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DDT Persistence and Volatility as Affected by Management Practices after 23 Years

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ABSTRACT

In 1971, an experiment was conducted in a field containing high amounts of residual DDT (dichlorodiphenyltrichloroethane) to evaluate deep plowing, followed by flooding, with and without organic matter applications, as soil and water management tools to reduce total DDT residues and preferentially degrade the residual DDT to DDD [l,l-dichloro-2,2-bis (p-chlorophenyl) ethane]. The experimental site was revisited in 1994 to determine residual soil concentrations of DDT isomers and their metabolites in soil, soil dust, and the atmosphere. Also, volatilization flux measurements were made to evaluate rates of movement into the atmosphere. Soil concentrations of all DDT isomers and metabolites had decreased in all plots, with p, p'-DDE [1, 1-dichloro-2,2-bis (p-chlorophenyl) ethylene] the major component of the total remaining residues (DDTR). The total DDTR residues in the surface 75 cm varied from 10 to 28% of their amounts in 1971. The highest concentrations were found in the deep plowed, unflooded plots with DDTR decreasing from 4 mg kg-' at 0 to15 cm to 0.3 mg kg^{-1} at 60 to 75 cm. Deep plowing evidently increased DDT persistence by placing it deeper into the soil profile, which protected it from degradation and volatilization. Concentrations of all isomers were lower in the previously flooded plots. Degrading DDT under reducing conditions brought about by flooding lessened or prevented the formation of DDE in the soil thus ultimately reducing its redistribution into the environment. Significant concentrations of both o,p' and p,p'-DDE and DDT were detected in the atmosphere above the plots. Measurable volatilization fluxes were observed over 48-h periods in February and September. Irrigating the soil with 20 mm water dramatically increased the volatilization flux of all the DDT isomers and metabolites, particularly p,p'-DDE. The finding that DDT isomers continue to volatilize from the soil surface has implications for long-range transport of DDT and contaminating forage or foodstuff. The possible health implications from exposure to humans or animals through the air route is unknown.

DDT IS HIGHLY PERSISTENT in soil and even though its use has been discontinued in the USA since 1973, soil residues remain in many areas with p,p'-DDE making up the major proportion of the total DDT residue in such soil (Ware et al., 1978; Cooke and Stringer, 1982; Boul et al., 1994). Under aerobic conditions, much of the p,p'-DDT in soils is degraded to DDE. Spencer and Cliath (1972) reported that the vapor pressure of p,p'-DDE was several times greater than that of p,p'-DDT, and Cliath and Spencer (1972) reported that DDE was the major DDT component found in the atmosphere over a field which previously received technical DDT. This led to the conclusion that much of the p,p'-DDT in well-aerated soils may be volatilized as p,p'-DDE (Spencer, 1975). Volatilization is a major mechanism for movement of such residues from soil to aboveground plant parts (Nash and Beall, 1970) and volatilization is a major process for movement of residues away from treated areas resulting in potential exposure to animals and humans through the air route (Taylor and Spencer, 1990; Willett et al., 1993; Hileman, 1994; Samuel and Pillai, 1989).

The presence of p,p'-DDE in the biosphere is of much concern to biologists. Metcalf et al. (1971) concluded that DDE is a highly persistent, lipid-partitioning metabolite of DDT that is responsible for the major portion of the environmental effects of concentrations and storage in animal tissues following the use of DDT. Soil and water management practices can be used to alter the pathway of DDT breakdown in soil and thereby change the relative amounts of the various compounds lost by volatilization. In laboratory studies under oxygen-deficient conditions caused by flooding and organic matter treatments, DDT was degraded to DDD and other water soluble metabolites (Guenzi and Beard, 1967, 1968).

In 1971, a field experiment was conducted to evaluate deep plowing followed by flooding, with and without organic matter applications, as soil and water management tools to reduce total DDT residues and preferentially degrade the residual DDT to DDD, thereby changing the ratio of the various compounds potentially evaporating from the soil surface (Farmer et al., 1974; Spencer et al., 1974). The experimental site was revisited in 1994. Soil samples were taken to a depth of 75 cm, soil dust samples were vacuumed from the soil surface and measurement of air concentrations and chamber volatilization flux measurements were made to evaluate atmospheric concentrations and movement into the atmosphere from the soil surface. This paper reports the effects of the past management treatments on amounts of various DDT residues presently in the soil and their movement into the atmosphere.

