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Volatilization of Surface-Applied Pesticides from Fallow Soil

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Various combinations of heptachlor, chlordane, lindane, trifluralin, and dacthal were sprayed as intimate mixtures onto bare soil and allowed to remain on the surface. Three field experiments were run on two soils. Volatilization losses were estimated from the measured decrease in soil residues and by vertical flux rates calculated by using the aerodynamic method and measured vapor density profiles over the field. Initial rapid volatilization rates from a moist silt loam soil were proportional to pure-compound saturation vapor densities. Half of all chemicals except dacthal disappeared in less than 3 days. Long-term losses were controlled by diffusion from a thin layer of soil. By contrast, loss rates from a very sandy soil were much slower, probably because the lack of capillary wetting created a dry soil surface: volatilization rates remained low until moisture was supplied to the surface, and peak rates coincided with dew formation after dark.

Volatilization and air transport is a major pathway of pesticide movement, and the scientific literature abounds with evidence that many different pesticides may be found at various times in the atmosphere (Lee, 1976). Some are evidently transported long distances and return to the surface as widespread environmental contamination (Eisenreich et al., 1981; Atlas and Giam, 1981; Zell and Ballschmitter, 1980; Harder et al. 1980). Factors controlling pesticide volatilization have been extensively studied in the laboratory and in microenvironmental chambers, but relatively few field measurements of post-application volatilization losses have been reported.

In pioneering work, Parmele et al. (1972) described various micrometeorological techniques for making field-scale measurements of pesticide volatilization rates. Although several techniques are feasible, only the aerodynamic, or momentum balance method has been widely used. Using this technique, Willis et al. (1972) estimated dieldrin losses from flooded, moist, or nonflooded fallow soil. Taylor et al. (1976) estimated seasonal losses of

Table I. Soil Properties of the Beltsville and Salisbury Field Locations

soil separates	% composition	
	Hatboro silt loam (Beltsville)	Norfolk sandy loam (Salisbury)
sand	23	75
silt	57	8
clay	20	17
organic matter	1.2	0.6

dieldrin and heptachlor incorporated into the soil of a growing corn crop. In a follow-up study, Taylor et al. (1977) compared losses of these same two pesticides from a 10-cm stand of orchard grass. Harper et al. (1976) studied soil and microclimate effects on volatilization of trifluralin from soil. White et al. (1977) estimated seasonal losses of trifluralin following shallow soil incorporation. Turner et al. (1978) compared volatilization losses of chlorpropham from applications of emulsion and microencapsulated formulations. Cliath et al. (1980) measured volatilization losses of eptam from water and wet soil following flood irrigation of alfalfa, and Willis et al. (1980, 1983) measured toxaphene and DDT volatilization from cotton fields.

We report the results of three field experiments. In each, we applied two or more pesticides to fallow soil as a homogeneous spray mixture. Their simultaneous volatil-

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ization allowed us to assess the importance of chemical properties, diffusion, solar energy input, and soil moisture distribution in controlling losses of unincorporated pesticides.

EXPERIMENTAL SECTION

Beltsville Site. Initial field measurements (experiments 1 and 2, described below) were made on the South Farm of the Beltsville Agricultural Research Center. A complete description of the site (South Farm plots 13 and 14), with topographic survey map, is given elsewhere (Glotfelty, 1981). Soil properties are described in Table I. The treated area was nearly rectangular, averaging about 90 m wide and 180 m long (1.6 ha), with the long axis running north to south. The field sloped downward 2.5–3% from east to west. A wooded area 200 m to the east and an interstate highway 600 m to the north were the nearest obstructions to wind flow. The most open and level surrounding terrain was in the north-to-west quadrant; fortunately, winds prevailed from this quadrant during many air sampling periods.

