

Volatilization of Organic Chemicals from Soil as Related to Their Henry's Law Constants

W. F. SPENCER,* M. M. CLIATH, W. A. JURY, AND LIAN-ZHONG ZHANG

ABSTRACT

The output from a pesticide screening model indicated that chemicals with low Henry's Law constants (K_H) will tend to accumulate at the soil surface when water is evaporating, resulting in an increased volatilization with time. Volatilization losses and surface distributions of two pesticides with widely differing K_H were measured to test the predictions of the screening model, particularly with respect to the importance of K_H in controlling relative volatilization and vapor behavior. Volatilization of prometon [2,4-bis(isopropylamino)-6-methoxy-s-triazine], a Category III compound with low K_H , increased with time with water evaporating and prometon accumulated at the soil surface. Volatilization of lindane (gamma isomer of 1,2,3,4,5,6-hexachloro-cyclohexane), a Category I compound with high K_H , decreased with time with or without water evaporating and did not accumulate at the surface with water evaporating. The experimental data confirmed the model predictions that volatilization of chemicals with low K_H is controlled by the air-boundary layer above the soil surface, whereas control of volatilization of Category I chemicals with high K_H is within the soil. Accumulation and increased volatilization of compounds with low K_H are controlled by boundary layer thickness and water evaporation rate as well as K_H . The phenomena of organic chemicals with low K_H accumulating at the soil surface following convective movement in evaporating water could greatly enhance their volatilization and increase their availability for photolysis and runoff into surface waters. Sufficient accumulation can occur that changes in adsorption coefficients with concentration must be taken into account in modeling their volatilization.

Volatilization and air transport are the principal means for widespread dispersion of pesticides and other organic chemicals in the environment. The importance of volatilization in transport of pesticides from treated areas has been established by direct field measurements (Taylor, 1978; Glotfelty et al., 1984). Laboratory research established that the rate of volatilization from soil is controlled by rate of movement of the organic chemical to the soil surface by mass flow in water and by diffusion

(Spencer and Cliath, 1973). The output from a pesticide screening model (Jury et al., 1984a) indicated that rate of movement to the soil surface relative to movement of the pesticide through the stagnant air boundary layer above the surface can also control volatilization and accumulation at the soil surface.

Volatilization rate from a surface deposit depends only on the rate of movement of the chemical away from the evaporating surface and its vapor pressure. In contrast, volatilization of soil-incorporated organic chemicals is controlled by their rate of movement away from the surface, their effective vapor pressure at the surface or within the soil, and their rate of movement through the soil to the vaporizing surface. Models developed for estimating volatilization rates are based on equations describing the rate of movement of the chemical to the surface by diffusion and/or by convection, and away from the surface through the air boundary layer by diffusion (Spencer et al., 1973; Mayer et al., 1974; Jury et al., 1980, 1983). Additionally, the proportion of the chemical in soil that will be lost by volatilization depends on the resistance of the chemical to degradation.

In a series of papers, Jury et al. (1983, 1984a, b, c) described and applied a model for assessing relative volatility, mobility, and persistence of pesticides and other trace organics in soil. The model allows the organics to be present in the soil in the adsorbed, solution, and

W.F. Spencer and M.M. Cliath. USDA-Agricultural Research Service, Pacific West Area, Dep. of Soil & Environ. Sci., Univ. of California, Riverside, CA 92521; W.A. Jury, Univ. of California, Riverside; and Lian-Zhong Zhang, Inst. of Environ. Chem., Academia Sinica, P.O. Box 934, Beijing, Peoples Republic of China (formerly visiting scientist at the Univ. of California, Riverside). Contribution from the USDA-ARS and the California Agric. Exp. Stn., Riverside, CA 92521. Received 14 Sept. 1987. ● Corresponding author.

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gaseous phases; they are free to move by vapor diffusion, liquid diffusion, and convection with the liquid solution. The soil surface boundary condition consists of a stagnant boundary layer connecting the soil and air through which the organic chemical and water vapor must move to reach the atmosphere. The model assumes that the gas and liquid concentrations are related by Henry's Law and that the adsorption isotherms relating liquid and adsorbed concentrations are linear. It also assumes that degradation occurs by first-order rate processes.

