Environmental and Economic Costs of Pesticide Use

An assessment based on currently available US data, although incomplete, tallies $8 billion in annual costs

David Pimentel, H. Acquay, M. Biltonen, P. Rice, M. Silva, J. Nelson, V. Lipner, S. Giordano, A. Horowitz, and M. D'Amore

Worldwide, approximately 2.5 million tons of pesticides are applied each year with a purchase price of $20 billion (Pesticide News 1990). In the United States, approximately 500,000 tons of 600 different types of pesticides are used annually at a cost of $4.1 billion, including application costs (Pimentel et al. 1991).

Pesticides make a significant contribution to maintaining world food production. In general, each dollar invested in pesticide control returns approximately $4 in crops saved. Estimates are that losses to pests would increase 10% if no pesticides were used at all; specific crop losses would range from zero to nearly 100%.

Despite the widespread use of pesticides in the United States, pests (principally insects, plant pathogens, and weeds) destroy 37% of all potential food and fiber crops (Pimentel 1990). Although pesticides are generally profitable, their use does not always decrease crop losses. For example, even with the tenfold increase in insecticide use in the United States from 1945 to 1989, total crop losses from insect damage have nearly doubled from 7% to 13% (Pimentel et al. 1991). This rise in crop losses to insects is, in part, caused by changes in agricultural practices. For instance, the replacement of rotating corn with other crops with the continuous production on approximately half the hectarage has resulted in nearly a fourfold increase in corn losses to insects, despite a thousandfold increase in insecticide use in corn production (Pimentel et al. 1991).

Indirect costs must be examined to facilitate a balanced, sound policy of pesticide use

Most benefits of pesticides are based only on direct crop returns. Such assessments do not include the indirect environmental and economic costs associated with pesticides. To facilitate the development and implementation of a balanced, sound policy of pesticide use, these costs must be examined. More than a decade ago, the US Environmental Protection Agency (EPA) pointed out the need for such a risk investigation (EPA 1977). So far only a few papers on this difficult subject have been published.

The obvious need for an updated and comprehensive study prompted our investigation of the complex of environmental and economic costs resulting from the nation's dependence on pesticides. Included in the assessment are analyses of pesticide impacts such as human health effects; domestic animal poisonings; increased control expenses resulting from pesticide-related destruction of natural enemies and from the development of pesticide resistance; crop pollination problems and honeybee losses; crop and crop product losses; groundwater and surface water contamination; fish, wildlife, and microorganism losses; and governmental expenditures to reduce the environmental and social costs of pesticide use.

Human health effects

Human pesticide poisonings and illnesses are clearly the highest price paid for pesticide use. A recent World Health Organization and United Nations Environmental Programme report (WHO/UNEP 1989) estimated there are 1 million human pesticide poisonings each year in the world, with approximately 20,000 deaths. In the United States, nonfatal pesticide poisonings reported by the American Association of Poison Control Centers total approximately 67,000 each year (Litovitz et al. 1990). J. Blondell[1] has indicated that because of demographic gaps, this figure represents only 73% of the total. According to Blondell, the number of accidental (no suicide or homicide) fatalities is approximately 27 per year.

Although developed countries, including the United States, annually use approximately 80% of all the pesticides produced in the world (Pimentel 1990), less than half of the pesticide-induced deaths occur in these countries (House of Commons Agri-

David Pimentel is a professor of insect ecology and agricultural sciences and H. Acquay, M. Biltonen, P. Rice, M. Silva, J. Nelson, V. Lipner, S. Giordano, A. Horowitz, and M. D'Amore are graduate students in the New York State College of Agriculture and Life Sciences, Cornell University, Ithaca, NY 14853.

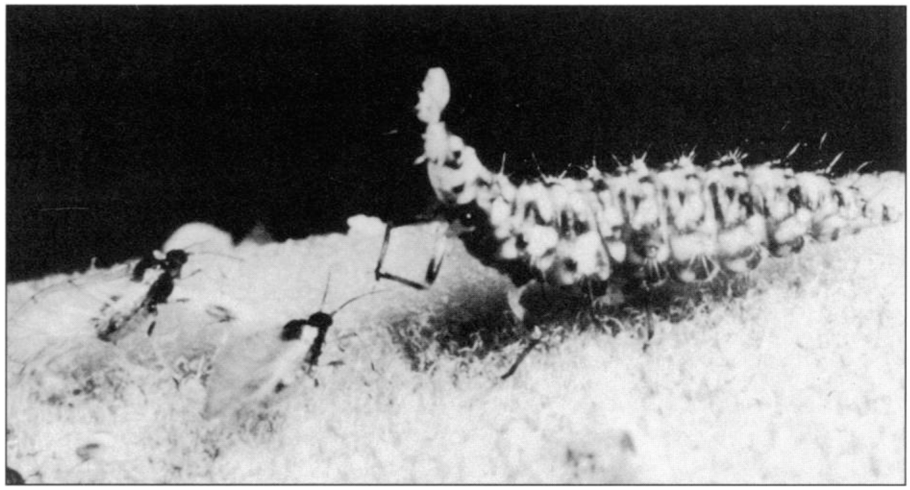
[1]J. Blondell, 1990, personal communication. Environmental Protection Agency, Washington, DC.

culture Committee 1987). A higher proportion of pesticide poisonings and deaths occurs in developing countries where there are inadequate occupational and other safety standards, insufficient enforcement, poor labeling of pesticides, illiteracy, inadequate protective clothing and washing facilities, and insufficient knowledge of pesticide hazards by users.

Both the acute and chronic health effects of pesticides warrant concern. The acute toxicity of most pesticides is well documented (Ecobichon et al. 1990), but information on chronic human illnesses resulting from pesticide exposure, including cancer, is weak. The International Agency for Research on Cancer found "sufficient" evidence of carcinogenicity for 18 pesticides and "limited" evidence of carcinogenicity for an additional 16 pesticides based on animal studies (WHO/UNEP 1989).

With humans, the evidence concerning cancer is also mixed. For example, a recent study in Saskatchewan indicated no significant difference in non-Hodgkin's lymphoma mortality between farmers and nonfarmers (Wigle et al. 1990), whereas other studies have reported some cancer in farmers (WHO/UNEP 1989). It is estimated that the number of US cases of cancer associated with pesticides in humans is less than 1% of the nation's total cancer cases.[2] Considering that there are approximately 1 million cancer cases per year (USBC 1990), Schottenfeld's assessment suggests that less than 10,000 cases of cancer are due to pesticides per year.

Many other acute and chronic maladies are beginning to be associated with pesticide use. For example, the recently banned pesticide, used for plant pathogen control, dibromochloropropane (DBCP) caused testicular dysfunction in animal studies (Foote et al. 1986) and was linked with infertility among human workers exposed to DBCP (Potashnik and Yanai-Inbar 1987). Also, a large body of evidence has been accumulated over recent years from animal studies suggesting pesticides can produce immune dysfunction (Thomas and House 1989). In a study of women who had chronically ingested groundwater contaminated with low levels of aldicarb (used for insect control; mean 16.6 ppb), Fiore et al. (1986) reported evidence of significantly reduced immune response, although these women did not exhibit any overt health problems.



Aphid lions can be purchased to fight insect pests. This late-stage larva (right), approximately 10 mm long, preys on aphids (left) and other small soft-bodied insects. With its hollow mandibles, the predator pierces its prey to suck out the blood. Photo: USDA.

