Environmental and Economic Effects of Reducing Pesticide Use

A substantial reduction in pesticides might increase food costs only slightly

David Pimentel, Lori McLaughlin, Andrew Zepp, Benyamin Lakitan, Tamara Kraus, Peter Kleinman, Fabius Vancini, W. John Roach, Ellen Graap, William S. Keeton, and Gabe Selig

Several studies suggest that it is technologically feasible to reduce pesticide use in the United States 35 to 50% without reducing crop yields (NAS 1989, OTA 1979). Denmark developed an action plan in 1985 to reduce pesticide use by 50% before 1997.[1] Sweden also approved a program in 1988 to reduce pesticide use by 50% within 5 years (NBA 1988). The Netherlands is developing a program to reduce pesticide use 50% in 10 years.[2] These proposals, along with the conclusion by Huffaker (1980) that the United States overuses pesticides, prompted us to investigate the feasibility of reducing the US annual use of synthetic organic pesticides by approximately one-half.

Farmers use an estimated 320 million kg (700 million lb) of pesticides annually at an approximate cost of $4.1 billion (Table 1). Indeed, investment in pesticide controls has been shown to provide significant economic benefits. Dollar returns for the direct benefits to farmers have been estimated to range from $3 to $5 for every $1 invested in the use of pesticides (Headley 1968, Pimentel et al. 1978). However, these cost figures do not reflect the indirect costs of pesticide chemical use such as human pesticide poisonings, reduction of fish and wildlife populations, livestock losses, destruction of susceptible crops and natural vegetation, honeybee losses, destruction of natural enemies, evolved pesticide resistance, and creation of secondary pest problems (Pimentel et al. 1980). Moreover, the economic benefits have been calculated for current agricultural practices, some of which actually increase pest problems. The direct and indirect benefits and costs of using pesticides in agriculture are complex.

There are many opportunities to reduce pesticide use

The objective of this article is to estimate the potential agricultural and environmental benefits and costs of reducing pesticide use by approximately 50% in the United States. To estimate the costs and benefits, we examine current pesticide use patterns in approximately 40 major US crops; evaluate current crop losses to pests; estimate the agricultural benefits and costs of reducing pesticide use by substituting currently available biological, cultural, and environmental pest-control technologies for some current pesticide-control practices; and assess the public health and environmental costs associated with reduced pesticide use.

Extent of pesticide use

Of the estimated 434 million kg of pesticides used annually in the United States, 69% are herbicides, 19% insecticides, and 12% fungicides (Table 1). The 320 million kg of pesticides used in agriculture are applied at an average rate of approximately 3 kg/ha to approximately 114 million ha—62% of the 185 million ha that are planted (Pimentel and Levitan 1986). Thus a significant portion (38%) of crops receives no pesticides.

The application of pesticides for pest control is not evenly distributed among crops. Overall, 93% of the hectarage of row crops, such as corn, soybeans, and cotton, is treated with some type of pesticide (Pimentel and Levitan 1986). In contrast, less than 10% of forage crop hectarage is treated.

Herbicides are currently being used on approximately 90 million ha in the United States—greater than half of the nation's cropland. Field corn alone accounts for 53% of agricultural herbicide use, and almost three-quarters of the herbicide is applied to corn and soybeans.

The unequal distribution is similar in insecticide use. Of the approximately 62 million kg of insecticides applied to 5% of the total agricultural land (Table 1), approximately 25% is used on cotton and corn. Some crops are treated as many as 20 times per

David Pimentel is a professor of insect ecology; Lori McLaughlin, Andrew Zepp, and Benyamin Lakitan are graduate students; and Tamara Kraus, Peter Kleinman, Fabius Vancini, W. John Roach, Ellen Graap, William S. Keeton, and Gabe Selig are undergraduate students in the College of Agriculture and Life Sciences, Cornell University, Ithaca, NY 14853.

[1] B. B. Mogensen, 1989, personal communication. National Environmental Research Institute, Copenhagen, Denmark.

[2] A. Pronk, 1990, personal communication. Wageningen Agriculrural University, Wageningen, The Netherlands.

season (e.g., apples and cotton), whereas other crop hectares may be treated only once (e.g., corn and wheat).

Insecticide use also varies considerably among geographic regions. Warm regions of the United States often suffer intense pest problems. For example, although only 13% of the alfalfa hectarage in the United States is treated with insecticides, 89% of the alfalfa area in the Southern Plains states is treated to control insect pests (Eichers et al. 1978). In the Mountain region, where large quantities of potatoes are grown, 65% of the potato cropland receives insecticide treatment, but in the Southeast, where only early potatoes are grown, 100% of the potato cropland receives treatment (USDA 1975). Cotton insect pests such as the boll weevil are also more of a problem in the Southeast than in other regions (USDA 1983). In the Southeast and Delta states, 84% of the cotton cropland receives treatment, whereas in the Southern Plains region less than half of the crop (40%) is treated.

Fungicides are primarily used on fruit and vegetable crops (Pimentel and Levitan 1986). Approximately 95% of grapes and 97% of potato hectarage are treated with fungicides, whereas neither corn nor wheat hectarage is treated.