MATERIALS AND METHODS

Site Description

The present investigation was carried out in Coachella Valley, near Indio, CA, at the site of the 197 1 experiment on Indio fine sandy loam (coarse-silty, mixed, calcareous, hyperthermic Typic Torrifluvents) with a pH of 7.8 and **<1 %** organic matter. Coachella Valley is part of the extensive desert region in southeastern California. The summers are very hot and dry with temperatures frequently reaching 45°C and the average January and July temperatures are 12 and 33°C, respectively. Average annual rainfall is approximately 82 mm with essentially all of it falling during the winter months. Prior to 1971, the field had received applications of technical DDT to sweet corn (Zea ***mays*** L.) for earworm [Heliothis yea (Boddie)] control at the rate of 3 kg/ha, 10 to 12 times per year with the last application in 1968, 34 mo before initiation of the 1971 study. During the 7-yr period of DDT applications, the field was repeatedly disked and plowed to a depth of at least

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Abbreviations: DDTR, total of all DDT isomers and metabolites; SFE, super critical fluid extraction system; PUF, polyurethane foam; CV, coefficient of variability or SD/mean; SD, standard deviation.

30 cm. In 1969, 2 yr prior to the initiation of the flooding and organic matter treatments, the area to be treated was deep-disk plowed to 60 cm. In 1971, part of the experimental area was flooded for 48 d with and without organic matter amendments in a randomized block design within the flooded area. The organic amendments consisted of feedlot manure, at 45 or 180 t/ha, and alfalfa meal, at 5.6 or 18 t/ha, disked into the soil to a depth of 15 cm. From 1971 to 1978, vegetable and field crops were grown in the field using a furrow irrigation system. In 1979, the field was planted to date trees with tangerine trees (Citrus *reticulata* Blanco) interplanted in the date tree rows. Both trees were irrigated with a drip irrigation system.

Flooding for a 7-wk period, either with or without manure or alfalfa meal applications, effectively degraded DDT isomers in the surface soil, primarily to the respective DDD isomers, but had little effect on DDE isomers (Farmer et al., 1974; Spencer et al., 1974). The results indicated that flooding soils in the field was an effective means of reducing the ratio of DDT to DDD in the soil. The addition of organic amendments was effective in reducing the flooding time necessary to bring about a particular reduction in the DDT/DDD ratio. Flooding, with or without organic amendment, had no effect on the level of the DDE in the soil. Regardless of treatment the major constituent vaporizing from the surface was p,p'-DDE (Spencer et al., 1974). It was speculated, however, that the total amount of DDE produced in the soil would eventually be less in the flooded areas since the DDT degraded to DDD during flooding would not be available later to degrade to DDE. This would potentially result in a decreased total quantity of DDE and increased DDD volatilized from the flooded soil.

Assuming a soil bulk density of 1.47 for this soil, the calculated total DDT residue (DDTR) within the surface 60 cm of soil in 1971 was 109 kg ha^{-1}. The amount of p,p'-DDE within the 0 to 60 cm depth was 45.9 kg ha^{-1} or 42% of the total DDTR (Farmer et al., 1974). Also, in 1971, p,p'-DDE air concentrations represented 62.8 % of the total DDTR concentrations in the air above the field (Spencer et al., 1974).

Soil Samples

On 28 Feb. 1994, soil samples were obtained to a depth of 75 cm with a Giddings coring rig. Eighteen cores were taken within the previously flooded area designated PF-. Three cores, approximately 7.5 m apart, were obtained in two replications of the 0, 45, and 180 t/ha manure plots. Three cores, approximately 15 m apart, were also taken from the deep plowed area outside the flooded plot (designated P) and from an area that had not been deep plowed or flooded (designated UP). All cores were taken from the wetted area within the tree row middles near the center of each plot. The 75-cm cores were sectioned in the field into 15-cm increments to be analyzed separately. The soil samples were stored frozen until extracted. The thawed samples were crushed, sifted, and mixed, and 25 g of soil was extracted with a soxhlet apparatus for 8 h using a 50:50 mixture of hexane and acetone.