Of particular concern are the chronic health problems associated with effects of organophosphorus pesticides, which have largely replaced the banned organochlorines (Ecobichon et al. 1990). The malady organophosphate-induced delayed polyneuropathy is well documented and includes irreversible neurological defects (Lotti 1984). Other defects in memory, mood, and abstraction have been documented. The evidence confirms that persistent neurotoxic effects may be present even after the termination of an acute poisoning incident (Ecobichon et al. 1990, Rosenstock et al. 1991).

Such chronic health problems are a public health issue, because everyone, everywhere is exposed to some pesticide residues in food, water, and the atmosphere. Fruits and vegetables receive the highest dosages of pesticides. Approximately 35% of the foods purchased by US consumers have detectable levels of pesticide residues (FDA 1990). From 1% to 3% of the foods have pesticide residue levels above the legal tolerance level (FDA 1990, Hundley et al. 1988). These residue levels could well be higher because the US analytical methods now employed detect only approximately one-third of the more than 600 pesticides in use (OTA 1988). Therefore, there are many reasons why 97% of the public is genuinely concerned about pesticide residues in their food (FDA 1989).

Medical specialists are concerned about the lack of public health data about pesticide effects in the United States (GAO 1986). Based on an investigation of 92 pesticides used on food, GAO (1986) estimates data on health problems associated with registered pesticides contains little or no information on tumors and birth defects.

Although no one can place a precise monetary value on a human life, studies done for the insurance industry have computed monetary ranges for the value of a "statistical life" between $1.6 and $8.5 million (Fisher et al. 1989). For our assessment, we use the conservative estimate of $2 million per human life. Based on the available data, estimates are that human pesticide poisonings and related illnesses in the United States total approximately $787 million each year (Table 1).

Animal poisonings and contaminated products

In addition to pesticide problems that affect humans, several thousand domestic animals are poisoned by pesticides each year; meat, milk, and eggs

[2]D. Schottenfeld, 1991, personal communication. College of Medicine, University of Michigan, Ann Arbor.

Table 1. Estimated economic costs of human pesticide poisonings and other pesticide-related illnesses in the United States each year.

Effects	Cost ($ million/year)
Hospitalization after poisonings: 2380* × 2.84 days @ $1000/day	6.759
Outpatient treatment after poisonings: 27,000† × $630‡	17.010
Lost work due to poisonings: 4680* workers × 4.7 days × $80/day	1.760
Treatment of pesticide-induced cancers: <10,000§ cases × $70,700†/case	707.000
Fatalities: 27 accidental fatalities† × $2 million	54.000
Total	786.529

*Keefe et al. 1990.
†J. Blondell, 1991, personal communication. EPA, Washington, DC.
‡Includes hospitalization, foregone earnings, and transportation (Castillo and Appel 1989).
§See text for details.

are also contaminated. Of 25,000 calls made to the Illinois Animal Poison Control Center in 1987, nearly 40% concerned pesticide poisonings in dogs and cats (Beasley and Trammel 1989). Similarly, Kansas State University reported that 67% of all animal pesticide poisonings involve dogs and cats (Barton and Oehme 1981). This large representation is not surprising, because dogs and cats usually wander freely about the home and farm and therefore have greater opportunity to come into contact with pesticides than other domesticated animals.

The best estimates indicate that approximately 20% of the total monetary value of animal production, or approximately $4.2 billion, is lost to all animal illnesses, including pesticide poisonings (Pimentel et al. in press). Colvin (1987) reported that 0.5% of animal illnesses and 0.04% of all animal deaths reported to a veterinary diagnostic laboratory were due to pesticide toxicosis. Thus, $30 million in domestic animals are lost to pesticide poisonings (Pimentel et al. in press).

This estimate is based only on poisonings reported to veterinarians. Many animal pesticide poisonings that occur in the home and on farms go undiagnosed and are attributed to other factors. In addition, when a farm animal poisoning occurs and little can be done for an animal, the farmer seldom calls a veterinarian but either waits for the animal to recover or destroys the animal.[3]

Additional economic losses occur when meat, milk, and eggs are contaminated with pesticides. In the United States, all animals slaughtered for human consumption, if shipped interstate, and all imported meat and poultry must be inspected by the US Department of Agriculture. This inspection is to ensure that the meat and products are wholesome, properly labeled, and do not present a health hazard. One part of this inspection, which involves monitoring meat for pesticide and other chemical residues, is the responsibility of the National Residue Program.

Of more than 600 pesticides now in use, National Residue Program tests are made for only 41,[4] which have been determined by the Federal Drug Administration, the Environmental Protection Agency, and Food Safety and Inspection Service to be of public health concern. Although the monitoring program records the number and type of violations, there is no significant cost to the animal industry because the meat is generally sold and consumed before the test results are available. Approximately 3% of the chickens with illegal pesticide residues are sold in the market (NAS 1987).

When the costs attributable to domestic animal poisonings and contaminated meat, milk, and eggs are combined, the economic value of all livestock products in the United States lost to pesticide contamination is estimated to be at least $29.6 million annually. Similarly, other nations lose significant numbers of livestock and large amounts of animal products each year due to pesticide-induced illness or death. Exact data concerning these livestock losses do not exist, and the available information comes only from reports of the incidence of mass destruction of livestock. For example, when the pesticide leptophos was used by Egyptian farmers on rice and other crops, 1300 draft animals were poisoned and lost.[5]

Destruction of beneficial natural predators and parasites

In both natural and agricultural ecosystems, many species, especially predators and parasites, control or help control herbivorous populations. Indeed, these natural beneficial species make it possible for ecosystems to remain foliated. With parasites and predators keeping herbivore populations at low levels, only a relatively small amount of plant biomass is removed each growing season (Hairston et al. 1960). Natural enemies play a major role in keeping populations of many insect and mite pests under control (DeBach 1964).

Like pest populations, beneficial natural enemies are adversely affected by pesticides (Croft 1990). For example, pests have reached outbreak levels in cotton and apple crops following the destruction of natural enemies by pesticides. Among such cotton pests are cotton bollworm, tobacco budworm, cotton aphid, spider mites, and cotton looper (OTA 1979). The apple pests in this category include European red mite, red-banded leafroller, San Jose scale, oystershell scale, rosy apple aphid, woolly apple aphid, white apple leafhopper, two-spotted spider mite, and apple rust mite (Croft 1990). Significant pest outbreaks also have occurred in other crops (Croft 1990, OTA 1979). Because parasitic and predacious insects often have complex searching and attack behaviors, sublethal insecticide dosages may alter this behavior and in this way disrupt effective biological controls.[6]

Fungicides also can contribute to pest outbreaks when they reduce fungal pathogens that are naturally parasitic on many insects. For example, the use of benomyl, used for plant pathogen control, reduces populations of entomopathogenic fungi. This effect results in increased survival of

[3]G. Maylin, 1977, personal communication. College of Veterinary Medicine, Cornell University, Ithaca, NY.
[4]D. Beerman, 1991, personal communication. Department of Animal Science, Cornell University, Ithaca, NY.
[5]A. H. El Sebae, 1992, personal communication. University of Alexandria, Alexandria, Egypt.
[6]L. E. Ehler, 1991, personal communication. University of California, Davis.

velvet bean caterpillars and cabbage loopers in soybeans. The increased number of insects eventually leads to reduced soybean yields (Johnson et al. 1976).

When outbreaks of secondary pests occur because their natural enemies are destroyed by pesticides, additional and sometimes more expensive pesticide treatments have to be made in efforts to sustain crop yields. This consequence raises overall costs and contributes to pesticide-related problems. An estimated $520 million can be attributed to costs of additional pesticide applications and increased crop losses, both of which follow the destruction of natural enemies by pesticides applied to crops (Pimentel et al. in press).