Crop losses and changes in agricultural technologies

Since 1945, the use of synthetic pesticides in the United States has grown 33-fold (Figure 1). The increase is largely due to changes in agricultural practices and cosmetic standards (Pimentel et al. 1977). At the same time, some new pesticides have at least tenfold greater effectiveness than older pesticides (Pimentel et al. 1991). For example, in 1945 DDT was applied at a rate of approximately 2 kg/ha. Today, similarly effective insect control is achieved with pytethroids and aldicarb applied at 0.1 kg/ha and 0.05 kg/ha, respectively.

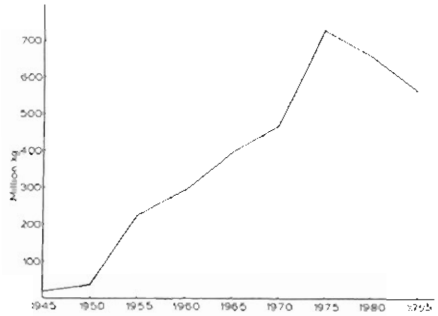

Figure 1. The amounts of synthetic pesticides (insecticides, herbicides, and fungicides) produced in the United States (Pimentel et al. 1991). Approximately 90% is sold in the United States. The decline in total amount produced is in large part due to the ten- to 100-fold increase in toxicity and effectiveness of new pesticides.

Currently, an estimated 37% of all crop production is lost annually to pests (13% to insects, 12% to plant pathogens, and 12% to weeds) in spite of the use of pesticides and nonchemical controls (Pimentel 1986). Although pesticide use has increased during the past four decades, crop losses have not shown a concurrent decline. According to survey data collected from 1942 to the present, losses from weeds have fluctuated with an overall slight decline, due to improved chemical, mechanical, and cultural weed-control practices, from 14% to 12% (Table 2). During that same period, US losses from plant pathogens, including nematodes, increased slightly, from 10.5% to approximately 12.0%. This increase results in part from reduced sanitation (because fungicides can substitute for sanitation), higher cosmetic standards, and abandonment of crop-rotation practices.

The share of crop yields lost to insects has nearly doubled during the last 40 years (Table 2), despite more than a tenfold increase in both the amount and toxicity of synthetic insecticide used (Pimentel et al. 1991). The increase in crop losses due to insects per hectare has been offset by increased crop yield obtained with higher-yielding varieties and greater use of fertilizers and other inputs, such as fertilizers, irrigation, and high-yielding crop varieties (USDA 1989).

This increase in crop losses despite intensified insecticide use is due to several major changes that have taken place in agricultural practices (Pimentel et al. 1991). These changes include:

- the planting of some crop varieties that are more susceptible to insect pests;
- the destruction of natural enemies of certain pests, which creates the need for additional pesticide treatments;
- the increase in pests resistant to pesticides;
- the reduction in crop-rotation practices;
- the increase in monocultures and the resultant reduced crop diversity;
- the lowering of Food and Drug Administration tolerance for insects and insect parts in foods and the enforcement of more stringent cosmetic standards by fruit and vegetable processors and retailers;
- the increased use of aircraft application technology;
- the reduction in sanitation, including less attention to the destruction of infected fruit and crop residues;
- the reduction in tillage, with more crop residues left on the land surface;

Table 1. US hectarage treated with pesticides (modified from Pimentel and Levitan 1986). Numbers are in millions.

		All pesticides		Herbicides		Insecticides		Fungicides	
Land-use category	Total hectares	Treated hectares	Quantity	Treated hectares	Quantity	Treated hectares	Quantity	Treated hectares	Quantity
Agricultural	472	114	320	86	220	22	62	4	38
Government and industrial	150	28	55	30	44	NA	11	NA	NA
Forest	290	2	4	2	3	<1	1	NA	NA
Household	4	4	55	3	26	3	25	1	4
Total	916	148	434	121	293	26	99	5	42

Total for hectarage treated with herbicides, insecticides, and fungicides exceeds total treated hectares because the same land area can be treated several times with several classes of chemicals. NA, not available.

- the planting of crops in climatic regions in which they are more susceptible to insect attack;
- the use of herbicides that have been found to alter the physiology of crop plants, making them more vulnerable to insect attack.

Estimated benefits/costs from reduced pesticide use

A reduction in US pesticide use would require substituting nonchemical alternatives for chemical pest control and improving the efficiency of pesticide application technology. Such changes in some cases increase and in other cases decrease pest control costs.

Crop losses to pests. Losses from pests for 40 major crops grown with pesticides have been estimated by examining data on current crop losses, by reviewing loss data based on experimental field tests, and by consulting pest control specialists. Combining these data, however, has often been difficult. For example, data based on published experimental field tests usually emphasize the benefits of pesticide use; thus loss data associated with pesticide treatments usually emphasize benefits over costs (Pimentel et al. 1978).

In addition, field tests often exaggerate total crop losses because assessments of insect, disease, and weed losses are carried out separately and then combined. For example, on untreated apples, insects were reported to cause a 50–100% crop loss, disease 50%–60%, and weeds 6% (Ahrens and Cramer 1985, Pimentel et al. 1991). This approach yields an estimated total loss of approximately 140% from all pests combined! A more accurate estimate of losses in the absence of pesticides ranges from 80% to 90% based on current cosmetic standards (Ahrens and Cramer 1985). Exactly how much overlap exists among insect, disease, and weed-loss figures for apples and for other crops is not known.