Soil Dust Samples

To determine the potential for exposure to DDT contaminated mobile dust on the soil surface, the vacuuming procedure described by Spencer et al. (1977) was used to obtain soil dust samples within the deep plowed, unflooded area (P) only. Samples of loose dust on the soil surface were obtained by passing a stainless steel nozzle attached to a portable vacuum cleaner over a l00-mesh screen installed on the bottom of a wooden frame. Six composite soil dust samples were obtained from 16 individual 450 cm^2 sampling sites. The dust samples were kept frozen until extracted. Prior to extraction the dry dust was moistened by adding the amount of water equivalent to 20% water content. The dust was soxhlet extracted for 8 h using the 50:50 acetone/hexane mixture. Also 5 g of dust samples were extracted with a Dionex model 703M supercritical fluid extraction system (SFE) (Lee Scientific, Sunnyvale, CA) under the following conditions: oven temperature 90°C, pressure 400 atm, restrictor 180°C, extraction time 70 min with CO_2, and a 15% modifier mixture composed of 7 parts dichloromethane, 2 parts acetone, and 1 part hexane by volume.

Air Concentrations and Volatilization Flux from the Soil Surface

Air concentrations and volatilization flux were measured for 48-h periods during winter and late summer seasons, 28 Feb. to 2 Mar. 1994 and 27 to 29 Sept. 1994. On both dates, air concentrations were measured at two heights, 20 and 80 cm, at three locations above the deep plowed, but unflooded area of the field (designated P). Samples were obtained by pulling air with a vacuum system at 40 L min^{-1} through 5 cm diam. polyurethane foam (PUF) plugs (Turner and Glotfelty, 1977). At each date, samples were obtained over 4-h periods during the day and over 12-h periods during the night. The day-time samples represented 9.6 m^3 air volume and the night-time samples 28.8 m'.

Volatilization rates were measured with modified flux chambers similar to that described by Schmidt and Balfour (1983); and Dupont and Reineman (1986). The chambers were 0.54 x 0.54 m covering an area of 0.29 m^2. Two chambers were used with each rotated between metal frames placed at three sites within the deep plowed plot. Each chamber was rotated into a frame over a new soil area at the time the PUF traps were changed at 4- or 12-h intervals.

At the second sampling on 27 to 29 Sept. 1994, soil within the chamber for one set of chambers was irrigated with 5.7 L of water equivalent to approximately 20 mm of water on the soil surface. The water was added manually with a sprinkling can only once at the beginning of the 48-h period on 27 Sept. 1994. This treatment tested the effect of wetting the soil on the flux of DDT and its degradation products. The PUF plugs were extracted by soxhlet extraction for 2 h using a 50:50 mixture of hexane and acetone.

Analytical Method

The extracts from soil, soil dust, and PUF traps were analyzed for the o,p'- and p,p'-isomers of DDD, DDE, and DDT using a Hewlett-Packard Model 5890 GLC with an electron capture detector. The final extract volumes were 5 and 1 mL hexane for soil and air samples, respectively. Separation of the DDT components was achieved in a DB-608 column (30 m long, 0.53 mm i.d.) with head pressure 0.02 MPa, column He carrier gas flow at 2.5 mL/min, the detector N_2 flow set at 30 mL/min, and temperature program: 140°C (1 min) ramped at 2°C/min to 250°C (2 min). The minimum detectable amounts were 0.0001 ng for the o,p'-isomers of DDD, DDE, and DDT and p,p'-DDE and 0.0005 ng for the p,p'-isomers of DDD and DDT.

Positive identification of the DDT components on the GLC were confirmed by comparison with standards on a Hewlett Packard Model 5890/5971 GC-MS with electronic pressure control. Conditions for GC-MS analysis were: flow rate 0.650 mL min^{-1}; temperature program: 60°C (1 min.) ramped 2°C/min to 250°C (2 min) using a DB-608 column (30 m long, 0.20 mm i.d.).