Worldwide, as in the United States, natural enemies are being adversely affected by pesticides. Although no reliable estimate is available concerning the impact of the loss in terms of increased pesticide use and/or reduced yields, general observations by entomologists indicate that the impact of loss of natural enemies is severe in many parts of the world. For example, from 1980 to 1985, insecticide use in rice production in Indonesia drastically increased (Oka 1991). This usage caused the destruction of beneficial natural enemies of the brown planthopper, and the pest populations exploded. Rice yields dropped to the extent that rice had to be imported into Indonesia for the first time in many years. The estimated loss in rice in just a two-year period was $1.5 billion (FAO 1988).

After that incident, entomologist I. N. Oka and his cooperators, who previously had developed a successful low-insecticide program for rice pests in Indonesia, were consulted by Indonesian President Soeharto's staff.[7] Their advice was to substantially reduce insecticide use and return to a sound treat-when-necessary program that protected the natural enemies. Following Oka's advice, President Soeharto mandated in 1986 that 57 of 64 pesticides would be withdrawn from use on rice and pest management practices would be improved. Pesticide subsidies to farmers also were eliminated. Subsequently, rice yields increased to levels well above those recorded during the period of heavy pesticide use (FAO 1988).

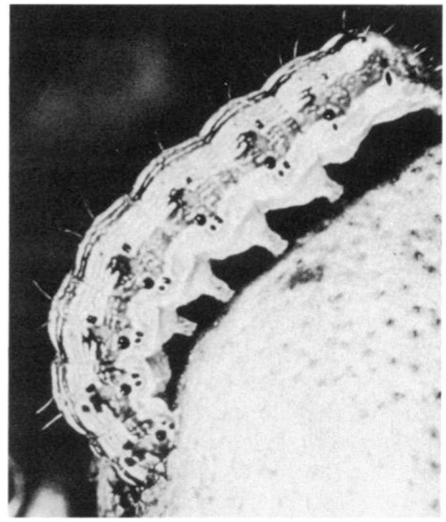
Biocontrol specialist D. Rosen[8] estimates that natural enemies account for up to 90% of the control of pest species achieved in agroecosystems and natural systems; we estimate that about half of the control of pest species is due to natural enemies. Pesticides give an additional control of 10%, and the remaining percentage is due to host-plant resistance and other limiting factors present in the agroecosystem.

Pesticide resistance in pests

In addition to destroying natural enemy populations, the extensive use of pesticides has often resulted in the development of pesticide resistance in insect pests, plant pathogens, and weeds. In a report of the United Nations Environment Programme, pesticide resistance was ranked as one of the top four environmental problems in the world (UNEP 1979). Approximately 504 insect and mite species (Georghiou 1990), a total of nearly 150 plant pathogen species, and about 273 weed species are now resistant to pesticides (Pimentel et al. in press).

Increased pesticide resistance in pest populations frequently results in the need for several additional applications of the commonly used and different pesticides to maintain expected crop yields. These additional pesticide applications compound the problem by increasing environmental selection for resistance traits. Despite attempts to deal with it, pesticide resistance continues to develop (Dennehy et al. 1987).

The impact of pesticide resistance, which develops gradually over time, is felt in the economics of agricultural production. A striking example of such development occurred in northeastern Mexico and the Lower Rio Grande of Texas (Adkisson 1972). Extremely high pesticide resistance had developed in the tobacco budworm population on cotton. Finally, in early 1970, approximately 285,000 ha of cotton had to be abandoned because pesticides were ineffective and there was no way to protect the crop from the budworm. The economic and social impacts on these Texan and Mexican farming communities that depend on cotton were devastating.



Cotton pests, such as this cotton boll worm, have reached outbreak levels after pesticides destroyed their natural enemies.

A study by Carrasco-Tauber (1989) indicates the extent of costs attributed to pesticide resistance. This study reported a yearly loss of $45 to $120/ha to pesticide resistance in California cotton. A total of 4.2 million hectares of cotton were harvested in 1984, thus assuming a loss of $82.50/ha; therefore, approximately $348 million of California cotton crop was lost to resistance. Because $3.6 billion of US cotton were harvested in 1984, the loss due to resistance for that year was approximately 10%. Assuming a 10% loss in other major crops that receive heavy pesticide treatments in the United States, crop losses due to pesticide resistance are estimated to be $1.4 billion/yr.

A detailed study by Archibald (1984) further demonstrated the hidden costs of pesticide resistance in California cotton. She reported that 74% more organophosphorus insecticides were required in 1981 to achieve the same kill of pests, like *Heliothis* spp. (cotton bollworm and budworm), than in 1979. Her analysis demonstrated that the diminishing effect of pesticides plus intensified pest control reduced the economic return per dollar of pesticide invested to only $1.14.

Furthermore, efforts to control resistant *Heliothis* spp. exact a cost on other crops when large, uncontrolled

[7]I. N. Oka, 1990, personal communication. Bogor Research Institute for Food Crops, Bogor, Indonesia.

[8]D. Rosen, 1991, personal communication. Hebrew University of Jerusalem, Jerusalem, Israel.

populations of *Heliothis* and other pests disperse onto other crops. In addition, the cotton aphid and the whitefly exploded as secondary cotton pests because of their resistance and their natural enemies' exposure to the high concentrations of insecticides.

The total external cost attributed to the development of pesticide resistance is estimated to range between 10% and 25% of current pesticide treatment costs (Harper and Zilberman 1990), or approximately $400 million each year in the United States alone. In other words, at least 10% of pesticide used in the United States is applied just to combat increased resistance that has developed in various pest species.

In addition to plant pests, a large number of insect and mite pests of both livestock and humans have become resistant to pesticides. Although a relatively small quantity of pesticide is applied for control of pests of livestock and humans, the cost of resistance has become significant. Based on available data, we estimate the yearly cost of resistance in such pests to be approximately $30 million for the United States.

Although the costs of pesticide resistance are high in the United States, its costs in tropical developing countries are significantly greater, because pesticides are used there not only to control agricultural pests but also for the control of disease vectors.

One of the major costs of resistance in tropical countries is associated with malaria control. By 1961, the incidence of malaria in India after early pesticide use had declined from several million cases to only 41,000 cases. However, because mosquitoes developed resistance to pesticides and malarial parasites developed resistance to drugs, the incidence of malaria in India now has exploded to approximately 59 million cases per year (NAS 1991). Similar problems are occurring in the rest of Asia, Africa, and South America, with the total incidence of malaria estimated to be 270 million cases (NAS 1991).

Bee poisonings and reduced pollination

Honeybees and wild bees are vital for pollination of crops including fruits and vegetables. Their direct and indirect benefits to agricultural production range from $10 billion to $33 billion each year in the United States (Robinson et al. 1989).[9] Because most insecticides used in agriculture are toxic to bees, pesticides have a major impact on both honeybee and wild bee populations. D. Mayer[10] estimates that 20% of all losses of honeybee colonies are due to pesticide exposure; this includes colonies that are killed outright or die during the winter. Mayer calculates that the direct annual loss reaches $13.3 million (Table 2). Another 15% of the bee colonies either are seriously weakened by pesticides or suffer losses when apiculturists have to move colonies to avoid pesticide damage.

According to Mayer, the yearly estimated loss from partial bee kills, reduced honey production, plus the cost of moving colonies totals approximately $25 million. Also, as a result of heavy pesticide use on certain crops, beekeepers are excluded from 4 to 6 million hectares of otherwise suitable apiary locations.[11] Mayer estimates the yearly loss in potential honey production in these regions is approximately $27 million.