Our analysis has other important limitations. The figures for current crop losses to pests, despite pesticide use, are based primarily on US Department of Agriculture data and other estimates obtained from specialists. We emphasize that these are estimates. For certain crops, little or no experimental data are available concerning yields with pesticide use and various alternatives. In addition, in some cases recent data were not available. With these crops, our estimates were generally extrapolated from data on closely related crops.

Although we recognize the limitations of the data used in this analysis, we believe there is a need to assemble available information to provide a first approximation of the potential for reducing pesticide use by one-half. We hope that better data will be available in the future, so that a more complete analysis of pesticide costs and benefits can be made.

Reduction of the risks associated with pesticides is in itself a complicated issue, particularly because environmental and health trade-offs are often associated with changes in technology. Because of the complexity of these trade-offs, they could not be included in the analysis. One example, however, involves the conflict between reducing pesticide use and promoting soil conservation through the use of no-till culture as well as reduced tillage. Although no-till and reduced-till culture significantly reduce soil erosion (Van Doren et al. 1977), they also significantly increase the need for herbicides, insecticides, and fungicides (Taylor et al. 1984).

However, although reducing pesticide use may require reducing the use of some no-till systems, highly cost-effective soil conservation alternatives to no-till do in fact exist. These include ridge-till, crop rotations, strip cropping, contour planting, terracing, windbreaks, mulches, cover crops, and green mulches (Moldenhauer and Hudson 1988). Ridge-planting, for example planting the crop on permanent ridges 20 cm high along the contour, is rapidly growing in popularity as an effective replacement for no-till practices for most row crops. It is a form of reduced-till that has many advantages over no-till (Forcella and Lindstrom 1988). For example, ridge-till can be employed without the use of herbicides, and it controls soil erosion more effectively than no-till (Russnogle and Smith 1988).[3]

Techniques to reduce pesticide use. The increase in crop losses associated with recent changes in agricultural practices suggests that some alternative strategies exist that might reduce pesticide use. Two important practices that apply to all agricultural crops include widespread use of monitoring and improved application equipment. Currently, a significant number of pesticide treatments are applied unnecessarily and at improper times due to a lack of treat-when-necessary programs. Furthermore, pesticide is unnecessarily lost during application (e.g., only 25–50% of the pesticide applied by aircraft actually reaches the target area; Akesson and Yates 1984, Mazariegos 1985). By increasing monitoring and improving application equipment, more efficient pest control can be achieved.

Insecticides

Corn and cotton account for approximately 25% of the total insecticide use in agriculture. Thus reducing insecticide use in these two crops by substituting nonchemical alternatives would contribute significantly to a reduction in insecticide use.

Corn. During the early 1940s, little or no insecticide was applied to corn, and losses to insects were only 3.5%

Table 2. Comparison of annual pest losses* in the United States. (After Pimentel et al. 1990.)

Period	Percentage of crops lost to pests				Crop value lost (billion dollars)
	Insects	Diseases	Weeds	Total	
1989	13.0	12.0	12.0	37	150
1974	13.0	12.0	8.0	33.0	77
1951–1960	12.9	12.2	8.5	33.6	30
1942–1951	7.1	10.5	13.8	31.4	27
1910–1935	10.5	NA	NA	NA	6
1904	9.8	NA	NA	NA	4

*Not adjusted for inflation.
NA = Not available.

[3]R. Thompson, 1985, personal communication. Farmer, Boone, IA.

(USDA 1954). Since then, insecticide use on corn has grown more than 1000-fold, whereas losses due to insects have increased to 12% (Ridgway 1980). This increase in insecticide use and the 3.4-fold increase in corn losses to insects are primarily due to the abandonment of crop rotation (Pimentel et al. 1991). Today approximately 40% of US corn is grown continuously, with 11 million kg of insecticide applied annually (Pimentel et al. 1991). By reinstituting crop rotations, large reductions in pesticide use could be achieved. Rotating corn with soybeans or a similar high-value crop generally increases yields and net profits (Helmers et al. 1986), although rotating corn with wheat or other low-value crops reduces net profits per hectare. From a more comprehensive perspective, however, the rotation of corn with other crops has several advantages, including reducing weed and plant-pathogen losses and decreasing soil erosion and rapid water-runoff problems (Helmers et al. 1986).

By combining crop rotations with the planting of corn resistant to the corn borer and chinch bug, it would be possible to avoid 80% of insecticide use on corn while concurrently reducing insect losses (Schalk and Ratcliffe 1977). Such a move is estimated to increase the cost of corn production by $10 per hectare above the current costs of corn grown continuously (Pimentel et al. 1991). A new approach, in which an attractant combined with insecticides fights rootworm, has been reported to reduce insecticide requirements 99% (Paul 1989).[4]

Cotton. The potential for reducing pesticide use in US agriculture is well illustrated by changes in insecticide use in Texas cotton production. Since 1966, insecticide use in Texas cotton has been reduced by almost 90% (OTA 1979). The technologies adopted to reduce insecticide use were: monitoring pest and natural enemy populations to determine when to treat, biological control, host-plant resistance, stalk destruction (sanitation), uniform planting date, water management, fertilizer management, rotations, clean seed, and changed tillage practices (King et al. 1986, OTA 1979).

[4]R. B. Metcalf, 1990, personal communication. University of Illinois, Champaign.

Table 3. Current and potential reduced use of pesticides in US crops. Total current pesticide costs plus total added alternative control costs (Pimentel et al. 1991).

