Pesticides: Amounts Applied and Amounts Reaching Pests

Often, less than 0.1% of pesticides applied to crops reaches target pests

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Almost 500 million kilograms (kg) of pesticides, primarily synthetic organic chemicals but also including 27 million kg of sulfur and copper sulfate fungicides, are used in the United States each year to control pest arthropods, plant pathogens, and weeds (USDA 1982a). It is estimated that 341 million kg are used by farmers in agriculture (Eichers and Serletis 1982), 55 million kg by government and industry, 55 million kg in and around homes, and about 4 million kg on forests. In addition to these synthetic organic pesticides, an estimated 500 million kg of creosote, petroleum, and coal-tar products are used as biocides to preserve wood and other materials (USDA 1982a, USITC 1982).

Clearly then, pesticides play an important role in controlling pests in the United States and, in the first analysis, appear remarkably successful. In economic terms, for the $3 billion invested in pesticidal control, about $12 billion are returned in increased crop yield, an excellent return on investment (see Headley 1971, Pimentel et al. 1978). Another explanation for the increasing use of pesticides in agriculture is that pesticide prices rose far more slowly than the price of other agricultural inputs from 1971–1981: 78% for pesticides compared with 217% overall, including a 319% increase in interest rates (Eichers and Serletis 1982). These figures, however, do not factor in the social and environmental costs of damages from pesticides, which are estimated to be at least $1 billion annually (Pimentel et al. 1980).

> **Excess pesticide moves throughout the environment, contaminating soil, water, and biota**

Pesticide damage to the environment and to society results from both the handling and application of toxic chemicals. Our objective in this article is to describe where and how pesticides are applied and how they enter the water, soil, air, and biota in ecosystems, thus showing that extremely little pesticide actually reaches target pests. Most of what is applied enters the environment, contaminating the soil, water, and air and perhaps poisoning or adversely affecting nontarget organisms.

Extent of pesticide use

Of the estimated 500 million kg of pesticides used in this nation, 60% are herbicides, 24% insecticides, and 16% fungicides (Table 1). The 341 million kg of pesticides used in agriculture are applied to about 114 million hectares (ha). Sixty-two percent of the 185 million ha that are planted to crops are treated (Table 2).

The application of toxic chemicals for pest control is not evenly distributed among all agricultural crops. For example, 93% of the hectarage planted to row crops—corn, cotton, soybeans, sorghum, and tobacco—are treated with some type of pesticide; in contrast, less than 10% of the hectarage in forage crops are treated. Herbicides for weed control are currently being used on more than 100 million ha in the United States, more than half the nation's cropland. About 74% of these herbicides are applied to just two major crops, corn and soybeans. Field corn alone accounts for 53% of agricultural herbicide use. Increased use of herbicides on corn has gone hand-in-hand with minimum-tillage agriculture, which saves time and machinery while reducing soil erosion, but which substitutes chemical weed control for plowing weeds under the soil. The demand for herbicides in agriculture correlates both with major changes in farming practices, such as tillage methods, and also with variations in land area planted to major field crops.

The quantity of insecticides used, on the other hand, varies with insecticide type. Newer synthetic insecticides, phosphates, and carbamates, for example, require smaller quantities per season than did the chlorinated hydrocarbons of an earlier generation, such as toxaphene. In 1981, 74 million kg of insecticides were applied to some 34 million ha of cropland.

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ble 1. US hectarage treated with pesticides. Sources: available from the authors.

Land-use category	Total hectares (×10⁶)	All pesticides: Treated hectares (×10⁶)	All pesticides: Quantity (×10⁶ kg)	Herbicides: Treated hectares (×10⁶)	Herbicides: Quantity (×10⁶ kg)	Insecticides: Treated hectares (×10⁶)	Insecticides: Quantity (×10⁶ kg)	Fungicides: Treated hectares (×10⁶)	Fungicides: Quantity (×10⁶ kg)
ricultural lands	473 1169	114	341	109	199	34	74	5	68
Croplands	185	113	337	108	195	34	74	5	68
Pasture	288	<1	4	1	4	—	<1	—	—
overnment and industrial lands	150	28	55	30	44	—	11	—	—
rest lands	290	2	4	2	3	<1	1	—	—
ousehold lands	4	4	55	3	26	3	25	1	4
Total	917	148	455	144*	272	<38	111	11	72

Total for hectarage treated with herbicides, insecticides, and fungicides exceeds total treated hectares because the same land area can be treated with several classes of chemicals.

early 40% of the total amount was sed on cotton alone.