Experiment 1. On Aug 8, 1975, a homogeneous spray mixture containing heptachlor (1,4,5,6,7,8,8-heptachloro-3a,4,7,7a-tetrahydro-4,7-methanoindene), trifluralin (α , α -trifluoro-2,6-dinitro-*N,N*-dipropyl-*p*-toluidine), and dacthal (dimethyl tetrachloroterephthalate) was applied to the field with a tractor-mounted sprayer. The spray mixture also contained a small amount of chlordane (1,2,4,5,6,7,8,8-octachloro-2,3,3a,4,7,7a-hexahydro-4,7-methanoindene), a heptachlor formulation impurity. Heptachlor and trifluralin were formulated as emulsifiable liquid concentrates, while dacthal was formulated as a 75% wettable powder. Nominal application rates were 2.84 kg ha⁻¹ trifluralin, 3.55 kg ha⁻¹ heptachlor, 0.72 kg ha⁻¹ chlordane, and 5.11 kg ha⁻¹ dacthal.

Air samples were taken throughout Aug 8–9, starting within 1 h of application and continuing for 23 chosen 1-h intervals. The soil was moist throughout this period. Soil samples were taken 1, 6, 10, 29, 34, and 52 h and 11 and 20 days after application. Five 4 cm diameter \times 5 cm deep cores from each of five field locations were taken at each sampling period.

Experiment 2. In a second experiment on the same site, trifluralin and lindane (γ ; 1,2,3,4,5,6-hexachlorocyclohexane) emulsions were applied as a spray mixture on June 10, 1977. Due to rain of the previous week and on the evening before spraying (2.0 cm on June 6–7 and 2.1 cm on June 9), the soil surface was more compacted than in the first experiment, and the field was damp and drying at the time of application. The nominal application rates were 1.10 kg ha⁻¹ lindane and 2.80 kg ha⁻¹ trifluralin. Air sampling operations began within 1 h of application and continued at chosen intervals until late on June 11: in all, air was sampled during 18 1-h periods. Soil samples were taken 1, 4, 20, 31, and 75 h after application. At each sampling, 16 cores were composited from each of five field locations.

Salisbury Site. A final field experiment (experiment 3, described below) was conducted at the University of Maryland's Vegetable Research Farm near Salisbury, MD. Soil properties are given in Table I. The site was a 1.6-ha plot in a level field surrounded by similar flat, bare fields in all directions. The nearest obstructions affecting wind flow were over 800 m north, 300 m east, 400 m south, and 2000 m west.

Experiment 3. On June 14, 1978, pesticides were applied as a homogeneous spray mixture of emulsifiable concentrates. The nominal application rates were 2.50 kg ha⁻¹ trifluralin, 3.75 kg ha⁻¹ heptachlor, 0.84 kg ha⁻¹

chlordane, and 0.62 kg ha⁻¹ lindane. The spray was applied in a manner that yielded a treated circle. By collection of air samples at the center of this circle, a constant 64-m fetch was obtained independent of wind direction.

Air sampling began 2 h after application and continued at intervals throughout June 14–15; in all, air was sampled during 18 1-h periods. Soil samples were taken from eight field locations at 5, 11, 29, 34, and 50 h after application. Soil sampling was done differently; instead of cores, a 0.02-m² metal template was forced 5 cm into the soil, and all the soil within the template was excavated.

Pesticide Analyses. The air sampling mast, collection media, and methods of analysis are described in detail elsewhere (Turner and Glotfelty, 1977; Glotfelty, 1981). Air samples were taken at 12 heights that were spaced at approximately equal intervals on a logarithmic scale above the surface. They were between 5 and 190 cm in experiment 1 and between 10 and 190 cm in experiments 2 and 3. At each level, air was drawn at 3–3.5 m³ h⁻¹ through 4.5 cm diameter \times 5 cm deep porous polyurethane foam (PPF) plugs inserted in light-shielded filter tubes. Sample flow rates were determined by momentarily attaching a rotameter (size no. 5, Gilmont Instruments, Inc.) to each sample intake. Tests showed that PPF plugs quantitatively trapped the pesticides under the study conditions. Pesticides were recovered from exposed plugs by Soxhlet extraction with hexane. Minimum detectable concentrations for all pesticides in the air were less than 1 ng/m³.