When Jury et al. (1984b) applied the screening model to a set of 20 pesticides for which chemical and physical properties were obtained from the literature or calculated, the relative magnitude of volatilization and its change with time depended on water evaporation rate and the physicochemical properties of the pesticides. Water evaporation had a considerable effect on volatilization of some chemicals and not of others. Also, volatilization of some chemicals decreased with time and volatilization of others increased with time when water was evaporating. The model output indicated that volatilization behavior of a chemical is controlled mainly by the ratio of its solution to vapor concentration or Henry's Law constant (K_H), which determines the extent to which the air boundary layer restricts volatilization from soil. The extent to which this boundary layer limits the volatilization flux was used as a criterion for classifying organic chemicals into general categories based on whether control of volatilization is within the soil (Category I) or within the air boundary layer (Category III). So-called Category I compounds are those with K_H much greater than 2.65×10^{-5} (dimensionless unit representing the ratio of saturation vapor density to solubility). Their volatility decreases with time under all conditions whether water is evaporating or not. Category III chemicals (with K_H much less than 2.65×10^{-5}) move to the surface in evaporating water faster than they can volatilize through the boundary layer. Consequently, their concentration increases at the soil surface under evaporative conditions and volatilization rate increases with time.

The purpose of the experiment reported herein was to test the predictions of the screening model of Jury et al. (1983), particularly with respect to the importance of K_H in controlling relative volatilization and vapor behavior of organic chemicals.

MATERIALS AND METHODS

Volatilization rates of two chemicals with widely differing Henry's Law constants and their distributions near the soil surface were measured under controlled conditions and results compared with predictions from the pesticide screening model. The volatilization apparatus has been previously described (Spencer et al., 1979; Spencer and Cliath, 1981). Briefly the gas flow system included a rectangular volatilization cell, made of Al, from which vapor losses were measured with air at controlled flow rates passing over treated soil. Soil water content was adjusted in the rectangular soil column through porous ceramic tubes installed in the bottom section; water loss from the soil was controlled by adjusting the relative humidity of the air passing over the soil surface. Vaporized pesticides were trapped from the moving airstream in polyurethane foam (PUP), extracted, and analyzed. The upper section of the volatilization cell con-

Table 1. Chemical properties of prometon and lindane used in predicting behavior when applied to mixed soil columns at 25°C.

	Prometon (III)	Lindane (I)
Vapor pressure (Pa)	0.29×10^{-4}	8.63×10^{-6}
Vapor density (g/m ³)	7.54×10^{-4}	1×10^{-4}
K_H (dimensionless)	750	7.5
K_{oc} (m ³ /Mg)	1.0305×10^{-7}	1.33×10^{-6}
		1300
Air diffusion coefficient, D_G (m ² /d)	0.432	0.432
Water diffusion coefficient, D_L (m ² /d)	4.32×10^{-4}	4.32×10^{-4}
Chemical applied (kg/ha):		
Series 1	15.0	4.2
series2	15.0	0.42

tains an air chamber matching the width of the evaporating surface. When the depth of the air chamber above the soil surface was 0.2 cm, an air flow rate of 1 L/min provided an average wind speed of approximately 1 km/h and a change of atmosphere in the space over the surface of 2.8 times per second (Series 1). In a second series of runs (Series 2), a 1-cm spacer was inserted between the soil and the upper section to increase the effective boundary layer thickness, or the depth of the stagnant air layer. The air flow rate remained at 1 L/min except for one set of measurements where it was increased to 2 L/min (Series 2A).

Soil containing a mixture of two model compounds—prometon [2,4-bis(isopropylamino)-6-methoxy-s-triazine], a Category III chemical, and lindane (gamma isomer of 1,2,3,4,5,6-hexachloro-cyclohexane), a Category I chemical, was used in the volatilization cell. The relevant chemical properties of the two chemicals are shown in Table 1. The vapor density is much lower and the solubility much higher for prometon than for lindane, resulting in a K_H of 1×10^{-7} for prometon and 1.33×10^{-4} for lindane. The soil used was San Joaquin sandy loam (thermic Abruptic Durixeralfs) with 0.72% organic C, 9.7% clay, and a pH of 6.2. Before treating the soil with the chemicals, it was autoclaved for 1 h at 0.11 MPa and 126°C, twice at 2-d intervals. The chemicals were atomized onto the air-dry soil in a 10-L carboy. Prometon was applied as 98.3% technical material obtained from Ciba-Geigy Corp., Greensboro, NC, and lindane as 100% analytical grade standard in 25 mL hexane to 2 kg soil. The hexane was allowed to evaporate; then the treated soils were mixed thoroughly for 1 h in a Twin Shell Blender (Patterson Kelley Co., East E. Stroudsburg, PA).