Fungicides and soil fumigants are sed primarily for fruits, vegetables, nd tobacco rather than field crops. ully one-third of the 15 million kg of oil fumigants used is applied to toacco fields to control nematodes.

Government agencies and industry ogether apply only an estimated 55 illion kg of pesticides, 80% of which are herbicides used on highways and powerline rights-of-way.

Virtually all households in the United States use pesticides in approximately equal amounts indoors and in urrounding lawn and garden areas Bennett et al. 1983, Savage et al. 980), for an estimated total of more han 55 million kg applied to some 4 nillion ha. Although this small mount of land receives a relatively igh dosage of pesticides (14 kg/ha), erhaps as much as a third of the esticides homeowners purchase is never applied and probably ends up n the trash, which eventually ends up n the environment.

Less than one percent of the 290 million ha of forest land is treated with pesticides (Table 1). Three times as much herbicide as insecticide is used in forests, primarily to clear sites for replanting and rights-of-way and to control competing vegetation (USDA 1982b).[1]

In sum, we calculate that a total of about 500 million kg of pesticide is applied on 150 million ha, an average dosage of about 3 kg per ha (see Table 1). About 16% of the total area of the United States thus receives some direct pesticide application each year.

Application methods

Pesticides are applied to destroy undesirable plants and animals. To combat some insects and pathogens, a protective coat of pesticide is placed on the susceptible portions of desirable plants and animals. For weeds and some public health and livestock insect pests, the goal is to get enough herbicide or insecticide onto the pest itself.

In fact, the amount of pesticide impinging on target pests is generally an extremely small percentage of the amount applied. For example, our calculations of pesticide consumed by *Pieris rapae* caterpillars in collards showed that 0.003% of the 1 kg/ha of pesticide applied was consumed by the target pests. These calculations were based on an infestation of 150,000 caterpillars/ha, each eating 0.1 cm^2/day, and included factors for plant leaf area and pesticide drift. This is about one-tenth the quantity calculated by Graham-Bryce (1975), who reported that aphids on field beans received only 0.03% and mirids on cocoa only 0.02% of the insecticides applied for their control. Even more striking, Joyce (1982) reported that only 0.0000001% of the DDT applied for *Heliothis* control reached these pests.

The amount of fungicide reaching target plant pathogens in a crop is

[1] J. Neisess, 1983, unpublished data. US Forest Service, Washington, DC.

Table 2. US croplands treated with pesticides. Sources: available from the authors.

Land-use category	Total hectares (×10⁶)	All pesticides: Treated hectares (×10⁶)	All pesticides: Quantity (×10⁶ kg)	Herbicides: Treated hectares (×10⁶)	Herbicides: Quantity (×10⁶ kg)	Insecticides: Treated hectares (×10⁶)	Insecticides: Quantity (×10⁶ kg)	Fungicides: Treated hectares (×10⁶)	Fungicides: Quantity (×10⁶ kg)
Croplands alone	185	113	337	108	195	34	74	5	68
Cotton	5	4.8	45	4.2	0.8	3	29	0.5	<1
Tobacco	0.5	0.5	2	0.3	0.5	0.4	1.4	0.5	<1
Corn	34	32	118	31	103	13	15	—	—
Soybeans	20	18	50	18	41	1.4	3.6	—	—
Vegetables	1.2	<1	11	—	} 9	1	5	0.5	6
Fruit	1.2	<1	89	—	}	1	10	1	60
Alfalfa & hay	24	1	5	0.2	1	0.4	2.7	—	—

probably even less than the proportion of insecticides reaching target insects because fungal targets are so small. In contrast, the amount of herbicide reaching target weeds is generally much higher. From 0.1 to 5% of postemergence herbicide applied to corn fields is calculated to reach the target weeds. When the herbicide is applied directly to a target weed tree, the proportion of the spray impinging on the tree might be as high as 80% (Haverty et al. 1983).