In addition to these direct losses caused by damage to bees and honey production, many crops are lost because of the lack of pollination. In California, for example, approximately 1 million colonies of honey bees are rented annually at $20 per colony to augment the natural pollination of almonds, alfalfa, melons, and other fruits and vegetables.[12] Because California produces nearly 50% of US bee-pollinated crops, the total cost for bee rental for the entire country is estimated at $40 million. Of this cost, we estimate at least one-tenth or $4 million is attributed to the effects of pesticides (Table 2).

Estimates of annual agricultural losses due to the reduction in insect pollination of crops by pesticides may range as high as $4 billion per year.[13] For most crops, both crop yield and quality are enhanced by effective pollination. For example, McGregor et al. (1955) demonstrated that for several cotton varieties, effective pollination by bees resulted in yield increases from 20% to 30%. Assuming that a conservative 10% increase in cotton yield would result from more efficient pollination and subtracting charges for bee rental, the net annual gain for cotton alone could be as high as $400 million. However, using bees to enhance cotton pollination is currently impossible because of the intensive use of insecticides on cotton.

Mussen (1990) emphasizes that poor pollination not only reduces crop yields, but, more important, it reduces the quality of crops, especially fruit such as melons. In experiments with melons, E. L. Atkins[14] reported that with adequate pollination melon yields were increased 10% and quality was raised 25% as measured by the dollar value of the crop.

Based on the analysis of honeybee and related pollination losses caused by pesticides, pollination losses attributed to pesticides are estimated to represent approximately 10% of pollinated crops and have a yearly cost of approximately $200 million. Adding these costs to the other environmental costs of pesticides on honeybees and wild bees, the total annual loss is calculated to be approximately $320 million (Table 2). Therefore, the available evidence confirms that the yearly cost of direct honeybee losses, together with reduced yields resulting from poor pollination, are significant.

Table 2. Estimated honeybee losses and pollination losses from honeybees and wild bees.

Loss	Cost ($ million/year)
Colony losses from pesticides	13.3
Honey and wax losses	25.3
Loss of potential honey production	27.0
Bee rental for pollination	4.0
Pollination losses	200.0
Total	319.6

[9]E.L. Atkins, 1990, personal communication. University of California, Riverside.
[10]D. Mayer, 1990, personal communication. Department of Entomology, Washington State University, Pullman.
[11]See footnote 10.
[12]R. A. Morse, 1990, personal communication. Department of Entomology, Cornell University, Ithaca, NY.
[13]J. Lockwood, 1990, personal communication. Department of Entomology, University of Wyoming, Laramie.
[14]See footnote 9.

Crop and crop product losses

Basically, pesticides are applied to protect crops from pests in order to preserve yields, but sometimes the crops are damaged by pesticide treatments. This damage occurs when the recommended dosages suppress crop growth, development, and yield; pesticides drift from the targeted crop to damage adjacent nearby crops (e.g., citrus adjacent to cotton); residual herbicides either prevent chemical-sensitive crops from being planted in rotation or inhibit the growth of crops that are planted; and/or excessive pesticide residues accumulate on crops, necessitating the destruction of the harvest. Crop losses translate into financial losses for growers, distributors, wholesalers, transporters, retailers, and food processors. Potential profits as well as investments are lost. The costs of crop losses increase when the related costs of investigations, regulation, insurance, and litigation are added to the equation. Ultimately, the consumer pays for these losses in higher marketplace prices.

Data on crop losses due to pesticide use are difficult to obtain. Many losses are never reported to state and federal agencies because the injured parties often settle privately.[14,15] For example, in North Dakota, only an estimated one-third of the pesticide-induced crop losses are reported to the State Department of Agriculture.[16] Furthermore, according to the Federal Crop Insurance Corporation, losses due to pesticide use are not insurable because of the difficulty of determining pesticide damage.[17]

Damage to crops may occur even when recommended dosages of herbicides and insecticides are applied to crops under normal environmental conditions.[18] Recommended (heavy) dosages of insecticides used on crops have been reported to suppress growth and yield in both cotton and strawberry crops (ICAITI 1977). The increased susceptibility of some crops to insects and diseases after normal use of 2,4-D and other herbicides was demonstrated by Oka and Pimentel (1976). Furthermore, when weather and/or soil conditions are inappropriate for pesticide application, herbicide treatments may cause yield reductions ranging from 2% to 50% (Akins et al. 1976).

Crops are lost when pesticides drift from target crops to nontarget crops, sometimes located several miles downwind (Barnes et al. 1987). Drift occurs with almost all methods of pesticide application, including both ground and aerial equipment. The potential problem is greatest when pesticides are applied by aircraft; 50% to 75% of pesticides applied miss the target area (ICAITI 1977, Mazariegos 1985, Ware 1983). In contrast, 10% to 35% of the pesticide applied with ground-application equipment misses the target area (Hall 1991). The most serious drift problems are caused by speed sprayers and mist-blower sprayers, because with these application technologies approximately 35% of the pesticide drifts away from the target area. In addition, more of the total pesticide used in the US is applied with sprayers than with aircraft.[19]

Crop injury and subsequent loss due to drift is particularly common in areas planted with diverse crops. For example, in southwest Texas in 1983 and 1984, almost $20 million of cotton was destroyed from drifting 2,4-D herbicide when adjacent wheat fields were aerially sprayed with the herbicide (Hanner 1984).

When residues of some herbicides persist in the soil, crops planted in rotation may be injured (Keeling et al. 1989). In 1988/1989, an estimated $25 to $30 million of Iowa's soybean crop was lost due to the persistence of the herbicide Sceptor in the soil.[20]

Additional losses are incurred when food crops must be destroyed because they exceed the EPA regulatory tolerances for pesticide residue levels. Assuming that all the crops and crop products that exceed the EPA regulatory tolerances were destroyed as required by law, approximately $550 million in crops annually would be destroyed because of excessive pesticide contamination (Pimentel et al. in press). Because most of the crops with pesticides above the tolerance levels are neither detected nor destroyed, they are consumed by the public, avoiding financial loss to farmers but creating public health risks. In general, excess pesticides in the food go undetected unless a large number of people become ill after the food is consumed.

Table 3. Estimated loss of crops and trees due to the use of pesticides.

Impact	Cost ($ million/year)
Crop losses	136
Crop applicator insurance	245
Crops destroyed because of excess pesticide contamination	550
Investigations and testing	
Government	10
Private	1
Total	942

A well-publicized 1985 incident in California illustrates this problem. More than 1000 persons became ill from eating contaminated watermelons, and approximately $1.5 million dollars' worth of watermelons were ordered destroyed.[21] It was later learned that several California farmers treated watermelons with the insecticide aldicarb (Temik), which is not approved or registered for use on watermelons. After this crisis, the California State Assembly appropriated $6.2 million to be awarded to growers affected by state seizure and freeze orders (Legislative Counsel's Digest 1986). According to the California Department of Food and Agriculture, an estimated $800,000 in investigative costs and litigation fees resulted from this one incident.[22] The California Department of Health Services was assumed to have incurred similar expenses, putting the total cost of the incident at nearly $8 million.

Such costs as crop seizures and insurance should be added to the costs of direct crop losses due to the use of

[15]B. D. Berver, 1990, personal communication. Office of Agronomy Services, Brookings, SD.
[16]J. Peterson, 1990, personal communication. Pesticide/Noxious Weed Division, Department of Agriculture, Fargo, ND.
[17]E. Edgeton, 1990, personal communication. Federal Crop Insurance Corp., Washington, DC.
[18]J. Neal, 1990, personal communication. Chemical Pesticides Program, Cornell University, Ithaca, NY.