	Pesticide use (million kg)		Cost (million dollars)	
	Current	Potential reduced	Total	Added alternative control
Insecticides	62.1	27.2	$ 817.8	156.5
Herbicides	219.6	98.9	3115.8	845.3
Fungicides	37.6	26.6	207.4	16.5
Total	319.3	152.7	4141.0	1018.3

Currently, a total of 29 million kg of insecticide is applied to cotton, and it is estimated that this amount could be reduced by approximately 40% through the use of readily available technologies (Pimentel et al. 1991). By effectively using a monitoring program, one might reduce insecticide use by approximately 20%. Through the use of pest-resistant cotton varieties and the alteration of planting dates in most growing regions, insecticide use could be reduced by another 3% (Frans 1985, Frisbie 1985). An additional 10% reduction in insecticide use could be achieved through the replacement of the price-support program with a free-land market (without commodity and price-support programs) and no price-support program for cotton production (NAS 1989). This change would allow cotton to be grown in regions with fewer insect pests, thus reducing the need for insecticide use. However, changing the current price-support program to allow society to take advantage of these benefits is politically unattractive.

The amount of insecticide reaching target areas could be increased by changing the type of application equipment employed, especially reducing the use of aircraft ultra-low-volume application equipment, which wastes 75% of pesticide applied. The amount of insecticide waste could be reduced by 25% if ground-application instead of air-application equipment were used (Mazariegos 1985, Pimentel and Levitan 1986). In addition, covering the spray boom with a plastic shroud can further decrease drift 85% (Ford 1986), thereby allowing for an additional reduction in pesticide use.

Insecticide use on cotton might be reduced by another 6% through the implementation of other pest-control techniques, including cultivation of short-season cotton, fertilizer and water management, improved sanitation, crop rotations, the use of crop seed cleaned of weed seeds during culture and processing, and altered tillage practices (Grimes 1985, OTA 1979). Depending on the particular environment, insecticide use on cotton might even be reduced much more. For example, Shaunak et al. (1982) reported that insecticide use in the Lower Rio Grande Valley of Texas could be reduced 97% by planting short-season cotton under dryland conditions. This practice also resulted in a twofold increase in net profits over conventional methods.

Thus, by implementing combinations of monitoring, application technology, short-season cotton, fertilizer and water management, improved sanitation, crop rotations, and tillage practices in cotton, insecticide use might be reduced 40%. These alternative controls should pay for themselves through reduced insecticide and application costs.

Herbicides

Corn and soybeans account for approximately 70% of the total herbicide applied in agriculture (Pimentel and Levitan 1986). We use these crops to illustrate the potential of decreasing herbicide use.

Corn. More than half (53%) of the herbicides used on crops are applied to corn (Pimentel and Levitan 1986). More than 3 kg of herbicide are applied per hectare of corn, and more than 90% of the corn hectarage planted is treated. By not requiring total elimination of weeds, in some cases herbicide use can be reduced by 75% (Schweizer 1989). At present, 91% of the corn land is also culti-

Table 4. Total estimated environmental and social costs for pesticides in the United States. (Modified and updated from Pimentel et al. 1980.)

Environmental factor	Cost ($ millions)
Human pesticide poisonings	250
Animal pesticide poisonings and contaminated livestock products	15
Reduced natural enemies	150
Pesticide resistance	150
Honeybee poisonings and reduced pollination	150
Losses of crops and trees	75
Fishery and wildlife losses	15
Government pesticide pollution regulations	150
Monitoring wells and groundwater	1200
Total	2155

vated to help control weeds (Duffy 1982).

The average costs and returns per hectare to no-till, reduced-till, and conventional-till culture have actually been found to be quite similar (Duffy and Hanthorn 1984). For example, added labor, fuel, and machinery costs for conventional-till practices for corn were approximately $24/ha higher than those for no-till. However, the costs for the added fertilizers, pesticides, and seeds in the no-till system were $22/ha higher than conventional-till (Duffy and Hanthorn 1984).

It might be possible to reduce herbicide use on corn by approximately 60% if the use of mechanical cultivation and rotations were increased (Forcella and Lindstrom 1988). Corn and soybean rotations have been found to provide substantially higher returns than either crop grown separately and continuously (Helmers et al. 1986). However, we estimate that weed control costs will increase by approximately 30%, because not all alternative practices and rotations are profitable.

Soybeans. The second-largest amount of herbicides is applied to soybeans, with approximately 96% of soybean hectarage receiving treatment for weed control; 96% of the hectarage also receives some tillage and mechanical cultivation for weed control (Duffy 1982). Several techniques have been developed that increase the efficiency of chemical applications. The rope-wick applicator has been used in soybeans to reduce herbicide use approximately 90%, and this applicator was found to increase soybean yields 51% over conventional treatments (Dale 1980). Also, a new model of recirculating sprayer saves 70–90% of the spray emitted that is not trapped by the weeds (Matthews 1985). Spot treatments are a third method of decreasing unnecessary pesticide applications.

In addition, alternative techniques are available to reduce the need for herbicide use on soybeans. These include ridge-till, tillage, mechanical cultivation, row spacing, planting date, tolerant varieties, crop rotations, spot treatments, and reduced dosages (Forcella and Lindstrom 1988, Helmers et al. 1986, Russnogle and Smith 1988, Tew et al. 1982). Employing several of these alternative techniques in combination might reduce herbicide use in soybeans by approximately 60%. Despite the results of Tew et al. (1982) that indicate no added control costs for the alternatives, we estimate that the costs of weed control would increase $10/ha (Pimentel et al. 1991).

