Amounts of Pesticides Reaching Target Pests: Environmental Impacts and Ethics

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Abstract *Less than 0.1% of pesticides applied for pest control reach their target pests. Thus, more than 99.9% of pesticides used move into the environment where they adversely affect public health and beneficial biota, and contaminate soil, water, and the atmosphere of the ecosystem. Improved pesticide application technologies can improve pesticide use efficiency and protect public health and the environment.*

Keywords: pesticides, pests, targets, application, technology, agriculture, environment.

Introduction

Although humans cultivate and consume approximately 25,000 crop species, almost 90% of human plant food is provided by only 15 species of food crops (Mangelsdorf, 1966). These 15 species, including many of the basic cereal crops are cultivated throughout the world and provide the major share of the food supply.

Worldwide an estimated 67,000 different pest species attack agricultural crops. Included are approximately 9,000 species of insects and mites, 50,000 species of plant pathogens (USDA, 1960), and 8,000 weeds (Ross and Lembi, 1985). In general, less than 5% are considered serious pests. From 30 to 80% of the pests in any geographic region are native to that region. In most instances the pests, which are specific to a particular region, have moved from feeding on native vegetation to feeding on crops which were introduced into the region (Pimentel, 1988; Hokkanen and Pimentel, 1989).

Despite the yearly application of an estimated 2.5 million tons of pesticides worldwide, plus the use of biological controls and other non-chemical controls, about 35% of all agricultural crop production is lost to pests (Pimentel, 1990). Insect pests cause an estimated 13% crop loss, plant pathogens 12%, and weeds 10% (Cramer, 1967). In the United States, yearly crop losses to pests are estimated to reach 37% (Pimentel et al., 1991). Indeed, pests are destroying an enormous amount of food and fibre despite all our efforts to control them with pesticides and various non-chemical controls.

Of the total 2.5 million tons of pesticides applied to crops, approximately 20% is applied in North America and 20% in developing countries (Pimentel, 1990). The remaining 60% is applied in Europe and elsewhere in the world. Few studies have investigated the question how much of the applied pesticide actually reaches the target pests. The objective of this study is to assess the amount of applied pesticides that reaches the target pests, the amount of drift that occurs, and the amount of pesticide that impacts on humans and other non-target species in the environment.

Extent of Pesticide Use Worldwide

Of the total amount of pesticide applied worldwide from 50 to 60% is herbicides, 20 to 30% is insecticides, and 10 to 20% is fungicides. Despite the fact that 2.5 million tons of pesticides are applied to crops, only about one-third of the world's cropland is treated with pesticides. This fact confirms that a significant portion of agricultural crops receives no pesticide treatments and therefore is protected to some extent by non-chemical biological and cultural controls.

Furthermore, the application of pesticides is not evenly distributed among crops. For example, most pesticide is used on high value crops like cotton, fruit, vegetable, maize, and rice crops. In contrast, little pesticide is used on forage crops and most small grain crops (Pimentel et al., 1991).

Although large quantities of pesticides are applied to few crops, less than 0.1% of these chemicals actually reaches the target pests (Pimentel and Levitan, 1986). This means that more than 99.9% of the applied pesticides move into the environment where they can adversely affect beneficial biota, like natural enemies, and contaminate the soil, water, and the atmosphere of our ecosystem (Pimentel et al., 1992).

Pesticide Drift and Application Technologies

Pesticide application technologies vary from handheld sprayers to aircraft (Matthews, 1992; Matthews and Hislop, 1993). A large amount of pesticide is lost using many of the common application technologies (Pimentel et al., 1991; Matthews, 1992). For instance, with the increasingly popular aircraft application technology using ultra-low volume (ULV) spray equipment only about 25% of the pesticide reaches the target area and the remainder drifts away (Mazariegos, 1985). ULV spray equipment breaks the pesticide spray into micro droplets to provide necessary coverage of the crop vegetation. Because the micro droplets are extremely small and light in weight, they are easily transported away from the target area by wind and updrafts. Note that the figure of 25% of pesticide applied by ULV reaching the target area refers to applications made under ideal weather conditions, that is under minimal wind conditions.