Soil samples were sealed in Teflon film and, if necessary, frozen for storage until analyzed. The moist samples were mixed and sieved through a standard no. 4-mesh screen to remove small stones. Pesticide content and moisture were determined on 50–100-g subsamples obtained by passing the sample through a riffle-type sample splitter (VWR Scientific, catalog no. 56720–060). The samples for pesticide analysis were extracted by vigorous shaking with 1:1 hexane-2-propanol for 30 min in a glass jar sealed with Teflon film. If necessary, water was added to the sample prior to extraction in order to bring it to at least 50% of field moisture capacity. After the soil settled, an aliquot of the extract was transferred to another flask and shaken with water. Upon phase separation, an aliquot of the upper hexane layer was injected directly into the gas chromatograph for analysis. Overall recovery was 90–100% using this technique.

All pesticides were analyzed by using a Tracor Model 222 gas chromatograph equipped with a ⁶³Ni electron-capture detector, operated in the pulsed mode with linearized output. The carrier gas was 95:5 Ar-CH₄. In the first Beltsville experiment, the 1.83 m \times 2 mm i.d. glass "U" column was packed with 3% DC-200 on 100–120-mesh Gas-Chrom Q (Applied Science Laboratories, Inc.) The carrier gas flow rate was 40 mL/min. In the second and third experiments, the column was packed with a 1:1 mixture of 1.5% OV-17 and 1.95% OV-210 on 100–120-mesh Chromosorb W-HP (Supelco, Inc.). The carrier gas flow was 50 mL/min. The inlet, oven, and detector temperatures were 225, 160, and 325 °C, respectively.

Micrometeorological Observations. The micrometeorological techniques to obtain vertical flux estimates have been described in detail elsewhere (Turner et al., 1978; Glotfelty, 1981). Briefly, we used the aerodynamic method, which requires that wind speed and temperature gradients be obtained simultaneously with pesticide gradients in the atmosphere over the field surface. Wind speed gradients were obtained by graphical interpolation of four or six level measurements using Thornthwaite rotating-cup anemometers. Temperature gradients between

Table II. Average Pesticide Vapor Densities Near the Field Surface Measured Shortly after Application to Moist Soil

	vapor pressure, mmHg (25 °C)	saturation vapor density, ^a μg/m ³	field-measured vapor densities			
			1-1-75, ^b μg/m ³	rel saturation, <i>d/d</i> ₀	1-1-77, ^c μg/m ³	rel saturation, <i>d/d</i> ₀
trifluralin	1.07×10^{-4} ^d	1900	106	0.06	134	0.07
heptachlor	3.0×10^{-4} ^e	6000	227	0.04		
lindane	6.3×10^{-5} ^f	990			89	0.09
chlordane	1.0×10^{-5} ^e	220	12.7	0.06		
dacthal	2.5×10^{-6} ^g	45	3.0	0.07		

^a $d_0 = PM_z/(RT)$; P = vapor pressure, M_z = molecular weight, R = gas constant, and T = temperature, K. ^b Lowest height (5 cm), first hour after application, 1975. ^c Lowest height (10 cm), first hour after application, 1977. ^d Spencer and Cliath (1974). ^e Worthing (1979). ^f Spencer and Cliath (1970a). ^g DePablo (1981).

30 and 80 cm were obtained from a strip-chart record of the output from an aspirated, light-shielded, 10-junction thermopile. We used the KEYPS diabatic function to correct for the effects of thermal stratification (Parmele et al., 1972). Although we considered all the data in arriving at our best estimates of the total profiles, vertical fluxes were calculated from interpolated values of the wind speed and pesticide concentrations for the same height interval as the differential air temperature measurements. If the geometric mean height at about 0.5 m is considered to be the plane through which fluxes were obtained, then the fetch-to-height ratio ranged from 130 to 360 in these experiments.

