (USDA 1993a).

[7] Regarding the distributional impact among consumers, Zilberman et al. argue that because pesticide use contributes to reducing food prices, consumers, particularly low-income consumers, benefit economically from use of pesticides.

[8] See also Fox et al. for a review up to the 1980s and Archer and Shogren for an analysis of input substitution in the presence of a chemical tax.

[9] However, on January 1998, the EPA announced that it could not grant a request to extend tolerances for bromoxynil to continue its use in cotton crops because the EPA could not ensure that there was a reasonable certainty of no harm under the FQPA (due to concerns about developmental risks to infants and children and studies showing that bromoxynil caused cancer in laboratory animals).

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