Fungicides

In considering the possible reduction of fungicide use, apples and potatoes were selected as examples. These two crops account for 26% of all the fungicides used in agriculture (Pimentel et al. 1991).

Apples. Most fungicides are applied to apples, peaches, citrus, and other fruit crops (Pimentel and Levitan 1986). Integrated pest management data from apples in New York State suggest that fungicide use on apples could be reduced approximately 10% by monitoring and better forecasting of disease based on weather data (Kovach and Tette 1988).

In addition, a recent design in spray nozzle and application equipment demonstrated that the amount of fungicide applied for apple scab control could be reduced by 50% (Van der Scheer 1984). Thus, by employing better weather forecasting and improved application technology combined with scouting, fungicide use on apples could be reduced an estimated 20% (Pimentel et al. 1991).

Potatoes. Approximately 96% of potato hectarage is treated with fungicides (Pimentel et al. 1991). Without fungicide treatments, losses from diseases ranged from 5% to 25% depending on the year, weather, and pathogen spread, whereas losses with fungicide treatments were reported to be approximately 20% in a controlled experiment (Teng and Bissonnette 1985). Shields et al. (1984) reported that the planting of short-season potatoes in Wisconsin reduced the number of required fungicide applications by one-third.

Correct storage, handling, and planting of seed tubers and proper management of soil moisture and fertility minimize losses to most diseases (Rich 1991). Forecasting and monitoring might also be employed to reduce fungicide use 15–25% (Royle and Shaw 1988). Monitoring should concentrate on disease incidence and forecasting weather conditions so fungicides can be applied before infection outbreak. Employing a combination of these controls, it might be possible to reduce fungicide use on potatoes approximately one-third, at an estimated cost of $5/ha (Pimentel et al. 1991).

Overall pesticide-reduction assessment

By substituting nonchemical alternatives for some pesticides used on 40 major crops, we estimate that total agricultural pesticide use can be reduced by approximately 50% (Pimentel et al. 1991). The added costs for implementing these alternatives are estimated to be approximately $1 billion (Table 3). These alternatives would increase total pest-control costs approximately 25% and would increase total food production costs at the farm 0.6%.

If alternative technologies that result in reduced crop yields became acceptable, the assessment of benefit and cost relationships would be quite different. For example, each 1.0% decrease in crop yield in agriculture results in a corresponding 4.5% increase in the farm price of goods.[5] It is also important to note that over-

[5]D. Sisler, 1988, personal communication. Cornell University, Ithaca, NY.

production is the prime reason that the United States spends $26 billion annually on price supports (USOMB 1989). Thus, if changes in pest control did in fact reduce yields, it might both increase farm income and decrease government subsidy expenses.

Environmental and health aspects

Society now pays a high price for its use of pesticides. Pesticide-control measures cost approximately $4.1 billion annually, not including the indirect environmental and public-health costs, which total more than $2.2 billion annually (Pimentel et al. 1991).

Perhaps the most serious social and environmental costs related to pesticide use are the human pesticide poisonings. Annually approximately 20,000 accidental poisonings occur, mostly from agricultural pesticides, with 2000 cases requiring hospitalization.[6] These poisonings result in approximately 50 fatalities per year. Pesticides are also implicated in numerous other human diseases, including cancer and sterility. An estimated 6000 human cases of pesticide-induced cancer occur each year (EPA 1987).

The costs of human poisonings and other detrimental environmental effects of pesticide use are delineated in Table 4:

- A large number of domestic animals are poisoned each year by pesticides. Significant amounts of meat and milk are contaminated with pesticides and must be destroyed.
- When pesticides are applied to crops, natural enemies important for controlling some pests are frequently destroyed (OTA 1979). This destruction causes pest outbreaks that must be controlled with additional pesticide applications.
- The development of pesticide resistance in pest populations is another major environmental problem. This resistance requires additional pesticide treatments and more costly controls.
- Large numbers of honeybees and wild bees are poisoned by pesticides, resulting in honey losses and reduced crop pollination.
- Some pesticides, especially when applied by aircraft, drift onto adjacent agricultural lands and damage or destroy crops and forest resources.
- Significant numbers of fish and other wildlife are killed by pesticides each year.
- The government program that attempts to regulate and limit pesticide pollution also incurs major administrative costs (Pimentel et al. 1991).
- Monitoring wells and groundwater for pesticide contamination is costly (Nielsen and Lee 1987).

This analysis is an incomplete assessment of the existing environmental problems caused by pesticide use. There is no completely satisfactory way to summarize all of the environmental and social costs or benefits in terms of dollars. For example, it is impossible to place a monetary value on human death, disease, or disability.

The nearly $1 billion attributed to environmental and social costs (Pimentel et al. 1980) represents only a small portion of the actnal costs. A more complete accounting of the indirect costs would also include unrecorded losses of fish, wildlife, crops, and trees; losses resulting from the destruction of soil invertebrates, microflora, and microfauna; even higher costs of human poisonings; chronic health problems such as cancer; groundwater contamination; and contamination of human food other than livestock products (Blume 1987). If the full environmental and social costs could be estimated, the total cost could rise to as much as $4 billion annually.