The use of ULV application technology by aircraft is expanding because a larger payload of pesticide can be carried per aircraft trip compared with the use of regular spray mixed with large quantities of water. For example, using water-diluted spray about 76 litres of mixed spray are applied per hectare, whereas using a spray concentrate with ULV only 16 litres of spray are applied per hectare (Yates et al., 1977). However, with nearly five times more spray applied with the diluted spray, the droplets are larger and more fall in the target area in contrast to the micro droplets produced by ULV spray equipment that easily drift away (Matthews, 1992).

With concentrated spray, the percentage of pesticide reaching the target area is about half compared with the water-diluted spray (Argauer et al., 1968; Ware et al., 1969; Ware et al., 1970; Ware et al., 1975; ICAITI, 1977; Akesson and Yates, 1981, 1984; Ware, 1983). Clearly, applying water-diluted spray doubles the total amount of pesticide in the target area compared with ULV equipment. However, it is still not satisfactory when impacts on the environment and waste of pesticide are considered.

Under ideal weather conditions and using water-diluted spray from an aircraft, about 50% drifts out of the target area. Approximately 7% of the total spray can be found as far as 48 m. to 0.8 km. downwind (Yates and Akesson, 1973). Pesticide drift from aircraft has damaged crops from 5 to 32 km. downwind and lawsuits have occurred because of this drift (Jensen, 1968).

The best technique to use when applying pesticides by aircraft is to spray the pesticide at a height of about 1.5 m. If the pesticide spray is applied at a height of 6 to 8 m., the amount of drift at 0.8 km. downwind is increased two-fold (Yates and Akesson, 1973). However, if weather conditions are even slightly unfavourable, then applying pesticides by aircraft will increase the drift problem. Pesticides may drift from 0.8 km. to ten times this distance even at the height of 1.5 m.

When pesticides are applied to forests by aircraft, large amounts of pesticide drift away from the target area because of the height at which the pesticides must be sprayed (Ekblad and Barry, 1984; Rafferty and Bowers, 1993; Teske and Barry, 1993; Teske and Bowers, 1993). For example, in investigations measuring the amounts of insecticide reaching ground level when sprayed from heights of 50 to 170 m. over mountainous forest terrain, only about 12% reached the trees and then only 5% reached the ground in the test area (Maksymiuk et al., 1975). However, others have reported up to 30% reaching the ground (Barry, 1993). Clearly, a significant amount of pesticide is wasted and drifts off into the environment to poison humans, birds, fish, and other natural biota when pesticides are applied by aircraft. For these reasons, aircraft application of pesticides is the most wasteful and hazardous method of applying pesticides both in agriculture and forestry.

In addition to aircraft, pesticides are applied using various kinds of ground-based equipment. Applying pesticides using a mist blower also causes significant drift, however, the drift is not as severe as with aircraft application. Pesticide drift, for example, from the mist blower was detected nearly 2 km. downwind from the targeted alfalfa crop, but was twice as great when applications to alfalfa were made by aircraft (Ware et al., 1969).

Airblast sprayers, which also blow a mist of spray toward the target, are utilized to treat orchards and other trees with pesticides (Matthews, 1992). Approximately 65% of the spray applied with airblast sprayers remains in the target area, but 35%

drifts away from the target area (Byers et al., 1985). Because more total pesticide is applied by airblast sprayers than by aircraft, more pesticide in general drifts away from the target area using airblast sprayers than occurs with aircraft application (Hall, 1991). However, a newly designed nozzle for airblast sprayers allows the amount of insecticide and miticide to be reduced by 50% while still maintaining the same effective control of pests (van der Scheer, 1984). Overall, drift is also reduced.