[19]See footnote 8.
[20]R. G. Hartzler, 1990, personal communication. Cooperative Extersion Service, Iowa State University, Ames.

[21]R. Magee, 1990, personal communication. California Department of Food and Agriculture, Sacramento.
[22]See footnote 21.

pesticides in commercial crop production. Then, the total monetary loss is estimated to be approximately $942 million annually in the United States (Table 3).

Groundwater and surface water contamination

Certain pesticides applied to crops eventually end up in groundwater and surface waters. The three most common pesticides found in groundwater are the insecticide aldicarb and the herbicides alachlor and atrazine (Osteen and Szmedra 1989). Estimates are that nearly one-half of the groundwater and well water in the United States is or has the potential to be contaminated (Holmes et al. 1988). EPA (1990a) reported that 10.4% of community wells and 4.2% of rural domestic wells have detectable levels of at least one pesticide of the 127 pesticides tested in a national survey. It would cost an estimated $1.3 billion annually in the United States to monitor well water and groundwater for pesticide residues (Nielsen and Lee 1987).

There are two major concerns about groundwater contamination with pesticides. First, approximately one-half of the population obtains its water from wells. Second, once groundwater is contaminated, the pesticide residues remain for long periods of time. Not only are there just a few microorganisms that have the potential to degrade pesticides, but the groundwater recharge rate averages less than 1% per year.

Monitoring pesticides in groundwater is only a portion of the total cost of US groundwater contamination. There is also the high cost of cleanup. For instance, at the Rocky Mountain Arsenal near Denver, Colorado, the removal of pesticides from groundwater and soil was estimated to cost approximately $2 billion (*New York Times* 1988). If all pesticide-contaminated groundwater were cleared of pesticides before human consumption, the cost would be approximately $500 million (based on the costs of cleaning water; Clark 1979). Note that the cleanup process requires a water survey to target the contaminated water for cleanup. Thus, adding monitoring and cleaning costs, the total cost of pesticide-polluted groundwater is estimated to be approximately $1.8 billion annually.

Fishery losses

Pesticides are washed into aquatic ecosystems by water runoff and soil erosion. Approximately 18 $t \bullet ha^{-1} \bullet yr^{-1}$ of soil are washed and/or blown from pesticide-treated cropland into adjacent locations, including streams and lakes (USDA 1989b). Pesticides also drift into streams and lakes and contaminate them (Clark 1989). Some soluble pesticides are easily leached into streams and lakes (Nielsen and Lee 1987).

Once in aquatic systems, pesticides cause fishery losses in several ways. High pesticide concentrations in water directly kill fish, low-level doses kill highly susceptible fish fry, and essential fish foods such as insects and other invertebrates are eliminated. In addition, because government safety restrictions ban the catching or sale of fish contaminated with pesticide residues, such unmarketable fish are considered an economic loss.

Each year, large numbers of fish are killed by pesticides. Based on EPA (1990b) data, we calculate that from 1977 to 1987 the cost of fish kills due to all factors has been 141 million fish/yr. Pesticides are the cause of 6–14 million of those deaths.

These estimates of fish kills are considered to be low. In 20% of the fish kills, no estimate is made of the number of fish killed. In addition, fish kills frequently cannot be investigated quickly enough to determine accurately the primary cause. Fast-moving waters in rivers dilute pollutants so that these causes of kills often cannot be identified. Moving waters also wash away some of the poisoned fish, whereas other poisoned fish sink to the bottom and cannot be counted. Perhaps most important, few if any of the widespread and more frequent low-level pesticide poisonings are dramatic enough to be observed. Therefore, most go unrecognized and unreported.

The average value of a fish has been estimated to be approximately $1.70, using the guidelines of the American Fisheries Society (AFS 1982); however, it was reported that Adolph Coors Company might be "fined up to $10 per dead fish, plus other penalties" for an accidental beer spill in a creek (*Barometer* 1991). At $1.70, the value of the low estimate of 6 to 14 million fish killed by pesticides per year is $10 to $24 million. The actual loss is probably several times this amount.

Wild birds

Wild birds are also damaged by pesticides; these animals make excellent indicator species. Deleterious effects on wildlife include death from direct exposure to pesticides or secondary poisonings from consuming contaminated prey; reduced survival, growth, and reproductive rates from exposure to sublethal dosages; and habitat reduction through elimination of food sources and refuges (McEwen and Stephenson 1979). In the United States, approximately 160 million ha/yr of land receives a heavy pesticide dose—averaging 3 kg per ha (Pimentel et al. 1991). With such a large area treated with heavy dosages, it is to be expected that the impact on wildlife is significant.

The full extent of bird and mammal destruction is difficult to determine because these animals are often secretive, camouflaged, highly mobile, and live in dense grass, shrubs, and trees. Typical field studies of the effects of pesticides often obtain extremely low estimates of bird and mammal mortality (Mineau and Collins 1988). Bird carcasses disappear quickly due to vertebrate and invertebrate scavengers, and field studies seldom account for birds that die a distance from the treated areas.

Nevertheless, many bird casualties caused by pesticides have been reported. For instance, White et al. (1982) reported that 1200 Canada geese were killed in one wheat field that was sprayed with a 2:1 mixture of parathion and methyl parathion at a rate of 0.8 kg/ha. Carbofuran applied to alfalfa killed more than 5000 ducks and geese in five incidents, whereas the same chemical applied to vegetable crops killed 1400 ducks in a single incident (Flickinger et al. 1991). Carbofuran is estimated to kill 1 to 2 million birds each year in the United States (EPA 1989). Another pesticide, diazinon, applied on just three golf courses, killed 700 Atlantic Brant geese or one-quarter of the wintering population of geese (Stone and Gradoni 1985).

Several studies report that the use of herbicides in crop production results in the elimination of weeds that harbor some insects (Potts 1986).[23] The use of herbicides has led to significant reductions in the gray partridge in the United Kingdom and the common pheasant in the United States. In the case of the partridge, population levels have decreased to less than 23% because partridge chicks (like pheasant chicks) depend on insects to supply them with protein needed for their development and survival (Potts 1986).[24]

Frequently, the form of a pesticide influences its toxicity to wildlife. For example, insecticide-treated seed and insecticide granules, including carbofuran, fensulfothion, fonofos, and phorate, are particularly toxic to birds when consumed. From 0.23 to 1.5 birds/ha are estimated to have been killed in Canada by these treated seed and granules, and in the United States estimates range from 0.25 to 8.9 birds/ha killed per year by the pesticides (Mineau 1988).

Pesticides also adversely affect the reproductive potential of many birds and mammals. Exposure of birds, especially predatory birds, to chlorinated insecticides has caused reproductive failure, sometimes attributed to eggshell thinning (Stickel et al. 1984). Most of the affected populations recovered after the ban of DDT in the United States. However, DDT and its metabolite DDE remain a concern; DDT continues to be used in developing countries, which contain wintering areas for numerous bird species (Stickel et al. 1984).

Although the gross values for wildlife are not available, expenditures are one measure of the monetary value. The money spent by bird hunters to harvest 5 million game birds was $1.1 billion, or approximately $216 per bird felled (USFWS 1988). It is estimated that approximately $0.40 per bird is spent for birdwatching (on travel and equipment), and $800 per bird is spent to rear and release a bird in the wild (Pimentel et al. in press). For our assessment, we place an average value per bird at $30.