Although the nonchemical alternative controls proposed as substitutes for pesticides in this study are significantly safer than pesticides, the alternatives themselves may cause some social and envitonmental problems (Pimentel et al. 1984). However, if one assumes that reducing pesticide use by 50% might also eventually reduce the environmental and public health risks from pesricides by approximately one-half, then the added costs for the nonchemical alternatives ($1 billion) might be offset by the reduced environmental and public health risks.

Conclusions

Pesticides cause serious public health problems and considerable damage to agricultural and natural ecosystems. A conservative estimate suggests that the environmental and social costs of pesticide use in the United States are at least $2.2 billion annually, and the actual cost is probably double this amount. In addition to these costs, the nation spends $4.1 billion annually to treat crops with 320 million kg of pesticides.

This article confirms previous reports that it is feasible to reduce pesticide use by one-half. The cost is estimated at $1 billion. Such a finding supports the projections of the Office of Technology Assessment (1979) and the National Academy of Sciences (1989), as well as the policies adopted by the Danish and Swedish governments intended to reduce pesticide use 50%.

The 50% pesticide reduction in our current assessment would help satisfy the concerns of the majority of the public, who worry about pesticide levels in their food as well as damage to the environment (Sachs et al. 1987). If pesticide use were reduced by one-half without any decline in crop yield, the total price increase in purchased food, due to increased costs of alternative controls, is calculated to be only 0.6%. If assured that pesticides in food and the environment were greatly reduced, it is likely that the public would be willing to pay this slight increase in food costs.

Higher cosmetic standards have resulted in greater quantities of pesticides being applied to food crops. The rapidly growing use of pesticides for cosmetic purposes is detrimental to both public health and the environment, and it is also contrary to public demand (Pimentel et al. 1977). The public would accept some reduction in cosmetic standards if it would result in a reduction in pesticide contamination of food (Healy 1989). This acceptance is indicated by the growing popularity of organic food

[6]J. Blondell, 1989, personal communication. US Environmental Protection Agency, Washington, DC.

stores and supermarkets that guarantee pesticide-free foods (Hammit 1986, Poe 1988). Furthermore, the presence of parts of soft-bodied insects in highly processed foods, such as catsup and applesauce, carries no risk to public health and even is of some nutritional value (Pimentel et al. 1977).

To estimate more accurately the potential of reduced pesticide use, more data are needed, especially concerning those agricultural technologies that have contributed to the increase in pesticide use during the past 40 years while simultaneously increasing crop losses to pests. We hope that more complete data will be assembled so that more detailed analyses can be made.

Implementing a program to reduce pesticide use in agriculture will require the combined education of farmers and the public and some new regulations. In addition, it will require that the federal government revise current policies, like its commodity and price-support program, that prevent farmers from employing crop rotations and other sound agricultural practices (NAS 1989). Several current government policies actually increase pest problems and pesticide use (NAS 1989).

At the same time, a greater investment is needed in research on alternative pest-control practices. Many opportunities exist to reduce pesticides through the implementation of new environmental, cultural, and biological pest controls (Pimentel 1991). We strongly support the National Academy of Sciences' research recommendations for alternative pest controls (NAS 1989).

If the public is concerned about pesticides contaminating their food and environment, do the small economic costs of reducing pesticide use outweigh the ecological and public health benefits? We hope that the public and state and federal governments will investigate the ecology, economics, and ethics of pesticide reduction in agriculture. A careful assessment must be made to evaluate the benefits and risks of pesticides and nonchemical alternatives for society.

Acknowledgments

We thank the following people for reading an earlier draft of this article, for their many helpful suggestions, and, in some cases, for providing additional information: B. Barclay and M. El-Ashry, World Resources Institute; R. Frans, University of Arkansas; J. Hatchett, Kansas State University; M. Harris, Texas A&M University; H. Hokkanen, Agricultural Research Centre, Jokioinen, Finland; D. Horn, Ohio State University; C. Huffaker, University of California, Berkeley; H. Janzen, Agriculture Canada; P. Johnson, University of New Hampshire; F. McEwen, University of Guelph; B. Mogensen, National Environmental Research Institute, Denmark; I. Oka, Bogor Research Institute for Field Crops, Indonesia; C. Osteen, USDA, Washington, DC; M. Pathak, International Rice Research Institute, Philippines; J. Pierce, Environmental Action, Washington, DC; E. Radcliffe, University of Minnesota; J. Schalk, USDA Vegetable Lab, Charleston, NC; D. Wen, Chinese Academy of Sciences; K. Stoner, Connecticut Agricultural Experiment Station; G. Surgeoner, University of Guelph; and G. Teetes, Texas A&M University. We also thank T. Dennehy, E. Glass, R. Roush, J. Tette, and C. Wien at Cornell University. We gratefully acknowledge the partial support of this study by a William and Flora Hewlett Foundation Grant to the Centre for Environmental Research, Cornell University.

References cited

Ahrens, C., and H. H. Cramer. 1985. Improvement of agricultural production by pesticides. Pages 151–162 in F. P. W. Winteringham, ed. *Environment and Chemicals in Agriculture*. Elsevier, New York.

Akesson, N. B., and W. E. Yates. 1984. Physical parameters affecting aircraft spray application. Pages 95–115 in W. Y. Garner and J. Harvey, eds. *Chemical and Biological Controls in Forestry*. American Chemical Society Series 238, Washington, DC.