Even spray booms which are extended about 0.3 m. above a crop with the spray nozzles directed downward lose some spray because of drift, depending on the crop and weather conditions (Miller, 1993). For example, with a spray boom from 70% to 90% of the spray lands in the target area and only 10% to 30% drifts out of the area (Pimentel and Levitan, 1986). If a shroud is placed over the boom and row, then less than 5% is lost during the application (Rogers, 1987). Using this type of equipment significantly improves the efficiency of placing the spray in the target area. A related technology includes placing a tunnel over the row and directing the spray on the crop within the tunnel (Matthews, 1985, 1992). With this device any added spray that is not captured by the crop is caught in troughs surrounding the bottom part of the tunnel and can be pumped back into the spray tank to be reused.

To control weeds, rope-wicks soaked in herbicide are dragged over the weeds in the rows of the crop (Dale, 1980; Matthews, 1992). By this means about 90% of the herbicide is placed on the weeds and there is no drift. Clearly, any application technology that places more of the pesticide on the target pest and less in the soil, water, air, and on non-target organisms wastes less pesticide, is more economical and is less hazardous to public health and the environment than those that do not restrict the pesticide to the target pests (Reardon, 1988).

Amounts of Pesticide Reaching Target Insect Pests

The amount of pesticide either actually coming in direct contact with or being consumed by target pests is an extremely small percentage of the amount applied. For example, when a carbaryl insecticide was applied to collards at a dosage of 1 kg/ha only 0.003% was consumed by the cabbage white butterfly caterpillars, *Pieris rapae*, the target pest (Pimentel and Levitan, 1986). The calculations were based on a field infestation of 150,000 caterpillars per hectare, each eating 0.1 cm.^{2} per day, and included measurements of 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%, while mirids on cocoa received only 0.02% of the insecticides applied for their control (Table 1). In contrast, Joyce (1982) reported that only 0.0000001% of the DDT applied for *Heliothis* reached the target pests.

Several assessments of the amounts of pesticides reaching target insects were based on data in the literature plus several assumptions on the insect pest density per hectare and their average weight. In most studies the amounts of pesticides reaching the target pests were found to be less than 0.3% and averaged only 0.089%. In most cases, the amounts reaching target pests will be extremely small because a large amount of pesticide has to be applied to the crop to cover the plant's leaves, fruits, and stems. The treatment goal is to poison the target pest after it consumes

Table 1
The amounts of insecticides reaching different target pests in various crops based on estimates for insect densities and weights for all except for aphids on beans, mirids on cocoa, and *Heliothis*

Insect	Population density/m^2	Insecticide g/ha	% Insecticide on target pests
Cereal aphid	20	Dimethoate 120	0.048
Cereal aphid	20	Permethrin 50	0.020
Diamondback moth	100	Difenthiuron 100	0.001
Diamondback moth	100	DFCD 100	0.001
Cabbage white	15	Sevin 1000	0.003
Budworm	10	Parathion, Methyl 25	0.28
Budworm	10	Methomyl 1000	0.25
Budworm	10	Permethrin 150	0.033
Bollworm	10	Parathion, Methyl 25	0.28
Bollworm	10	Methomyl 1000	0.25
Bollworm	10	Permethrin 150	0.033
Potato beetle	10	Fenalerate 1100	0.08
Aphids on beans	—	—	0.03
Mirids on cocoa	—	—	0.02
Heliothis	—	DDT	0.0000001

Sources of data: cereal aphid: Cayley et al. (1987); diamondback moth: Kadir and Knowles (1991); budworm and bollworm: Herzog and Ottens (1982); potato beetle: Zehnder and Evanlylo (1989); aphids on beans and mirids on cocoa: Graham-Bryce (1975); *Heliothis*: Joyce (1982); cabbage white: Pimentel and Levitan (1986).

only a small portion of any crop plant. Therefore, the amount of the crop plant and in turn the amount of pesticide on the tiny fraction of the plant consumed by a pest is minute (Pimentel and Levitan, 1986).