If we assume that the damage pesticides inflict on birds occurs primarily on the 160 million ha of cropland that receives most of the pesticide, and the bird population is estimated to be 4.2 birds/ha of cropland (Blew 1990), then 672 million birds are directly exposed to pesticides. If it is conservatively estimated that only 10% of the bird population is killed, then the total number killed is 67 million birds. Note this estimate is at the lower end of the range of 0.25 to 8.9 birds/ha killed per year by pesticides mentioned earlier in this section. Also, this estimate is conservative because secondary losses to pesticide reductions in invertebrate-prey poisonings were not included in the assessment. Assuming the average value of a bird is $30, then an estimated $2 billion in birds are destroyed annually.

The US Fish and Wildlife Service spends $102 yearly on its Endangered Species Program, which aims to reestablish species, such as the bald eagle, peregrine falcon, osprey, and brown pelican, that in some cases were reduced by pesticides (USFWS 1991). Thus, when all the above costs are combined, we estimate that US bird losses associated with pesticide use represent a cost of approximately $2.1 billion/yr.

Table 4. Total estimated environmental and social costs from pesticides in the United States.

Impact	Cost ($ million/year)
Public health impacts	787
Domestic animal deaths and contamination	30
Loss of natural enemies	520
Cost of pesticide resistance	1400
Honeybee and pollination losses	320
Crop losses	942
Fishery losses	24
Bird losses	2100
Groundwater contamination	1800
Government regulations to prevent damage	200
Total	8123

Microorganisms and invertebrates

Pesticides easily find their way into soils, where they may be toxic to arthropods, earthworms, fungi, bacteria, and protozoa. Small organisms are vital to ecosystems because they dominate both the structure and function of natural systems.

For example, an estimated 4.5 tons/ha of fungi and bacteria exist in the upper 15 cm of soil. They, with the arthropods, make up 95% of all species and 98% of the biomass (excluding vascular plants). The microorganisms are essential to proper functioning of the ecosystem because they break down organic matter, enabling the vital chemical elements to be recycled (Atlas and Bartha 1987). Equally important is their ability to fix nitrogen, making it available for plants. The role of microorganisms cannot be overemphasized, because in nature, agriculture, and forestry they are essential agents in biogeochemical recycling of the vital elements in all ecosystems (Brock and Madigan 1988).

Although these invertebrates and microorganisms are essential to the vital structure and function of all ecosystems, it is impossible to place a dollar value on the damage caused by pesticides to this large group. To date, no relevant quantitative data has been collected for use in estimating the value of the microorganisms destroyed.

Government funds for pesticide-pollution control

A major environmental cost associated with all pesticide use is the cost of carrying out state and federal regulatory actions, as well as the pesticide monitoring programs needed to control pesticide pollution. Specifically, these funds are spent to reduce the hazards of pesticides and to protect the integrity of the public health and the environment.

At least $1 million is spent each year by the state and federal government to train and register pesticide applicators.[25] Also, more than $40 million is spent each year by EPA for just registering and re-registering pesticides (GAO 1986). We estimate that the federal and state governments together spend approximately $200 million/yr for pesticide pollution control (Table 4).

Although enormous amounts of government money is currently being

[23]R. Beiswenger, 1990, personal communication. University of Wyoming, Laramie.
[24]See footnote 23.

[25]D. Rutz, 1991, personal communication. Department of Entomology, Cornell University, Ithaca, NY.

spent to reduce pesticide pollution, costly damage still results. Also, many serious environmental and social problems remain to be corrected by improved government policies. A recent survey by Sachs et al. (1987) confirmed Sachs' data that confidence in the ability of the US government to regulate pesticides declined from 98% in 1965 to only 46% in 1985. Another survey conducted by the Food and Drug Administration (1989) found that 97% of the public were genuinely concerned that pesticides contaminate their food.

Conclusions

An investment of approximately $4 billion dollars in pesticide control saves approximately $16 billion in US crops, based on direct costs and benefits (Pimentel et al. 1991). However, the indirect environmental and public-health costs of pesticide use need to be balanced against these benefits. Based on the available data, the environmental and social costs of pesticide use total approximately $8 billion each year (Table 4). Users of pesticides in agriculture pay directly for only approximately $3 billion of this cost, which includes problems arising from pesticide resistance and destruction of natural enemies. Society eventually pays this $3 billion plus the remaining $5 billion in environmental and public health costs (Table 4).

Our assessment of the environmental and health problems associated with pesticides is incomplete because data are scarce. What is an acceptable monetary value for a human life lost or for a cancer illness due to pesticides? Equally difficult is placing a monetary value on wild birds and other wildlife, invertebrates, microbes, food, or groundwater.

In addition to the costs that cannot be accurately measured, there are additional costs that have not been included in the $8 billion/yr. A complete accounting of the indirect costs should include accidental poisonings like the aldicarb/watermelon crisis; domestic animal poisonings; unrecorded losses of fish and wildlife and of crops, trees, and other plants; losses resulting from the destruction of soil invertebrates, microflora, and microfauna; true monetary costs of human pesticide poisonings; water and soil pollution; and human health effects such as cancer and sterility. If the full environmental and social costs could be measured as a whole, the total cost would be significantly greater than the estimate of $8 billion/yr. Such a complete long-term cost/benefit analysis of pesticide use would reduce the perceived profitability of pesticides.

Human pesticide poisonings, reduced natural enemy populations, increased pesticide resistance, and honeybee poisonings account for a substantial portion of the calculated environmental and social costs of pesticide use in the United States. Fortunately, some losses of natural enemies and some pesticide resistance problems are being alleviated through carefully planned use of integrated pest management practices. But a great deal remains to be done to reduce these important environmental costs (Pimentel et al. 1991).

The major environmental and public health problems associated with pesticides are in large measure responsible for the loss of public confidence in state and federal regulatory agencies as well as in institutions that conduct agricultural research. Public concern about pesticide pollution confirms a national trend toward environmental values. Media emphasis on the issues and problems caused by pesticides has contributed to a heightened public awareness of ecological concerns. This awareness is encouraging research in environmentally sound agriculture, including non-chemical pest management.

This investigation not only underscores the serious nature of the environmental and socioeconomic costs of pesticides, but it emphasizes the great need for more detailed investigation of the environmental and economic impacts of pesticides. Pesticides are and will continue to be a valuable pest control tool. Meanwhile, with more accurate, realistic cost/benefit analyses, we will be able to work to minimize the risks and to develop and increase the use of nonchemical pest controls to maximize the benefits of pest control strategies for all society.

Acknowledgments

We thank the following people for reading an earlier draft of this manuscript, for their many helpful suggestions, and, in some cases, for providing additional information: A. Blair, National Institutes of Health; J. Blondell, US Environmental Protection Agency; S. A. Briggs, Rachel Carson Council; L. E. Ehler, University of California, Davis; E. L. Flickinger, US Fish and Wildlife Service; T. Frisch, NYCAP; E. L. Gunderson, US Food and Drug Administration; R. G. Hartzler, Iowa State University, Ames; H. Lehman and G. A. Surgeoner, University of Guelph; P. Mineau, Environment Canada; I. N. Oka, Bogor Food and Agriculture Institute, Bogor, Indonesia; C. Osteen, US Department of Agriculture; O. Pettersson, Swedish University of Agricultural Sciences; D. Rosen, Hebrew University of Jerusalem, Jerusalem, Israel; J. Q. Rowley, Oxfam, UK; P. A. Thomson and J. J. Jenkins, Oregon State University; C. Walters, Acres, U.S.A.; G. W. Ware, University of Arizona; and D. H. Beerman, T. Brown, E. L. Madsen, R. Roush, and C. R. Smith, Cornell University.