Blume, E. 1987. Poisoned peaches, toxic tomatoes: reckoning pesticide risks. *Nutrition Action News Letter* October: 8–9.

Dale, J. E. 1980. Rope wick applicator—tool with a future. *Weeds Today* 11(2): 3–4.

Duffy, M. 1982. Pesticide use and practices, 1982. Economic Research Service, Agricultural Information Bulletin No. 462, US Department of Agriculture, Washington, DC.

Duffy, M., and M. Hanthorn. 1984. Returns to corn and soybean tillage practices. Economic Research Service, Agricultural Economic Report No. 508, US Department of Agriculture, Washington, DC.

Eichers, T. R., P. A. Andrilenas, and T. W. Anderson. 1978. Farmers' use of pesticides. Economic and Statistical Cooperative Service, Agricultural Economic Report No. 418, US Department of Agriculture, Washington, DC.

Environmental Protection Agency (EPA). 1987. Unfinished business: a comparative assessment of environmental problems. Appendix #1. EPA, Washington, DC.

Forcella, F., and M. J. Lindstrom. 1988. Movement and germination of weed seeds in ridge-till crop production systems. *Weed Sci.* 36: 56–59.

Ford, R. J. 1986. Field trials of a method for reducing drift from agricultural sprayers. *Can. Agric. Eng.* 28: 81–83.

Frans, R. 1985. A summary of research achievements in cotton. Pages 53–61 in R. E. Frisbie and P. L. Adkisson, eds. *Integrated Pest Management on Major Agricultural Systems*. Texas Agricultural Experiment Station, College Station.

Frisbie, R. 1985. Regional implementation of cotton IPM. Pages 638–651 in R. E. Frisbie and P. L. Adkisson, eds. *Integrated Pest Management on Major Agricultural Systems*. Texas Agricultural Experiment Station, College Station.

Grimes, D. W. 1985. Cultural techniques for management of pests in cotton. Pages 365–382 in R. E. Frisbie and P. L. Adkisson, eds. *Integrated Pest Management on Major Agricultural Systems*. Texas Agricultural Experiment Station, College Station.

Hammit, J. K. 1986. Estimating consumer willingness to pay to reduce food-borne risk. Rand Corporation, Santa Monica, CA.

Headley, J. C. 1968. Estimating the production of agricultural pesticides. *Am. J. Agr. Econ.* 50: 13–23.

Healy, M. 1989. Buyers prefer organic food. *USA Today* 20 March 1989.

Helmers, G. A., M. R. Langemeir, and J. Atwood. 1986. An economic analysis of alternative cropping systems for east-central Nebraska. *American Journal of Alternative Agriculture* 4: 153–158.

Huffaker, C. B. 1980. *New Technology of Pest Control*. John Wiley & Sons, New York.

King, E. G., J. R. Phillips, and R. B. Head. 1986. Thirty-ninth annual conference report on cotton insect research and control. Pages 126–135 in *Proceedings of the Beltwide Cotton Production Research Conference*. National Cotton Council, Memphis, TN.

Kovach, J., and J. P. Tette. 1988. A survey of the use of IPM by New York apple producers. *Agric. Ecosyst. & Environ.* 20: 101–108.

Matthews, G. A. 1985. Application from the ground. Pages 93–117 in P. T. Haskell, ed. *Pesticide Application: Principles and Practice*. Clarendon Press, Oxford, UK.

Mazariegos, F. 1985. The use of pesticides in the cultivation of cotton in Central America. *UNEP Industry and Environment* July/August/September: 5–8.

Moldenhauer, W. C., and N. W. Hudson, eds. 1988. *Conservation Farming on Steep Lands*. Soil and Water Conservation Society, Ankeny, IA.

National Academy of Sciences (NAS). 1989. *Alternative Agriculture*. National Academy Press, Washington, DC.

National Board of Agriculture (NBA). 1988. Action programme to reduce the risks to health and the environment in the use of pesticides in agriculture. General Crop Production Division, NBA, Stockholm, Sweden.

Nielsen, E. G., and L. K. Lee. 1987. The magnitude and costs of groundwater contamination from agricultural chemicals. US Department of Agriculture Economic Research Service, National Research Economics Division, Staff Report AGES 870318, Washington, DC.

Office of Technology Assessment (OTA). 1979. *Pest Management Strategies. vol. II. Working papers.* OTA, Washington, DC.

Paul, J. 1989. Getting tricky with rootworms. *Agrichemical Age* 33(3): 6–7.

Pimentel, D. D. 1986. Agroecology and economics. Pages 299–319 in M. Kogan, ed. *Ecological Theory and Integrated Pest Management Practice.* John Wiley & Sons, New York.

Pimentel, D., ed. 1991. *Handbook of Pest Management in Agriculture.* CRC Press, Boca Raton, FL.

Pimentel, D., D. Andow, R. Dyson-Hudson, D. Gallahan, S. Jacobson, M. Irish, S. Kroop, A. Moss, I. Schreiner, M. Shepard, T. Thompson, and B. Vinzant. 1980. Environmental and social costs of pesticides: a preliminary assessment. *Oikos* 34: 127–140.

Pimentel, D., C. Glenister, S. Fast, and D. Gallahan. 1984. Environmental risks of biological pest controls. *Oikos* 42: 283–290.