RESULTS AND DISCUSSION

Spencer and Cliath (1975) estimate that a surface application of one kg ha⁻¹ results in a pesticide concentration as high as 150 ppm in the top 0.5 mm of soil. If moisture is adequate, the vapor density of a weakly polar pesticide in equilibrium with such a high soil concentration may approach saturation. For example, at 73-ppm trifluralin vapor density over moist Gila silt loam was the same as pure trifluralin (Spencer and Cliath, 1974). As wind moves over the soil these vapors are diluted and dispersed horizontally and vertically away, resulting in vapor loss from the surface to the atmosphere.

Figure 1 shows vapor density profiles over the treated field for the four pesticides applied in the first Beltsville experiment. Each data point is the time-averaged concentration at that height during the first hour after application. Although the vapor densities span nearly 2 orders of magnitude, the profiles are very much alike. The approximately 7-fold dilution of all compounds is caused by turbulent mixing, a property of the atmosphere. This concentration gradient leads to diffusion and rapid loss. The major differences in the profiles are established by the different vapor densities of the chemicals at the surface.

Table II shows the field-measured vapor densities at the lowest sampling height during the first hour after application in the two Beltsville experiments. In both cases the soil was moist and freshly sprayed, and the measured vapor densities of all mixture components was nearly a constant fraction of their respective saturation vapor densities at 25 °C. Hartley (1969) and Spencer et al. (1973) reasoned that potential volatility of surface deposits could be predicted with reasonable accuracy from vapor pressures, provided flux of a reference compound was known. This seems valid for unincorporated residues freshly sprayed on moist soil.

Spencer and Cliath (1974) studied factors affecting vapor loss of trifluralin from soil. In the laboratory, the maximum volatilization rate at 30 °C following a 10 kg ha⁻¹ surface application to moist soil was 4 kg ha⁻¹ day⁻¹. They expected field rates to be greater because air exchange

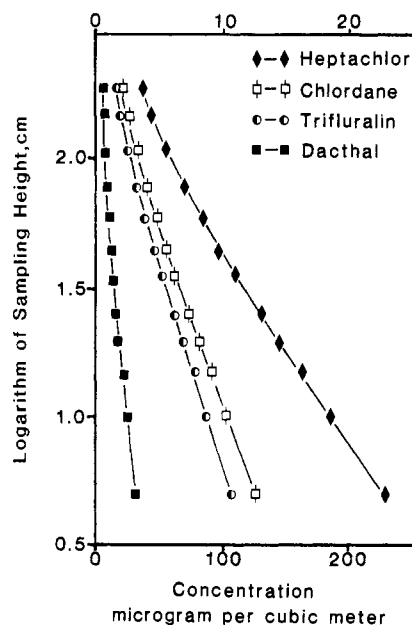


Figure 1. Pesticide vapor density profiles following surface application to moist soil. Data are from the first hour after application in the 1975 Beltsville experiment. The upper concentration scale refers to chlordane and dacthal; the lower scale refers to heptachlor and trifluralin.

rates are greater in the field. Our maximum measured trifluralin volatilization rate occurred during the initial period of the second Beltsville experiment. Under conditions of a brisk wind (5.0 m s⁻¹ at 1 m) and a surface soil temperature of 19 °C, the indicated rate of trifluralin loss was 195 g ha⁻¹ h⁻¹, equivalent to 4.7 kg ha⁻¹ day⁻¹. In order to compare field and laboratory rates, temperature differences must be taken into account. Volatilization rates from moist soil increase with temperature so that losses will be greater at 30 °C than at 19 °C. In these early periods in the field, air concentrations, and therefore volatilization losses, appear to be proportional to the saturation vapor density of the pure chemical (Table II). Since the saturation vapor density of trifluralin decreases about 5-fold between 30 and 19 °C, our field-measured rates may be as much as 5-6 times greater than is predicted from laboratory measurements.