References cited

Adkisson, P. L. 1972. The integrated control of the insect pests of cotton. *Tall Timbers Conf. Ecol. Control Habitat Mgmt.* 4: 175–188.

Akins, M. B., L. S. Jeffery, J. R. Overton, and T. H. Morgan. 1976. Soybean response to preemergence herbicides. *Proc. South Weed Sci. Soc.* 29: 50.

American Fisheries Society (AFS). 1982. Monetary values of freshwater fish and fish-kill counting guidelines. Special publication #13, AFS, Bethesda, MD.

Archibald, S. O. 1984. A dynamic analysis of production externalities: pesticide resistance in California. Ph.D. dissertation, University of California, Davis.

Barnes, C. J., T. L. Lavy, and J. D. Mattice. 1987. Exposure of non-applicator personnel and adjacent areas to aerially applied propanil. *Bull. Environ. Contam. Toxicol.* 39: 126–133.

Barometer. 1991. Too much beer kills thousands. *Oregon State University Barometer* 14 May: 7.

Barton, J., and F. Oehme. 1981. Incidence and characteristics of animal poisonings seen at Kansas State University from 1975 to 1980. *Vet. Human Toxicol.* 23: 101–102.

Beasley, V. R., and H. Trammel. 1989. Insecticide. Pages 97–107 in R. W. Kirk, ed. *Current Veterinary Therapy: Small Animal Practice.* W.B. Saunders, Philadelphia.

Blew, J. H. 1990. Breeding bird census. 92 conventional cash crop farm. *J. Field Ornithol.* 61(Suppl.): 80–81.

Brock, T., and M. Madigan. 1988. *Biology of Microorganisms.* Prentice Hall, London.

Carrasco-Tauber, C. 1989. Pesticide productivity revisited. Masters dissertation, University of Massachusetts, Amherst.

Clark, R. B. 1989. *Marine Pollution.* Clarendon

Press, Oxford, UK.
Clark, R. M. 1979. Water supply regionalization: a critical evaluation. *Proc. Am. Soc. Civil Engr.* 105: 279–294.
Colvin, B. M. 1987. Pesticide uses and animal toxicoses. *Vet. Human Toxicol.* 29(Suppl. 2).
Croft, B. A. 1990. *Arthropod Biological Control Agents and Pesticides.* John Wiley & Sons, New York.
DeBach, P. 1964. *Biological Control of Insect Pests and Weeds.* Rheinhold, New York.
Dennehy, T. J., J. P. Nyrop, R. T. Roush, J. P. Sanderson, and J. G. Scott. 1987. Managing pest resistance to pesticides: a challenge to New York's agriculture. *NY Food Life Sci. Q.* 17: 4, 13–17.
Ecobichon, D. J., J. E. Davies, J. Doull, M. Ehrich, R. Joy, D. McMillan, R. MacPhail, L. W. Reiter, W. Slikker, and H. Tilson. 1990. Neurotoxic effects of pesticides. Pages 131–199 in C. F. Wilkinson and S. R. Baker, eds. *The Effect of Pesticides on Human Health.* Princeton Scientific Publ., Princeton, NJ.
Environmental Protection Agency (EPA). 1977. Minutes of administrator's pesticide policy advisory committee, March. EPA, Washington, DC.
______. 1989. Carbofuran: a special review technical support document. EPA Office of Pesticides and Toxic Substances, Washington, DC.
______. 1990a. National pesticide survey: summary. EPA, Washington, DC.
______. 1990b. Fish kills caused by pollution, 1977–1987. Draft report of EPA Office of Water Regulations and Standards, Washington, DC.
Fiore, M. C., H. A. Anderson, R. Hong, R. Golubjatnikov, J. E. Seiser, D. Nordstrom, L. Hanrahan, and D. Belluck. 1986. Chronic exposure to aldicarb-contaminated groundwater and human immune function. *Environ. Res.* 41: 633–645.
Fisher, A., L. G. Chestnut, and D. M. Violette. 1989. The value of reducing risks of death: a note on new evidence. *Journal of Policy Analysis and Management* 8: 88–100.
Flickinger, E. L., G. Juenger, T. J. Roffe, M. R. Smith, and R. J. Irwin. 1991. Poisoning of Canada geese in Texas by parathion sprayed for control of Russian wheat aphid. *J. Wildl. Dis.* 27: 265–268.
Food and Agriculture Organization of the United Nations (FAO). 1988. Integrated pest management in rice in Indonesia. United Nations, Jakarta, Indonesia.
Food and Drug Administration (FDA). 1989. Food and Drug Administration pesticide program: residues in foods, 1988. *J. Assoc. Off. Anal. Chem.* 72: 133A-152A.
______. 1990. Food and Drug Administration pesticide program: residues in foods, 1989. *J. Assoc. Off. Anal. Chem.* 73: 127A–146A.
Foote, R. H., E. C. Schermerhorn, and M. E. Simkin. 1986. Measurement of semen quality, fertility, and reproductive hormones to assess dibromochloropropane (DBCP) effects in live rabbits. *Fund. Appl. Toxicol.* 6: 628–637.
General Accounting Office (GAO). 1986. *Pesticides: EPA's Formidable Task to Assess and Regulate Their Risks.* Washington, DC.
Georghiou, G. P. 1990. Overview of insecticide resistance. Pages 18–41 in M. B. Green, H. M. LeBaron, and W. K. Moberg, eds. *Managing Resistance to Agrochemicals: from Fundamental Research to Practical Strategies.* American Chemical Society, Washington, DC.
Hairston, N. G., F. E. Smith, and L. B. Slobodkin. 1960. Community structure, population control and competition. *Am. Nat.* 94: 421–425.
Hall, F. R. 1991. Pesticide application technology and integrated pest management (IPM). Pages 135–170 in D. Pimentel, ed. *Handbook of Pest Management in Agriculture.* CRC Press, Boca Raton, FL.
Hanner, D. 1984. Herbicide drift prompts state inquiry. *Dallas (Texas) Morning News* 25 July: 7.
Harper, C. R., and D. Zilberman. 1990. Pesticide regulation: problems in trading off economic benefits against health risks. Pages 181–196 in D. Zilberman and J. B. Siebert, eds. *Economic Perspectives on Pesticide Use in California.* University of California, Berkeley.
Holmes, T., E. Nielsen, and L. Lee. 1988. Managing groundwater contamination in rural areas: rural development perspectives. US Department of Agriculture Economic Research Service, Washington, DC.
House of Commons Agriculture Committee. 1987. *The Effects of Pesticides on Human Health: Report and Proceedings of the Committee.* 2nd special report, vol. I. Her Majesty's Stationery Office, London.
Hundley, H. K., T. Cairns, M. A. Luke, and H. T. Masumoto. 1988. Pesticide residue findings by the Luke method in domestic and imported foods and animal feeds for fiscal years 1982–1986. *J. Assoc. Off. Anal. Chem.* 71: 875–877.
ICAITI. 1977. An environmental and economic study of the consequences of pesticide use in Central American cotton production: final report. Central American Research Institute for Industry, United Nations Environment Programme, Guatemala City, Guatemala.
Johnson, D. W., L. P. Kish, and G. E. Allen. 1976. Field evaluation of selected pesticides on the natural development of the entomopathogen, *Nomuraea rileyi*, on the velvetbean caterpillar in soybean. *Environ. Entomol.* 5: 964–966.
Keefe, T. J., E. P. Savage, S. Munn, and H. W. Wheeler. 1990. Evaluation of epidemiological factors from two national studies of hospitalized pesticide poisonings, U.S.A. Exposure Assessment Branch, Hazard Evaluation Division, EPA Office of Pesticides and Toxic Substances, Washington, DC.
Keeling, J. W., R. W. Lloyd, and J. R. Abernathy. 1989. Rotational crop response to repeated applications of korflurazon. *Weed Technol.* 3: 122–125.
Legislative Counsel's Digest (State of California). 1986. Legislative Assembly Bill no. 2755. Sacramento, CA.
Litovitz, T. L., B. F. Schmitz, and K. M. Bailey. 1990. 1989 annual report of the American Association of Poison Control Centers National Data Collection System. *Am. J. Emerg. Med.* 8: 394–442.
Lotti, M. 1984. The delayed polyneuropathy caused by some organophosphorus esters. Pages 247–257 in C. L. Galli, L. Manzo, and P. S. Spencer, eds. *Recent Advances in Nervous Systems Toxicology.* Plenum, New York.
Mazariegos, F. 1985. *The Use of Pesticides in the Cultivation of Cotton in Central America.* United Nations Environment Programme, Industry and Environment, Guatemala.
McEwen, F. L., and G. R. Stephenson. 1979. *The Use and Significance of Pesticides in the Environment.* John Wiley & Sons, New York.
McGregor, S. E., C. Rhyne, S. Worley, and F. E. Todd. 1955. The role of honeybees in cotton pollination. *Agron. J.* 47: 23–25.
Mineau, P. 1988. Avian mortality in agroecosystems. I. The case against granule insecticides in Canada. Pages 3–12 in M. P. Greaves, B. D. Smith, and P. W. Greig-Smith, eds. *Field Methods for the Study of Environmental Effects of Pesticides.* British Crop Protection Council monograph 40, Thornton Heath, London.
Mineau, P., and B. T. Collins. 1988. Avian mortality in agro-ecosystems. II. Methods of detection. Pages 13–27 in M. P. Greaves, B. D. Smith, and P. W. Greig-Smith, eds. *Field Methods for the Study of Environmental Effects of Pesticides.* British Crop Protection Council monograph 40, Thornton Heath, London.
Mussen, E. 1990. California crop pollination. *Glean. Bee Cult.* 118: 646–647.
National Academy of Sciences (NAS). 1987. *Regulating Pesticides in Food.* National Academy Press, Washington, DC.
______. 1991. *Malaria Obstacles and Opportunities.* National Academy Press, Washington, DC.
New York Times. 1988. Shell loses suit on cleanup cost. 20 December: A24.
Nielsen, E. G., and L. K. Lee. 1987. *The Magnitude and Costs of Groundwater Contamination from Agricultural Chemicals: A National Perspective.* ERS staff report AGES870318, US Department of Agriculture, Economic Research Service, Natural Resource Economics Division, Washington, DC.
Office of Technology Assessment (OTA). 1979. *Pest Management Strategies.* Congress of the United States, OTA, Washington, DC.
______. 1988. *Pesticide Residues in Food: Technologies for Detection.* Congress of the United States, OTA, Washington, DC.
Oka, I. N. 1991. Success and challenges of the Indonesian national integrated pest management program in the rice-based cropping system. *Crop Prot.* 10: 163–165.
Oka, I. N., and D. Pimentel. 1976. Herbicide (2,4-D) increases insect and pathogen pests on corn. *Science* 193: 239–240.
Osteen, C. D., and P. I. Szmedra. 1989. *Agricultural Pesticide Use Trends and Policy Issues.* Agricultural Economics report 622, US Department of Agriculture, Economic Research Service, Washington, DC.
Pesticide News. 1990. Towards a reduction in pesticide use. 43: 17–20.
Pimentel, D. 1990. Estimated annual world pesticide use. In *Facts and Figures.* Ford Foundation, New York.
Pimentel, D., H. Acquay, M. Biltonen, P. Rice, M. Silva, J. Nelson, V. Lipner, S. Giordano, A. Horowitz, and M. D'Amore. In press. Assessment of environmental and economic costs of pesticide use. In D. Pimentel and H. Lehman, eds. *The Pesticide Question: Envi-*