Pimentel, D., J. Krummel, D. Gallahan, J. Hough, A. Merrill, I. Schreiner, P. Vittum, F. Koziol, E. Back, D. Yen, and S. Fiance. 1978. Benefits and costs of pesticide use in United States food production. *BioScience* 28: 772, 778–784.

Pimentel, D., and L. Levitan. 1986. Pesticides: amounts applied and amounts reaching pests. *BioScience* 36: 86–91.

Pimentel, D., L. McLaughlin, A. Zepp, B. Lakitan, T. Kraus, P. Kleinman, F. Vancini, W. J. Roach, E. Graap, W. S. Keeton, and G. Selig. 1991. Environmental and economic impacts of reducing U.S. agricultural pesticide use. Pages 679–718 in D. Pimentel, ed. *Handbook of Pest Management in Agriculture.* vol. 1. CRC Press, Boca Raton, FL.

Pimentel, D., E. C. Terhune, W. Dritschilo, D. Gallahan, N. Kinner, D. Nafus, R. Peterson, N. Zareh, J. Misiti, and O. Haber-Schaim. 1977. Pesticides, insects in foods, and cosmetic standards. *BioScience* 27: 178–185.

Poe, C. A. 1988. Where cleanliness means profits. *Time* September 5: 51.

Rich, A. E. 1991. Potato diseases. Pages 623–676 in D. Pimentel, ed. *Handbook of Pest Management in Agriculture.* vol. 3. CRC Press, Boca Raton, FL.

Ridgway, R. 1980. Assessing agricultural crop losses caused by insects. Pages 229–233 in *Crop Loss Assessment: Proceedings of the E. C. Stakman Commemorative Symposium.* University of Minnesota, St. Paul.

Royle, D. J., and M. W. Shaw. 1988. The costs and benefits of disease forecasting in farming practice. Pages 231–246 in B. C. Clifford and E. Lester, eds. *Control of Plant Diseases: Costs and Benefits.* Blackwell Scientific, Palo Alto, CA.

Russnogle, J., and D. Smith. 1988. More dead weeds for your dollar. *Farm J.* 112(2): 9–11.

Sachs, C., D. Blair, and C. Richter. 1987. Consumer pesticide concerns: a 1965 and 1984 comparison. *Journal of Consumer Affairs* 21: 96–107.

Schalk, J. M., and R. H. Ratcliffe. 1977. Evaluation of the United States Department of Agriculture program on alternative methods of insect control: host plant resistance to insects. *FAO Plant Prot. Bull.* 25: 9–14.

Schweizer, E. E. 1989. Weed free fields not key to highest profits. *Agric. Res.* May: 14–15.

Shaunak, R. K., R. D. Lacewell, and J. Norman. 1982. Economic implications of alternative cotton production strategies in the lower Rio Grande Valley of Texas, 1923–1978. Texas Agricultural Experiment Station B-1420, College Station.

Shields, E. J., J. R. Hygnstrom, D. Curwen, W. R. Stevenson, J. A. Wyman, and L. K. Binning. 1984. Pest management for potatoes in Wisconsin—a pilot program. *Am. Pot. J.* 61: 508–516.

Taylor, F., G. S. V. Raghaven, S. C. Negi, E. McKyes, B. Vigier, and A. K. Watson. 1984. Corn grown in a Ste. Rosalie clay under zero and traditional tillage. *Can. Agric. Eng.* 26: 91–95.

Teng, P. S., and H. L. Bissonnette. 1985. Potato yield losses due to early blight in Minnesota fields, 1981 and 1982. *Am. Pot. J.* 62: 619–628.

Tew, B. V., M. E. Wetzstein, J. E. Epperson, and J. D. Robertson. 1982. Economics of selected integrated pest management production systems in Georgia. University of Georgia College Agricultural Experiment Station Research Report 395, Athens.

United States Department of Agriculture. 1954. *Losses in Agriculture.* Agricultural Research Service 20-1, Washington, DC.

______. 1975. Farmers' use of pesticides in 1971. . . extent of crop use. Economic Research Service, Agricultural Economic Report No. 268, Washington, DC.

______. 1983. Agricultural Handbook 589. Agricultural Research Service, Washington, DC.

______. 1989. Agricultural Statistics 1989. US Government Printing Office, Washington, DC. [1988 data used.]

United States Office of Management and Budget (USOMB). 1989. Budget of the United States Government. USOMB, US Government Printing Office, Washington, DC.

Van der Scheer, H. A. T. 1984. Testing of crop protection chemicals in fruit growing. Pages 70–77 in *Annual Report, Research Station for Fruit Growing.* Wilhelminadorp, The Netherlands.

Van Doren, D. M., G. B. Triplett Jr., and J. E. Henry. 1977. Influence of long-term tillage and crop rotation combinations on crop yields and selected soil parameters for an Aeric Ochraqualf soil [Maize]. Research Bulletin of the Ohio Agricultural Research Development Center 1091, Wooster.

BioScience is the monthly magazine for biologists in all fields. It includes articles on research, policy, techniques, and education; news features on developments in biology; book reviews; announcements; meetings calendar; and professional opportunities. Published by the American Institute of Biological Sciences, 730 11th Street, NW, Washington, DC 20001-4521; 202/628-1500. 1991 membership dues, including *BioScience* subscription: Individual $45.00/year; Student $25.00/year. 1991 Institutional subscription rates: $99.50/year (domestic), $127.00/year (foreign).