Figure 2 shows the flux intensities for four chemicals measured during the first 2 days of the 1975 experiment. Similar data were obtained in the 1977 experiment. Although of different magnitudes, the flux intensity curves are remarkably similar, showing pronounced peaks near solar noon. This diurnal pattern, which has been noted before (Taylor et al., 1977), obviously results from solar energy being added to the atmosphere and soil. Integration of these curves gives the total vapor loss during periods for which flux intensity could be calculated. Vapor losses

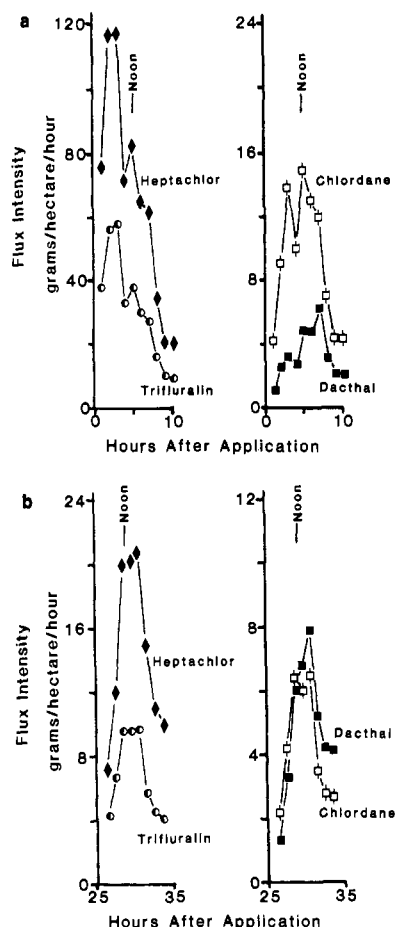


Figure 2. (a) Pesticide vertical flux intensities throughout the first day following application in the first Beltsville experiment; (b) flux intensities on the second day. From the 11th to the 25th hour, vertical flux was indeterminate due to calm winds.

Table III. Linear Regression Analysis of Pesticide Loss from Beltsville Soil, Using Equation 1

	experiment 1		experiment 2	
	k^a	r^2 ^b	k	r^2
trifluralin	0.11 ± 0.03^c	0.92		
heptachlor	0.12 ± 0.04	0.89		
chlordane	0.05 ± 0.02	0.89		
lindane			0.12 ± 0.08	0.89
dacthal	0.03 ± 0.02	0.69		

^a $k = [-\log(m/m_0)]t^{-1/2}$; t in hours of daylight. ^b r^2 = variance. ^c \pm = 95% confidence interval.

clearly account for the dissipation of these pesticides from the soil. Although measurements were taken, fluxes were indeterminate between the 10th and 25th hours after application (1830 on Aug 8 to 1000 on Aug 9) because winds were low.

The data on the disappearance of the pesticides from the soil in the first two experiments are presented in Figure 3 and Table III. Statistical analysis of these data shows that they are best described by the equation

$$\log m = \log m_0 - kt^{1/2} \quad (1)$$

where m_0 = initial soil residue, m = residue at time t , measured in hours of daylight after application. In experiment 1, this equation described the disappearance of 99% of trifluralin and heptachlor and 80% of the chlordane (based on first-hour soil analysis) over a period of 20 days. The dacthal data are consistent with the equation, but the much slower dacthal loss yielded less reliable kinetic data. In experiment 2, this equation described the