The treated soil was placed into the volatilization cells about 1 cm at a time as the wetting front moved upward. The soil was lightly and evenly tamped to produce and maintain a constant bulk density while the soil was wetted from the bottom through the porous ceramic tubes. Soil suction was maintained at zero tension at the bottom of the soil column. The relative humidity of the air passing over the soil surface was controlled by adjusting the proportion of the air passing through the water saturators. Water tension at the porous ceramic tubes was controlled, and water added, with a constant level inflow device. Water loss rates were determined by measuring the amount of water added to the bottom of the column to replace that evaporated from the surface. The soil and atmospheric conditions for the prometon/lindane mixed soil columns for Series 1 and 2 runs are shown in Table 2. The soil concentration for prometon was 10.3 µg/g throughout, whereas lindane concentration was 3.0 µg/g for Series 1 and 0.3 µg/g for Series 2.

Since predicted volatilization flux is a function of the effective boundary layer thickness, d , an effective d value had to be established for the simulations which represented the boundary layer thickness for the volatilization cells containing the treated soil. We established an "experimental" d value for Series 1 and Series 2 by measuring volatilization flux with unabsorbed prometon in the volatilization cell in the same geometric con-

¹ Trade and company names are used for the benefit of readers and do not imply endorsement by the USDA.

figuration as the treated soils. Then d was calculated from the measured vapor flux with the boundary layer transfer equation:

$$d = D_G (C_s - C_a) / J_p$$

where D_G is the diffusion coefficient of prometon in air, C_s is prometon vapor concentration at the surface, C_a vapor concentration in the outgoing airstream as it passes through the PUF trap, and J_p is the measured prometon flux. The effective boundary layer thickness was calculated as 0.022 cm and 0.15 cm for Series 1 and 2, with and without the 1-cm spacer, respectively, at 1 L/min flow rates. At 2 L/min in Series 2A, d was 0.12 cm.

The distribution of the prometon and lindane within the soil columns was determined at the end of the volatilization period, which varied from 14 to 23 d in Series 1 and was 20 d in Series 2. Each volatilization cell was made up of four demountable sections producing a 10 cm deep soil column. Soil in the moist columns was sampled by extruding the soil from the top of the column after removing the bottom plate from the volatilization cell. The soil was extruded from the top of the column with an elevator device in which one turn of the elevator screw raised the soil column 0.29 cm. Slices of soil, varying in depth depending on the distance from the surface, were obtained from the soil column. Water content was determined on a portion of each sample and the remainder was extracted in a Soxhlet extractor (Fischer Scientific, Springfield, NJ) with an azeotropic mixture of hexane and acetone. The hexane/acetone extracts were concentrated to about 10 mL in a rotary evaporator. Concentrations of lindane and prometon in the extracts were determined with a Varian 3700 gas chromatograph (GC) (Varian Instruments, Sunnyvale, CA) using electron capture and thermionic specific N-P detectors, respectively. For lindane, a 2 m by 2 mm Pyrex glass column packed with OV-101 3% on Gas Chrom Q (80/100 mesh) (Alltech Assoc., Inc., Los Altos, CA) was used with the following operating parameters: N carrier flow, 30 mL/min; with inlet, column, and detector temperatures of 230, 180, and 270°C, respectively. For prometon, a 1 m by 2 mm Pyrex glass column packed with Carbowax-20m on Ultra-bond (100/120 mesh) (Alltech Assoc., Inc., Los Altos, CA) was used with the following operating parameters: N carrier flow, 30 mL/min; H, 18 mL/min; air, 20 mL/min; with inlet, column, and detector temperatures of 200, 170, 250°C, respectively. Total recoveries for lindane and prometon were calculated from the amounts volatilized and amounts extracted from the soil following volatilization measurements.

The adsorption isotherm at 25°C for prometon on San Joaquin sandy loam was measured at a soil/water ratio of 1:5 by the batch-slurry technique similar to that described by McCall et al. (1981). Various concentrations of prometon were equilibrated with 10 g of soil in 50 mL of water for 24 h by shaking on a mechanical shaker at 25°C prior to separating the soil and water by centrifuging in a refrigerated centrifuge at a relative centrifugal force of 23 500 \times g (14 000 rpm) for 10

min. Prometon was extracted from the water phase in methylene dichloride. Prometon was extracted from the soil with hexane/acetone in a Soxhlet extractor for 4 h. Concentrations of prometon in each phase were determined with GC as above.

Degradation of prometon was measured at 25°C under conditions used in the volatilization studies. San Joaquin sandy loam soil amended with 10 μ g/g prometon was adjusted to 20% water content and incubated in a series of glass jars. The soils in individual glass jars were extracted and analyzed for prometon by GC at various times after initiation of incubation. Degradation was assumed to be equivalent to decreases in extractable prometon with time.