Except for direct spraying of weeds and trees, most sprayed pesticides do not reach target pests, particularly when applied to control flying insects like mosquitoes. To hit flying insects, spray droplets must be in the 2- to 16-micron (μ) size (Lofgren et al. 1973). Such small droplets are difficult to produce in large numbers and many drift beyond the target area, never touching the pests. Larger droplets, on the other hand, tend to bounce off the target surface or settle rapidly, with a low probability of coming into contact with their targets. Even under ideal laboratory conditions, where 200 spray droplets averaging 53 μ were applied to each square centimeter of leaf surface (Munthali and Scopes 1982), only about 10% of red spider mite eggs on the leaves were hit by droplets. It is thus nearly impossible to control insect and mite pests on crops by attempting to apply insecticides directly.

Controlling crop insects and pathogens may be done more effectively by spraying a protective cover on the vegetation. With this method, the amount of pesticide reaching targeted crop plants depends on droplet size, application method, height of the applicator nozzle head above the ground, and weather. For example, a spray boom with the nozzles directed downward, relatively close to the crops and ground and under relatively calm conditions, will place 90% or more of the spray in the target area. If, however, the spray is a mist of fine droplets (about 50 μ) and there is a 16-kph wind, then only 50–70% might remain in the target area (ICAITI 1977).

Aircraft are used to apply 20–25% of pesticides.[2] Spray drift from aerial application is about five times greater than from ground-rig applications for row crops (Medved 1975, Ware et al. 1969). For this reason, up to 30% more pesticide is sometimes applied per hectare from aircraft than from the ground (Bull 1982). In most situations, however, sufficient pesticide is applied so that if even as little as one-quarter of it reaches the target crop, it will usually be effective. Dosages recommended by manufacturers usually compensate for variation in application techniques and conditions.

But even under ideal aerial application conditions, only about 50% of the pesticide reaches the target area. In a carefully controlled test in cotton fields in Central America, for example, only 44% of the spray fell within the target area; the remainder fell beyond the borders of the 20-ha field or stayed in the air (ICAITI 1977). Similar results came from tests with cotton and alfalfa in Arizona; Ware et al. (1970) reported that less than 50% of the pesticide applied during the season landed in the target area.

When pesticides are applied aerially to forests, even more can be lost than from applications to field crops, partly because of the height from which the pesticides are sprayed. For example, in investigations measuring the amounts of insecticide reaching ground level when sprayed from heights of 50–170 m over mountainous forest terrain, only about 12% reached the trees and another 5% reached the ground in the test area (Maksymiuk et al. 1975). Under windy conditions with significant updrafts over forests or cropland, less than 10% of aerially sprayed pesticide may land in the target area.

Pesticide movement

Atmosphere. Pesticide droplets and vapor in the atmosphere can be widely distributed and may ultimately fall on soil, water, and nontarget organisms. In one study, all soil samples taken from Oregon coastal mountains 64 km from the western edge of agricultural regions contained DDT residues (Moore and Loper 1980). Since progressively greater concentrations of DDT were found in the soils closer to the agricultural region, DDT was very likely transported through the atmosphere from the cropland to the mountain soils.

Pesticide residues have been found in the atmosphere all over the globe but, as expected, at higher concentrations close to the regions where they were applied. DDT concentrations in the atmosphere over the Arabian Sea and Indian Ocean, offshore from nations where DDT is still heavily used, are 25–40 times the level in the atmosphere over the North Atlantic Ocean offshore from the United States, where DDT has been banned since the early 1970s (Bidleman and Leonard 1982). As expected, residue concentrations varied considerably among sampling stations within the same geographic region, suggesting that atmospheric pesticide concentration is a function of the location of the pesticide source, the wind direction moving particular air masses, and atmospheric transport time.

Volatilization is another major pathway by which pesticides reach the atmosphere and move from treated plants, soil, and water to other ecosystems. Maybank et al. (1978) reported that as much as 35% of the butyl ester of 2,4-D volatilized after being applied to Canadian prairie soils during the summer. This high level of vapor drift compares with only a 3% droplet drift resulting from ground applications of 2,4-D. In Austria, 75% of spray damage from herbicides may be caused by vapor rather than droplet drift (Thompson 1983).

The amount and rate at which pesticides volatilize depend on the pesticide's vapor pressure; environmental conditions, especially temperature; soil type; and soil management practices. Not unexpectedly, pesticides volatize more rapidly if they are applied to the soil surface rather than incorporated into the soil (Talekar et al. 1983).