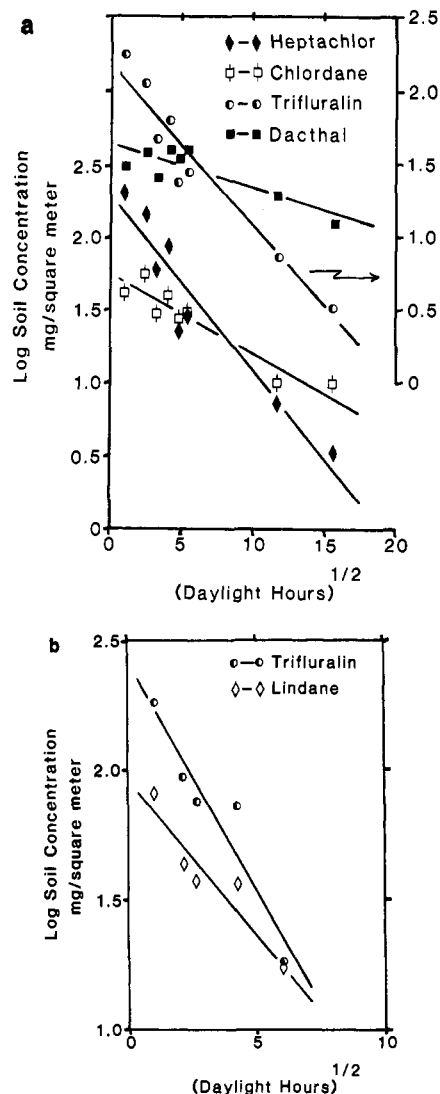


Figure 3. Decline of soil residues with time after application in the two Beltsville experiments. (a) Experiment 1: the right concentration scale refers to trifluralin data. (b) Experiment 2. The lines were determined by linear regression analysis.

disappearance of 80% of the lindane and 90% of the trifluralin. The confidence intervals for the k values in this experiment, however, reflect the fact that there were only 3 degrees of freedom in the regression analysis.

Equation 1 thus describes the disappearance of almost all the pesticide residues applied to and left on the surface of a moist, bare soil. It indicates that the loss rate not only depends upon the amount of residue remaining but also decreases in proportion to the inverse square root of the hours of daylight since application. Other relations, such as that developed by assuming first-order kinetics (rate dependent only on amount remaining), give a poorer description of the field data.

Equation 1 can be interpreted in terms of the measured volatilization losses, the diurnal changes in the volatilization rates, and the distribution of the residues in the soil resulting from the spray application. The reason for dependence upon daylight hours is evident from Figure 2, which shows the strong effect of insolation; losses are high near solar noon and very small at night. The dependence upon the square root of time suggests a diffusion-controlled process. Such a process will arise if the original spray was absorbed into a thin, porous layer of soil. After the immediate surface residue is depleted, pesticides will move upward by diffusing through this very shallow layer of soil

Table IV. Comparison of Pesticide Losses from Beltsville and Salisbury Soils

	% remaining on the soil after 50 h	
	Beltsville	Salisbury
heptachlor	25	60
trifluralin	29 (13) ^a	75
lindane	26 ^a	100
chlordane	55	100

^a 1977 experiment.

penetrated by the spray. We interpret eq 1 therefore to imply that volatilization controlled the fate of these pesticides in the soil (especially heptachlor, trifluralin, lindane, and chlordane) and that the volatilization rate of the individual pesticides was controlled both by solar energy input and by diffusion through a depleted thin layer of soil. As discussed below, this mechanism is only valid for pesticides evaporating from soil surfaces that remain moist, as was the case in experiments 1 and 2.

The rates of loss from the surface application to the Salisbury site were much lower than at Beltsville for all pesticides tested. The specific volatilization rates of heptachlor, trifluralin, lindane, and chlordane in the early hours after application ranged from 5 to 40 times slower than during the corresponding periods at Beltsville. The soil residue data further confirms the slower volatilization rates at the Salisbury site. Fifty hours after application, 60% and 75% of the heptachlor and trifluralin remained in the treated area, while losses of lindane and chlordane were too small to measure by soil residue changes. This contrasts sharply with the substantial losses of all four compounds over a comparable period of time at Beltsville (Table IV).

On the basis of soil properties, especially organic matter contents, we expected much greater volatilization rates at Salisbury than at Beltsville. Weakly polar pesticides become more strongly adsorbed as soil organic matter content increases. This stronger adsorption restricts vapor losses, and thus pesticide vapor density over different soils decreases as soil organic matter increases. For example, Spencer and Cliath (1974) found the vapor density of trifluralin to be 3.19, 1.73, and 0.62 $\mu\text{g}/\text{L}$ when added at 10 $\mu\text{g}/\text{g}$ to Imperial clay [0.20% organic matter (OM)], Gila silt loam (0.58% OM), and Kentwood sandy loam (1.62% OM), respectively. Similar effects are observed with other pesticides. On this basis, one might expect that the volatilization rate from the Salisbury sandy loam (0.6% OM) would be as much as twice as large as that from the Beltsville silt loam (1.2% OM). This was not the case.