RESULTS AND DISCUSSION

The adsorption isotherm for prometon conformed with the Freundlich equation, $x/m = kc^{1/n}$, where k and n are constants, x is the mass of prometon adsorbed by mass m of soil, and c is the solution concentration. For prometon adsorption over five equilibrium solution concentrations ranging from 0.62 to 31.3 mg/L, $k = 2.94$ and $1/n = 0.81$. Since San Joaquin sandy loam contains 0.72% organic C, the organic C partition coefficient, K_{oc} , is then equal to 408, based on the Freundlich k of 2.94 and equal to 305 based on K_p equal 2.2 at 10.3 μ g/g prometon-the concentration incorporated into the soil columns.

Prometon degraded very little when incubated in autoclaved/sterilized San Joaquin sandy loam under conditions used in the Series 1 volatilization measurements. Extractable prometon did not decrease below that for Day 0 for Days 2, 4, 8, and 16, but extractable recoveries were reduced to 88% of the initial concentration at Days 32 and 64. This indicates that degradation of prometon was not a significant pathway for loss during Series 1 measurements, and the total recovery of prometon verified this conclusion.

Series 1

Figure 1 shows measured volatilization of prometon in Series 1 compared with predicted fluxes using the screening model with $d = 0.022$ cm as the effective boundary layer thickness or stagnant air-layer depth. Extremely good agreement was observed between measured and predicted vapor flux values both with and without water evaporating. The total prometon volatilized, in percent of applied, was 7.61% measured compared with 7.49% predicted with water evaporating; and 1.54% measured compared with 1.57% predicted without water

Table 2. Soil and atmospheric conditions for Series 1 and 2 prometon/lindane mixed soil columns.

Property	Series 1	Series 2
Soil porosity (m^3/m^3)	0.411	0.41
Bulk density (Mg/m^3)	1.56	1.57
Organic C fraction	0.0072	0.0072
Water content (m^3/m^3)	0.31	0.37
Depth of incorporation (cm)	10	10
Temperature (°C)	25	25
Atmospheric relative humidity, + E	0.425	0.425
- E	1.0	1.0
Water evaporation rate (cm/d), + E	0.55	0.37
- E	0	0
Effective boundary layer thickness (cm)†	0.022	0.15

† Determined with unadsorbed prometon in the volatilization cell.

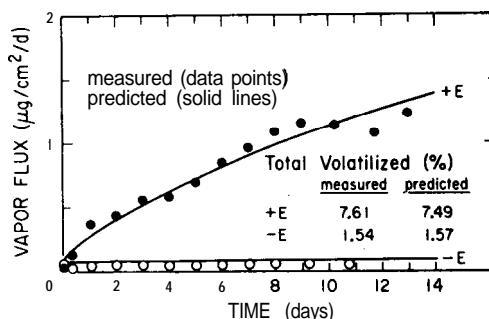


Fig. 1. Volatilization of prometon from San Joaquin sandy loam with (+ E) and without (- E) water evaporating (Series 1).

evaporating. Volatilization of prometon increased from 0.03 $\mu\text{g}/\text{cm}^2$ per day during the first 5 h to 1.25 after 14 d with water evaporating at 0.55 cm/d. This is a 41-fold increase in volatilization rate over the 14-d period due to accumulation of prometon at the soil surface as water evaporated.

Figure 2 shows the measured volatilization of lindane in Series 1 compared with that predicted. Again, good agreement was observed between measured and predicted values, and, as has been observed many times with other Category I chemicals, volatilization decreased with time with or without water evaporating. The total volatilized with water evaporating was 7.9% measured, compared 8.09% predicted; without water evaporating the total measured was 5.48% compared with 5.62% predicted.

Prometon accumulated at the soil surface with water evaporating. Figure 3 shows the good agreement between measured and predicted distributions of prometon in the soil column after 14 d with water evaporating at 0.55 cm/d. Concentration in the surface 0.3 cm increased from 10 to 81 $\mu\text{g}/\text{g}$. Lindane distribution after 14 d with water evaporating at 0.55 cm/d is shown in Fig. 4. A slight

decrease in concentration at the surface and good agreement between measured and predicted values were observed.

Total recoveries, calculated from the amounts volatilized and extracted from the soil following volatilization, were 88 and 87% for prometon and 95 and 98% for lindane from columns with and without water evaporating, respectively. This indicates that no significant degradation of either chemical occurred during volatilization in Series 1. Consequently the degradation coefficient, μ , was assumed to be 0 in the above simulations.