ronment, Economics and Ethics*. Chapman and Hall, New York.
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 on Pest Management in Agriculture*. CRC Press, Boca Raton, FL.
Potashnik, G., and I. Yanai-Inbar. 1987. Dibromochloropropane (DBCP): an 8-year reevaluation of testicular function and reproductive performance. *Fertil. Steril.* 47: 317–323.
Potts, G. R. 1986. *The Partridge: Pesticides, Predation and Conservation*. Collins, London.
Robinson, W. E., R. Nowogrodzki, and R. A. Morse. 1989. The value of honey bees as pollinators of U.S. crops. *Am. Bee J.* 129: 477–487.
Sachs, C., D. Blair, and C. Richter. 1987. Consumer pesticide concerns: a 1965–1984 comparison. *Journal of Consumer Affairs* 21: 96–107.
Stickel, W. H., L. F. Stickel, R. A. Dyrland, and D. L. Hughes. 1984. DDE in birds: lethal residues and loss rates. *Arch. Environ. Contam. Toxicol.* 13: 1–6.
Stone, W. B., and P. B. Gradoni. 1985. Wildlife mortality related to the use of the pesticide diazinon. *Northeast. Environ. Sci.* 4: 30–38.
Thomas, P. T., and R. V. House. 1989. Pesticide-induced modulation of immune system. Pages 94–106 in N. N. Ragsdale and R. E. Menzer, eds. *Carcinogenicity and Pesticides: Principles, Issues, and Relationships*. American Chemical Society, Washington, DC.
United Nations Environmental Program (UNEP). 1979. *The State of the Environment: Selected Topics—1979*. UNEP Governing Council Seventh Session, Nairobi, Kenya.
US Bureau of the Census (USBC). 1990. *Statistical Abstract of the United States*. USBC, US Department of Commerce, Washington, DC.
US Department of Agriculture (USDA). 1989. *The Second RCA Appraisal: Soil, Water, and Related Resources on Non-federal Land in the United States, Analysis of Conditions and Trends*. USDA, Washington, DC.
US Fish and Wildlife Service (USFWS). 1988. *1985 Survey of Fishing, Hunting, and Wildlife Associated Recreation*. USFWS, Department of the Interior, Washington, DC.
______. 1991. *Federal and State Endangered Species Expenditures*. USFWS, Washington, DC.
Ware, G. W. 1983. Reducing pesticide application drift-losses. College of Agriculture, Cooperative Extension, University of Arizona, Tucson.
White, D. H., C. A. Mitchell, L. D. Wynn, E. L. Flickinger, and E. J. Kolbe. 1982. Organophosphate insecticide poisoning of Canada geese in the Texas Panhandle. *J. Field Ornithol.* 53: 22–27.
Wigle, D. T., R. M. Samenciw, K. Wilkins, D. Riedel, L. Ritter, H. I. Morrison, and Y. Mao. 1990. Mortality study of Canadian male farm operators: non-Hodgkin's lymphoma mortality and agricultural practices in Saskatchewan. *J. Natl. Canc. Inst.* 82: 575–582.
World Health Organization/United Nations Environment Programme (WHO/UNEP). 1989. *Public Health Impact of Pesticides Used in Agriculture*. WHO/UNEP, Geneva, Switzerland.