Moreover, the diurnal change in flux intensity was very different than the "typical" pattern shown by the Beltsville data in Figure 2. This is demonstrated by the heptachlor flux intensity curve for the second day at Salisbury, shown in Figure 4. During the last sampling period of the previous day, about 1700 EDT, heptachlor flux was less than 10 $\text{g ha}^{-1} \text{h}^{-1}$. At 0630 h of the second day (24 h after application), air concentrations were high and flux was greater than 30 $\text{g ha}^{-1} \text{h}^{-1}$. Heptachlor flux quickly fell and remained less than 10 $\text{g ha}^{-1} \text{h}^{-1}$ from 0900 to 1830 h. Flux again rose above 10 $\text{g ha}^{-1} \text{h}^{-1}$ after 1900 h EDT. Although heptachlor air concentrations peaked near 180 $\mu\text{g m}^{-3}$, flux intensity declined somewhat after 2100 h EDT because winds became nearly calm. Thus, the flux intensity pattern is nearly the reverse of that found at Beltsville, and the noon-day rise corresponding to maximum insolation, surface temperature, and turbulence is virtually nonexistent.

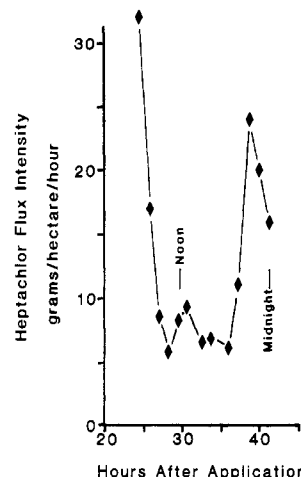


Figure 4. Heptachlor vertical flux intensity for the second day after application in the Salisbury experiment.

We believe this remarkable reduction of volatilization and change in the flux intensity pattern is caused by inhomogeneous soil moisture distribution. Because of its coarser texture, sandy loam retains much less moisture than silt loam. Although the bulk moisture content of the Salisbury soil was roughly 50% of field capacity, restricted capillary wetting allowed the top centimeter or so of the soil to become very dry during the day. The pesticide residues were concentrated in this dry surface layer.

Dry soil restricts pesticide vapor losses. The different pesticides vary in their degree of adsorption to soil, and water competes for soil adsorption sites. The more strongly a pesticide is adsorbed, the greater the moisture content must be in order to achieve maximum pesticide vapor density in the soil. Thus, as the soil dries, vapor losses of the more strongly adsorbed pesticides will be reduced sooner than the less strongly adsorbed.

In laboratory studies, the vapor densities of the organochlorine insecticides dieldrin and lindane were not significantly reduced until the moisture content fell below one monomolecular layer of water on the soil (Spencer and Cliath, 1969, 1970b). On the other hand, the vapor density of trifluralin was restricted at a higher moisture content than lindane (Spencer and Cliath, 1974). Comparing the initial flux rates at Salisbury with those at Beltsville (where losses were unrestricted) shows that vapor losses were increasingly restricted in the order heptachlor \leq chlordane $<$ lindane $<$ trifluralin. This order is consistent with the effects of soil drying.

The dominating effect of small changes in surface soil moisture is clearly shown by the heptachlor flux intensity curve in Figure 4. During both the first and second evenings, we observed that dew formed on the soil surface. In addition, some moisture probably reached the surface from below by capillary wetting as evaporation demand subsided in the evening. Compared to the low-flux, dry soil condition of the first afternoon, air concentrations and fluxes were high over the remoistened soil early in the morning of the second day (24 h after application). As the sun rose and moisture loss again exceeded upward capillary movement, volatilization rates dropped quickly to small values and remained small until evaporation demand subsided and dew again started to form during the second evening. Thus, relatively small amounts of moisture added to the dry surface layer resulted in a marked increase in pesticide volatility.