Series 2

In Series 2 measurements with the 1-cm spacer above the soil surface, the measured water evaporation (E) was 0.37 cm/d and the effective boundary layer thickness (d) determined with pure chemicals in the cell, was 0.15 cm instead of 0.022 cm without the spacer. In Series 2, based on total percentage recovery of approximately 75% for prometon and 45% for lindane, some degradation evidently occurred, probably because of one of two reasons: (i) the soil was inadequately sterilized, or (ii) the water content was slightly higher and transient anaerobic conditions caused some breakdown of the lindane and prometon. The model simulations were adjusted for degradation rate (μ) as determined by the percent recovery of the total pesticide at the end of each run.

Without water evaporating, extremely good agreement was observed between predicted and measured vapor flux values and soil distribution for prometon (Fig. 5). Prometon distribution near the surface was changed very little from the concentration added.

With water evaporating, however, the measured volatilization rate of prometon was much greater than

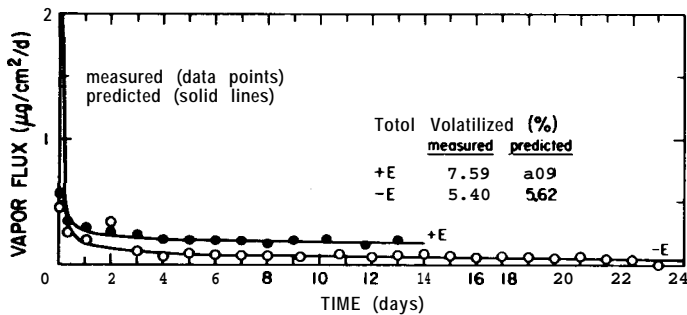


Fig. 2. Volatilization of lindane from San Joaquin sandy loam with (+E) and without (-E) water evaporating (Series 1).

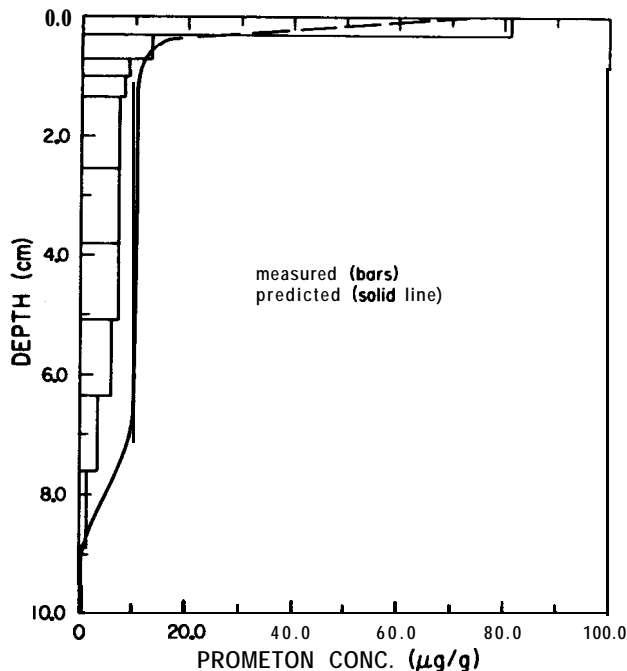


Fig. 3. Distribution of prometon in soil after 14 d with water evaporating at 0.55 cm/d (Series 1).

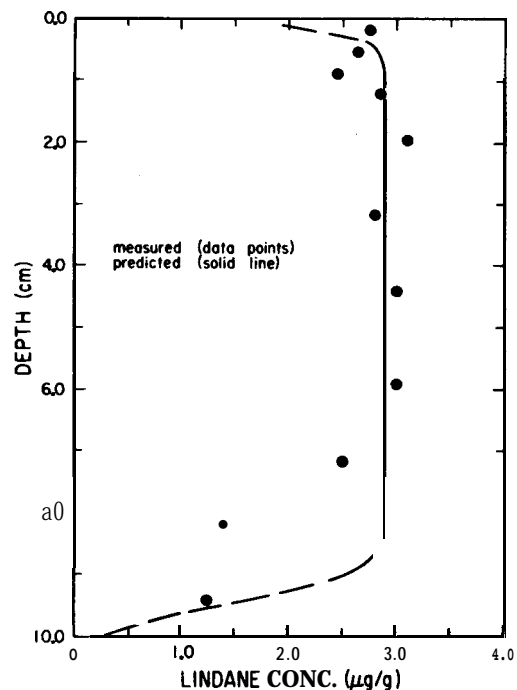


Fig. 4. Distribution of lindane in soil after 14 d with water evaporating at 0.55 cm/d (Series 1).