If the target insect pests could be attracted to feed on pesticide-treated bait, the amount needed for pest control would be extremely small. A new technique developed for control of the corn rootworm in corn is based on this idea. Using a pheromone attractant, corn rootworm adults are attracted to come to an insecticide poisoned bait (Metcalf and Lampman, 1989a, 1989b). With this technique, the amount of insecticide required to control the target pest can be reduced by more than 99%.

Unfortunately, at present there are only a few technologies that attract pest insects to insecticide-treated baits. Therefore, in most cases the crop plant must be covered with a coating of the pesticide to ensure killing target insect pests.

A similar approach is employed for plant pathogen control in crops using fungicides. Although it has not been investigated, the amount of fungicide reaching target fungal pathogens is probably less than the amount of insecticide reaching target insect pests (Pimentel and Levitan, 1986). For weed control, slightly more herbicide reaches the target weeds than insecticide that reaches target insect pests. However, the amount is estimated to be less than 1%. An exception would be when the herbicide is injected directly into the target weed-tree (Haverty et al., 1983).

Although seldom used for insect control in crops, fine mists are used to control flying pest insects in the home, yards, and urban areas. To ensure insects fly into the insecticide spray droplets, they must have a size of 2- to 16 micron (Lofgren et al., 1973). Such small droplets are difficult to produce and most drift beyond the target area, frequently never touching a target pest. Larger droplets, on the other hand, tend to bounce off the target surface or settle rapidly, diminishing the probability that they will come into contact with their targets. Using a mist for flying insect control probably results in less pesticide reaching the pest than when pesticides are sprayed to cover plants. The estimate is that less than 0.0001% of the insecticide applied as a mist reaches the flying pest insects.

Even under ideal laboratory conditions, where 200 spray droplets averaging 53 microns were applied to each square centimeter of leaf surface, only about 10% of the red spider mite eggs on the leaves were hit by the droplets (Munthali and Scopes, 1982). This shows how difficult it is to control insect and mite pests on crops by applying insecticides directly on the target pests on the crop itself.

Pesticide Movement in the Atmosphere

Earlier it was mentioned that pesticide droplets can be carried long distances by wind and air currents and fall on soil, water, and non-target plants and animals far distant from the treated area. In addition to the ease with which droplets can be carried in the wind and air currents, most pesticides are volatile and can be carried in the vapour phase for extremely long distances. Pesticides have been found in places far distant from where any pesticide had been applied, such as in ocean fog (Schomburg and Glotfelty, 1991); in arctic snow (Gregor and Gummer, 1989; Bidleman et al., 1990; Gregor, 1990); and, in the Atlantic Ocean (Seba and Prospero, 1971; Graham and Duce, 1982). An investigation in Oregon showed that soil samples taken from the coastal mountains 64 km. from the western edge of the agricultural region contained DDT residues (Moore and Loper, 1980). Progressively greater concentrations of DDT were found in the soils close to the agricultural region, indicating that the pesticides were likely transported by the prevailing winds from the treated crop to the mountain soils.

In addition to some insecticides, many herbicides volatilize rapidly and are detected in the atmosphere. For instance, in Saskatchewan, Canada, as much as 20% of the herbicide 2,4-D iso-octyl ester was found to be volatilized within 24 hours after application and 99.9% had volatilized from the plant surfaces after five days (Shewchuk, 1982). This is the reason some crops like grapes were injured after areas adjacent to the vineyards were sprayed with 2,4-D (Farwell et al., 1976). Other herbicides, such as triallate and trifluralin, lost by volatilization about 50% of the deposit within a few days after application, especially when application was made to moist soil surfaces (Grover, 1986). Analyses have shown that insecticides and herbicides, including heptachlor, lindane (BHC), chlordane, atrazine, simazine, alachlor, metachlor, toxaphene, and DCPA, volatilize from the soil and enter the atmosphere (Spencer and Cliath, 1990; Glotfelty et al., 1990). Another example of pesticide volatilization is that of the herbicide EPTC from irrigation water. Spencer and Cliath (1990) report that about 74% of it volatilized within 52 hours after application.