A similar effect of dew fall upon the volatility of toxaphene from mature cotton plants was observed by Willis et al. (1980). In a study of soil and microclimate effects

Table V. Summary of Pesticide Volatility Studies

treatment	% lost	time	reference
Trifluralin			
(Vapor Pressure = 1.1×10^{-4} mmHg at 25 °C)			
soil incorporation (2.5 cm)	22	120 days	White et al. (1977)
soil incorporation (7.5 cm)	3.4	90 days	Taylor (1978)
dry soil surface	2-25 ^a	50 h	experiment 3 ^b
moist soil surface	50	3-7.5 h ^c	experiments 2 and 1
	90	2.5-7 days ^c	experiments 2 and 1
Heptachlor			
(Vapor Pressure = 3×10^{-4} mmHg at 25 °C)			
soil incorporation (7.5 cm)	7	167 days	Taylor et al. (1976)
orchard grass	90	7 days	Taylor et al. (1977)
dry soil surface	14-40 ^a	50 h	experiment 3
moist soil surface	50	6 h ^c	experiment 1
	90	6 days ^c	experiment 1
Lindane			
(Vapor Pressure = 6.3×10^{-5} mmHg at 25 °C)			
dry soil surface	12	50 h	experiment 3
moist soil surface	50	6 h ^c	experiment 2
	90	6 days ^c	experiment 2
Chlordane			
(Vapor Pressure = 1×10^{-5} mmHg at 25 °C)			
dry soil surface	2	50 h	experiment 3
moist soil surface	50	2.5 days	experiment 1
Dacthal			
(Vapor Pressure = 2.5×10^{-6} mmHg at 25 °C)			
moist soil surface	2	34 h	experiment 1

^a Range between integrated flux and soil loss. ^b Experiment numbers refer to data obtained in 1975 or 1977 (Beltsville site) or 1978 (Salisbury site) of this work. ^c From eq 1 and Table III, assuming 12 h of daylight.

on trifluralin volatilization, Harper et al. (1976) clearly demonstrated that surface-soil moisture controlled the vapor loss even of incorporated trifluralin. Trifluralin flux decreased to very low levels during the daytime when soil surface water content was low, even though turbulence, soil temperature, and evaporation demand were high. During the nighttime, when evaporation demand subsided, trifluralin flux increased as soil-surface water increased.

SUMMARY AND CONCLUSIONS

The results of these field experiments support predictions based upon laboratory data and show that, if moisture is adequate, pesticides applied to the surface of fallow soil initially volatilize at rates proportional to the vapor density of the pure chemical. In the longer run, if the soil remains moist, volatilization responds to solar energy input and appears to be controlled by diffusion from a thin layer of treated soil. However, the moisture distribution may become the critical factor, and control of volatilization passes from energy and soil organic matter content to timing and supply of moisture to the soil surface. In the field, as in the laboratory, pesticide adsorption to dry soil is reversible, and volatilization resumes when the soil is rewetted.

A summary of pesticide volatility is given in Table V. Perhaps the information is best summarized by noting that volatilization losses of a particular compound to the atmosphere depends upon how it is used. Even shallow soil

incorporation greatly restricts volatilization losses of a compound as volatile as trifluralin (White et al., 1977; Taylor, 1978). On the other hand, application to vegetation or the soil surface may yield extremely rapid volatilization that results not only in reduced efficacy but also in environmental contamination. Under such conditions, actual "persistence times" within the treated area may be measured in days, rather than the much longer times required for the pesticide to be dissipated after incorporation into soil.

Registry No. Heptachlor, 76-44-8; chlordane, 12789-03-6; lindane, 58-89-9; trifluralin, 1582-09-8; dacthal, 1861-32-1.

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