Although pesticide vapors can be toxic, they can rapidly disperse to harmless concentrations. When Harris and Lichtenstein (1961) exposed house flies 0.6–1.3 cm above soils treated with lindane, aldrin, dieldrin or phorate, 50% of the flies died; however, mortality was only 8–11% when the flies were held 3.1–3.8 cm from the soil.

Soil. Soil is the primary receptacle for pesticides that miss or run off from

[2] R. L. Zimdahl, 1982, personal communication. Department of Botany and Plant Pathology, Colorado State University, Fort Collins.

pesticides include crops, such as cotton, orchards, corn, soybeans, and vegetables receiving large quantities; areas adjoining heavily treated croplands, which receive pesticide drift, especially where aircraft apply the pesticides, and/or the pesticides have high volatilization rates; and aquatic ecosystems, which often receive runoff from pesticide-treated areas. Integrated pest management (IPM) programs attempt to reduce stress on these systems by decreasing the total quantities of pesticides applied and employing pesticides with less impact on beneficial predator and parasite populations (ICAITI 1977, Pimentel 1982).

When enough pesticides reach an ecosystem, they alter both its structure and function. Because pesticides are poisons, a certain number of species belonging to the ecosystem will be eliminated in the affected area, or their populations will be significantly reduced. When species richness is seriously reduced, parasites and predators high in the trophic system that depend on hosts and prey below them will be seriously affected (Pimentel and Edwards 1982, Risch et al. 1986). Thus, parasites and predators are often more severely affected than organisms low in the trophic hierarchy.

Reducing species richness and altering an ecosystem's structure may well change its stability. When some predator and parasite species are reduced, outbreaks of certain prey and host species may also take place in crops (Croft and Brown 1975, Pimentel et al. 1979). Studies of pesticide effects on soil fauna have reported increased numbers of Collembola and Acarina because the toxic chemicals had reduced the populations of these species' natural enemies (Edwards and Thompson 1973, van de Bund 1965).

In addition to energy flow, the recycling of vital elements such as C, N, H, P, K, Ca, and Mg is essential to ecosystem functioning. Pesticides can alter the chemical makeup of plants and soils. Certain organochlorine insecticides, for example, have increased the amounts of some macro- and microelement constituents (N, P, K, Ca, Mg, Mn, Fe, Cu, B, Al, Sr, and Zn) of corn and beans and decreased the amounts of others (Cole et al. 1968). Also, the sensitivity of some soil microbes to pesticides can alter the speed or efficiency of nutrient cycling. The herbicide EPTC, for instance, was found to impair the decomposition of cellulose in soil (Sobieszczanski 1969), and other herbicides have been reported to inhibit nitrification (Debona and Audus 1970). Therefore, pesticides that directly affect plants and one or many decomposer organisms may significantly alter the productivity and stability of ecosystems.

Conclusion

Of the approximately 500 million kg of pesticides applied in the United States, often less than 0.1% of those applied to crops actually reaches target pests. Thus, over 99% moves into ecosystems to contaminate the land, water, and air. Research is desperately needed to develop means of delivering more pesticide directly to target pests. Most of the nation's 200,000 some species of plants and animals are affected directly or indirectly by the enormous quantity of pesticides released into the environment. Many natural parasitic and predator species are reduced, resulting in outbreaks of pests that were previously not a problem (Adkisson 1977); about $153 million is spent each year on additional pesticides to control these newly created pests (Pimentel et al. 1980). The excess pesticide in the environment also exposes pest populations to widespread selective pressures, thus contributing to the development of pesticide resistance (Dover and Croft 1984; see p. 78 this issue), a problem estimated to cost the nation at least $134 million per year.

Human poisonings are clearly the highest price paid for pesticide use. An estimated 45,000 total human poisonings occur annually, including about 3000 cases admitted to hospitals and about 200 fatalities (~ 50 accidental deaths) (Pimentel et al. 1980).

At present, direct costs for pesticides and their application amount to some $3 billion annually; social and environmental costs account for about another $1 billion. For this $4 billion associated with pesticide use, we gain some $12 billion in benefits from pest control (Pimentel et al. 1980). Improved pesticide application technologies should help reduce pesticide use by at least half without diminishing the effectiveness of pest control. Such an accomplishment would greatly benefit public health and the environment.

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