Pesticide residues have been found in the atmosphere throughout the world, and, as expected, at higher concentrations close to the regions where they were applied. DDT concentrations in the offshore atmosphere over the Arabian Sea and Indian Ocean, from adjacent nations where DDT is still heavily used, are 25 to 40 times the level found in the atmosphere over the North Atlantic Ocean near the United States, where DDT has been banned since the early 1970s (Bidleman and Leonard, 1982). Giam et al. (1980) reported that average DDT levels in the atmosphere over the Arabian Sea and Indian Ocean were ten times the levels found over the North Atlantic. As expected, residue concentrations varied considerably among sampling stations within the same geographic region, suggesting that the atmospheric pesticide concentration is a function of the location of the pesticide source, the wind direction, and the atmospheric transport time.

DDT and BHC, chlorinated insecticides, have been transported to the Antarctica via the atmosphere and ocean currents (Tanabe et al., 1983). As mentioned, the concentrations of DDT and BHC were much higher over the Indian Ocean than over the Atlantic Ocean (Tanabe and Tatsukawa, 1980). These investigators propose that in addition to the atmosphere, most of the pesticides are transported through the Indian Ocean and Atlantic Ocean to the Antarctic region.

In addition to the observed regional variation, seasonal variation in the presence of DDT and BHC was detected in the atmosphere. Tanabe et al. (1983) reported that these pesticides were significantly more abundant in the summer than in the winter. This would be expected because most pesticides are applied during the summer months when crops are grown. Pesticides are removed from the atmosphere by rain and snowfall and deposited in aquatic and terrestrial ecosystems.

The problem of chlorinated pesticides drifting and moving in the environment will continue as long as these persistent chemicals continue to be used. In fact, the use of DDT and BHC is increasing in some developing countries. For instance, the use of DDT and BHC has been growing in India and now these two insecticides make up 70% of pesticide use in India (Singh, 1993).

The amounts of pesticides and other organic compounds transported in the atmosphere are enormous. In the atmosphere of the Netherlands, the amounts of BHC, DDT, and heptachlor were reported to be 4600, 1064, and 190 pg/m^3, respectively (Plimmer and Johnson, 1991). The deposition of organic compounds in the Netherlands is estimated to be 89,000 tons per year (Plimmer and Johnson, 1991). However, a great many other types of pesticides were also measured in the atmosphere.

Because large amounts of pesticides are easily transported in the atmosphere they can have major deleterious effects upon environments far distant from where they were applied. The amounts reaching non-target ecosystems depend on the quantities of pesticides applied nearby, their vapour pressure, prevailing winds, rain and snowfall, and temperatures. Also, there is a variation in the amounts being deposited in ecosystems depending on the season. On average, more is deposited during the summer months than the winter.

Environmental and Health Hazards of Pesticides Missing Target Pests

Human pesticide poisonings and illnesses are the highest price paid when pesticides reach non-target areas. A recent World Health Organization and United Nations Environmental Programme report (WHO/UNEP, 1989) estimated there are one million human pesticide poisonings each year in the world, with about 20,000 reported deaths. In the United States, non-fatal pesticide poisonings reported by the American Association of Poison Control Centers total about 67,000 each year (Litovitz et al., 1990). The number of accidental fatalities (no suicides or homicides) is about 27 per year in the United States.

Based on the available data, the health and environmental costs of pesticide use in the United States total approximately $8 billion each year (Pimentel et al., 1992). The environmental costs include domestic animal poisonings; beneficial natural enemy destruction; honey bee and wild bee kills; fish kills; development of pesticide resistance; destruction of non-target crops; bird and wild mammal kills; and pesticide contamination of groundwater.

However, it must be emphasized that the public health costs of pesticides cannot be accurately assessed and are probably underestimated (Pimentel et al., 1992). In addition there are other additional costs that have not been included in the $8 billion/yr. figure. A complete accounting of the indirect costs should include: accidental poisonings like the "aldicarb/watermelon" crisis in California; domestic animal poisonings; unrecorded losses of fish, wildlife, crops, trees and other plants; losses resulting from the destruction of soil invertebrates, microflora, and microfauna; true costs of human pesticide poisonings; water and soil pollution; and human health effects like cancer and sterility (Pimentel et al., 1992). If all the environmental and health costs could be measured, the total cost would be significantly greater than the estimate of $8 billion/yr.