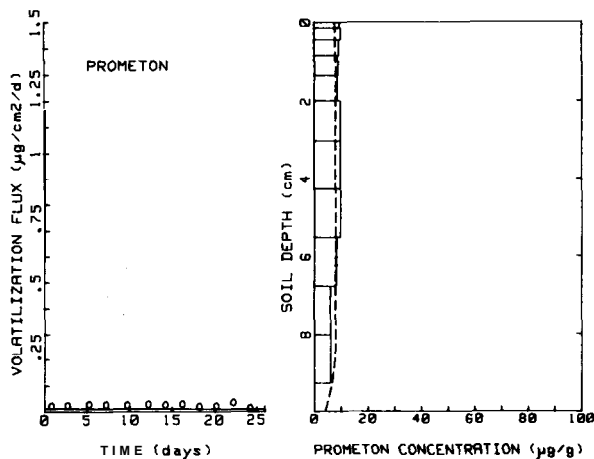


Fig. 5. Prometon volatilization without water evaporating and soil distribution after 26 d. Data points and bars: Measured (Series 2, rep. 1). Lines: Predicted with $K_{oc} = 305$.

that predicted by the model when the measured K_{oc} of 305 for $10.3 \mu\text{g/g}$ prometon in San Joaquin sandy loam was used in the calculation, except for the first day (Fig. 6). We postulate that the reason for this lack of agreement in Series 2 measurements, except for the first day, is the decreased adsorption, or K_{oc} , associated with the very high concentrations of prometon built-up on the soil surface with the increased boundary layer thickness. We failed to observe this effect in Series 1 measurements because the difficulty in accurately estimating the effective d at the very low boundary layer thickness may have masked any effect of the smaller concentration buildup on K_{oc} . Data to support this conclusion follows.

Figure 7 shows the horizontal and vertical distribution of prometon in the surface 1 cm of soil after 20 d of volatilization with water evaporating at 0.37 cm/d . This is a schematic of a vertical cross-section of the surface 1 cm of the volatilization cell with the incoming air passing from left to right at 1 L/min . The volumetric water content was $0.32 \text{ m}^3/\text{m}^3$ or greater within this 1-cm depth. The prometon concentration was originally $10.3 \mu\text{g/g}$ throughout the column. Concentration in the surface 0.1

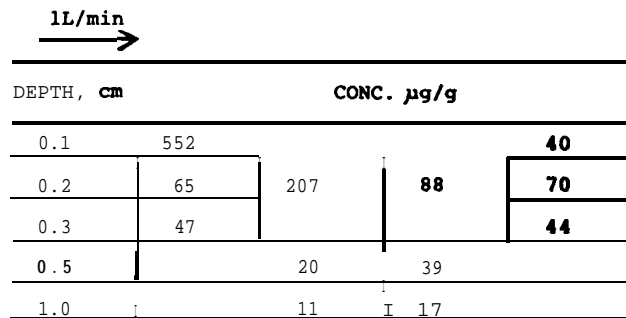


Fig. 7. Cross section of the surface 1-cm of soil showing distribution of prometon after 20 d of volatilization with water evaporating at 0.37 cm/d . Air flow from left to right (Series 2, rep. 1).

cm near the incoming airstream was $552 \mu\text{g/g}$ with concentrations decreasing toward the outlet side of the cell. Concentrations closer to the surface were probably greater than those indicated here for the 0.1- or 0.3-cm depth. The fact that the measured prometon adsorption isotherm on this soil conformed with the Freundlich equation with $k = 2.94$ and $1/n = 0.81$ indicates that K_p will decrease with increasing concentrations of prometon. Calculated K_{oc} values at different prometon concentrations in this soil using the measured Freundlich constants decreased from 305 for $10.3 \mu\text{g/g}$ (the initial concentration in the soil) to 122 for $500 \mu\text{g/g}$.