Nonetheless, based on what is known, these data confirm the need for more research to improve the technologies of pesticide application to place more chemical on target pests and to minimize undesirable impacts on human health and the environment.

Conclusion

Even though about 2.5 million tons of pesticides are applied worldwide each year, approximately 35% of all agricultural crop production is lost to pests. Insecticides make up 20 to 30% of the total pesticide applied while 50 to 60% are herbicides and 10 to 20% are fungicides.

Although large quantities of pesticides are applied to crops, only a few crops receive most of this pesticide. These include cotton, fruit, vegetable, maize, and rice crops. Little pesticide is used on forage crops and most grain crops.

Despite the application of 2.5 tons of pesticide, in general less than 0.1% actually reaches the target pests. The two major causes for this small amount of pesticide reaching target pests are: (i) the pesticide application technologies employed; and

(ii) the minuscule amount of pesticide picked and/or ingested by each target pest. A large amount of pesticide is lost during the application process. For instance, with the increasingly popular aircraft application technology of using ultra-low volume (ULV) spray equipment only about 25% of the pesticide reaches the target crop area while the remainder drifts away. Therefore even under ideal conditions, most of the pesticide applied using ULV equipment drifts off into the environment rather than reaching the target area and pests. The reason for the popularity of ULV is that about five times more pesticide can be carried per application air-trip. Of course, to achieve adequate coverage of the crop plants, the droplets of pesticide have to be extremely small which facilitates the droplets easily being carried outside the target area.

Even using the normal diluted spray in aircraft applications, only 50% falls in the target area while the other half drifts off into the environment under ideal weather conditions. Pesticide drift from aircraft is not only a problem to the environment, but also a problem to other crops when beneficial organisms are eliminated. Although evidence of pesticide drift commonly is found from 48 m. to 0.8 km. downwind from the target area, drift has reached as far as from 5 to 32 km. downwind.

Although ground application equipment places significantly more pesticide in the target area than aircraft application, it also has some drawbacks. For example, airblast sprayers, that are frequently used to treat orchards and other trees, place about 65% of the pesticide spray in the target area, while about 35% drifts away. With the application of pesticides employing a spray boom, that extends about 30 cm. above the crop with the spray nozzles directed downward, from 70 to 90% of the spray is contained in the target area and when a shroud is placed over the spray boom and row, up to 95% of the spray can be contained in the target area.

Relatively little pesticide is required to kill the pests. Usually a pest consumes and/or injures a maximum of 0.1 to 0.5 $cm.^2$ of the crop plant before it dies from the pesticide. Based on research data it is estimated that pest insects consumed from 0.28 to 0.0000001% of the total pesticide applied. Improved methods of application, that include using a poisoned bait for some insect pests, have demonstrated that the amount of pesticide used in the crop can be reduced by 99%. This technology not only uses 99% less pesticide but helps reduce environmental pollution. Further research is needed on using baits to control insect pests.

In addition to pesticide droplets being carried in the wind and air currents, most pesticides are volatile and thus can be carried in the vapour phase in the atmosphere thousands of kilometers downwind. For example, measurable amounts of various pesticides have been found over the Arabian Sea, Indian Ocean, and North Atlantic Ocean. Some pesticides have been transported as far as Antarctica via the atmosphere and oceans.

In conclusion, generally less than 0.1% of the pesticide applied to crops reaches the target pests. Pesticide application methods must be improved to ensure that more pesticide reaches the target pests and less pesticide escapes and causes serious damage to public health and the environment. Better and safer application technologies will reduce the waste of pesticide and at the same time help protect farmers, improve the economics of pest control, and make agriculture environmentally and ethically sound.

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