Thus, assuming that we should have used a decreasing K_{oc} in the simulations as concentrations at the surface increased, measured and simulated volatilization rates and soil distributions with various K_{oc} values were compared. Figure 8 shows measured prometon volatilization and soil distributions compared with those predicted with $K_{oc} = 150$ or 100 . The measured volatilization rates after 5 d are above those predicted with $K_{oc} = 150$, but below those predicted with $K_{oc} = 100$. Evidently, the correct K_{oc} value for the higher concentrations falls somewhere between 100 and 150. In a duplicate volatilization cell which undoubtedly had a slightly different surface prometon distribution, good agreement was observed between measured and predicted flux and soil distributions

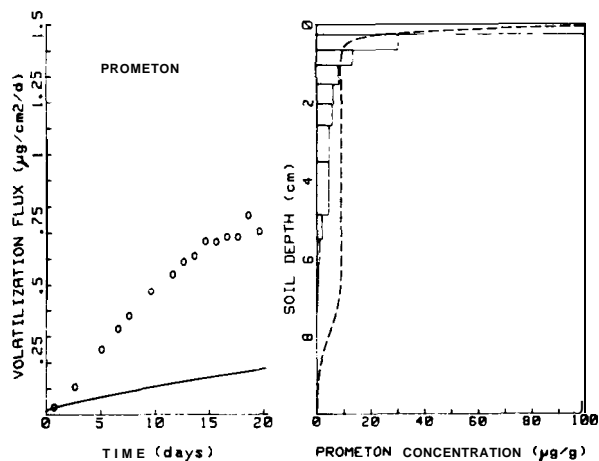


Fig. 6. Prometon volatilization with water evaporating and soil distribution after 20 d. Data points and bars: Measured (Series 2, rep. 1). Lines: Predicted with $K_{oc} = 305$.

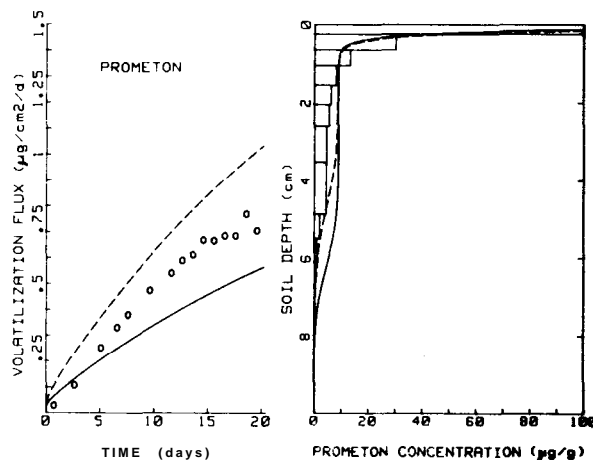


Fig. 8. Prometon volatilization with water evaporating and soil distribution after 20 d. Data points and bars: Measured (Series 2, rep. 1). Solid lines: Predicted with $K_{oc} = 150$. Dashed lines: Predicted with $K_{oc} = 100$.

when a K_{oc} of 100 was used for prometon in the simulations as shown in Fig. 9. In this case, the total amount volatilized was 8.2% measured compared with 9.8% predicted.

With lindane, good agreement was observed between measured and predicted volatilization rates with the additional 1-cm air gap, both with and without water evaporating. Lindane did not appear to accumulate at the soil surface with or without water evaporating. Concentrations in the surface 1 cm were all below those originally added to the soil and the values with water evaporating were slightly higher than those without water evaporating as would be expected.

Series 2A

When the airflow rate was increased to 2 L/min with the 1-cm spacer inserted, the water evaporation rate increased to 0.52 cm/d and the calculated effective boundary layer thickness (d) was 0.12 cm. Again, using a K_{oc} of 305 related to the initial concentration of prometon, the predicted volatilization was much lower than measured (1.5% predicted compared with 11.4% measured). When a K_{oc} of 100 was used for the predicted prometon volatilization, much better agreement between measured and predicted prometon volatilization was observed (10.8% predicted vs. 11.4% measured).

CONCLUSIONS

Measurements of volatilization losses and surface accumulations of two pesticides with widely differing Henry's Law Constants (K_H) agreed with model predictions that relative volatilization of pesticides from soil is controlled mainly by the ratio of their vapor to solution concentrations. The experimental data confirmed the model predictions that volatilization of chemicals with low K_H is controlled by the air boundary layer above the soil surface, whereas control of volatilization of Category I chemicals with high K_H is within the soil. Measurements with different air boundary layer thicknesses indicated that accumulation and volatilization of compounds with low K_H are a function of boundary layer

thickness and water evaporation rate as well as K_H . Consequently, if the air boundary layer is sufficiently large when the water is evaporating, accumulation of some pesticides may be great enough that changes in adsorption coefficient, (K_d) with concentration must be taken into account in modeling volatilization of such compounds. For this purpose, a nonlinear adsorption isotherm should be incorporated into the volatilization model for more accurate predictions.

The phenomena of organic chemicals accumulating at the soil surface following convective movement in evaporating water has ramifications that deserve further study. First, this mechanism could greatly enhance the volatilization of chemicals with low K_H , which formerly were considered to be essentially nonvolatile from wet soils due to their low K_H , or ratio of vapor pressure to solubility. Secondly, this mechanism of chemicals accumulating at the soil surface could significantly increase the amounts of some chemicals available for photolysis, or for runoff into surface water bodies from rainfall or irrigation water. This phenomena could be very important in soil-covered waste dumps where upward movement in evaporating water could concentrate organic chemicals at the surface of the soil cover or within the soil near the surface in a waste disposal pit. However, on the other hand, the phenomena might actually lessen the amounts available for transport downward into groundwater.

REFERENCES

- Glotfey, D.E., A.W. Taylor, B.C. Turner, and W.H. Zoller. 1984. Volatilization of surface-applied pesticides from fallow soil. *J. Agric. Food Chem.* **32**:638-643.
- Jury, W.A., W.J. Farmer, and W.F. Spencer. 1984a. Behavior assessment model for trace organics in soil: II. Chemical classification and parameter sensitivity. *J. Environ. Qual.* **13**:567-572.
- Jury, W.A., R. Grover, W.F. Spencer, and W.J. Farmer. 1980. Modeling vapor losses of soil-incorporated triallate. *Soil Sci. Soc. Am. J.* **44**:445-450.
- Jury, W.A., W.F. Spencer, and W.J. Farmer. 1983. Behavior assessment model for trace organics in soil: I. Model description. *J. Environ. Qual.* **12**:558-564.
- Jury, W.A., W.F. Spencer, and W.J. Farmer. 1984b. Behavior assessment model for trace organics in soil: III. Application of screening model. *J. Environ. Qual.* **13**:573-579.
- Jury, W.A., W.F. Spencer, and W.J. Farmer. 1984c. Behavior assessment model for trace organics in soil: IV. Review of experimental evidence. *J. Environ. Qual.* **13**:580-586.
- Mayer, R., J. Letev, and W.J. Farmer. 1974. Models for predicting volatilization of soil-incorporated pesticides. *Soil Sci. Soc. Am. proc.* **38**:563-568.
- McCall, P. J., D.A. Laskowski, R.L. Swann, and H.J. Dishburger. 1981. Measurement of sorption constants of organic chemicals and their use in environmental fate analysis. p. 89-109. *In* Test protocols for environmental fate and movement of toxicants. Assoc. of Off. Anal. Chem., Arlington, VA.
- Spencer, W.F., and M.M. Cliath. 1973. Pesticide volatilization as related to water loss from soil. *J. Environ. Qual.* **2**:284-289.
- Spencer, W.F., and M.M. Cliath. 1981. Evaluating volatility of toxicants in soil and water. p. 101-121. *In* Test protocols for environmental fate and movement of toxicants. Assoc. of Off. Anal. Chem., Arlington, VA.
- Spencer, W.F., W.J. Farmer, and M. M. Cliath. 1973. Pesticide volatilization. *Residue Rev.* **49**:1-47.
- Spencer, W.F., T.D. Shoup, M.M. Cliath, W.J. Farmer, and R. Haque. 1979. Vapor pressures and relative volatility of ethyl and methyl parathion. *J. Agric. Food Chem.* **27**:273-278.
- Taylor, A.W. 1978. Post-application volatilization of pesticides under field conditions. *J. Air Pollut. Control Assoc.* **28**:922-927.

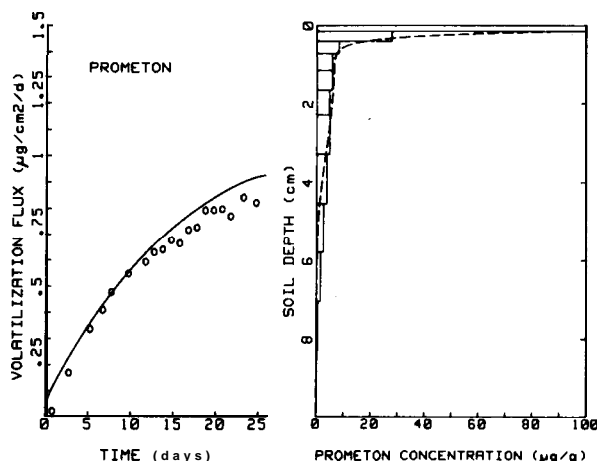


Fig. 9. Prometon volatilization with water evaporating and soil distribution after 24 d. Data points and bars: Measured (Series 2, rep. 2). Lines: Predicted with $K_{oc} = 100$.