Table 1. Concentrations of DDT isomers and metabolites in soil cores sampled 28 Feb. 1994 as affected by the 1971 management treatments of deep plowing (P) and flooding (F), with and without organic amendments (M).

		Soil concentrations							
		o,p'-isomers			p,p'-isomers			Total	
Treatment†	Depth	DDD	DDE	DDT	DDD	DDE	DDT	DDTR	CV‡
	cm	mg kg^{-1}							
UP	0–15	0.028	0.106	0.147	0.041	3.367	0.453	4.143	0.359
	15–30	0.027	0.104	0.211	0.050	3.251	0.630	4.272	0.235
	30–45	0.008	0.039	0.064	0.016	1.243	0.174	1.544	0.767
	45–60	0.001	0.005	0.009	0.003	0.198	0.039	0.255	0.597
	60–75	0.001	0.001	0.001	0.001	0.029	0.008	0.040	0.551
P	0–15	0.023	0.072	0.116	0.164	3.361	0.354	4.089	0.315
	15–30	0.022	0.077	0.164	0.068	3.850	0.585	4.767	0.283
	30–45	0.020	0.051	0.093	0.053	2.945	0.438	3.599	0.473
	45–60	0.006	0.014	0.043	0.027	0.857	0.208	1.157	0.563
	60–75	0.001	0.002	0.004	0.003	0.245	0.046	0.301	0.634
PF-OM	0–15	0.032	0.029	0.055	0.024	1.525	0.249	1.913	0.171
	15–30	0.050	0.042	0.090	0.042	1.987	0.395	2.606	0.219
	30–45	0.018	0.021	0.092	0.049	0.978	0.338	1.495	0.770
	45–60	0.005	0.009	0.029	0.014	0.340	0.161	0.557	0.848
	60–75	0.001	0.001	0.002	0.002	0.054	0.017	0.078	0.827
PF-45M	0–15	0.037	0.029	0.050	0.030	1.531	0.186	1.865	0.185
	15–30	0.038	0.032	0.063	0.042	1.398	0.266	1.839	0.213
	30–45	0.013	0.010	0.040	0.042	0.441	0.183	0.729	0.671
	45–60	0.004	0.003	0.014	0.018	0.121	0.070	0.229	0.752
	60–75	0.001	0.001	0.001	0.004	0.035	0.013	0.055	1.354
PF-180M	0–15	0.041	0.031	0.049	0.045	1.526	0.204	1.897	0.282
	15–30	0.050	0.033	0.062	0.121	1.497	0.264	2.026	0.408
	30–45	0.020	0.014	0.059	0.082	0.645	0.271	1.090	0.849
	45–60	0.004	0.003	0.016	0.015	0.182	0.126	0.346	0.815
	60–75	0.001	0.001	0.001	0.001	0.047	0.008	0.058	0.886

† 1971 treatment designations: UP is unplowed; P is deep plowed to 60 cm; F is flooded for 7 wk; M is manure applied at 0, 45, or 180 t ha^{-1}.
‡ CV = SD/mean.

RESULTS AND DISCUSSION

Soil Concentrations

Table 1 shows soil concentrations of the various DDT isomers and metabolites and total residues (DDTR) in 15-cm depth increments of the 75-cm deep soil cores. The metabolite, p,p'-DDE was the major component of the total DDTR. Concentrations of all isomers were lower in the previously flooded plots (PF-). Table 2 shows kg ha^{-1} amounts of the DDT isomers and metabolites calculated from concentrations assuming a soil bulk density of 1.47. The plots that had been previously flooded (PF-) contained less total DDTR than the plots not receiving the flooded treatment. This was mostly due to the much lower amounts of DDE in the flooded plots. The previously deep plowed plots without flooding (P) were highest in both DDE and total DDTR. The unplowed and unflooded plots (UP) were intermediate in DDTR and p,p'-DDE. Deep plowing of the plots without the flooding treatment evidently resulted in greater persistence of the DDTR at lower depths since higher concentrations were present, particularly in the 30 to 45 cm depth than in plots that were deep plowed, and flooded. The proportion of the total soil residue (DDTR) recovered as p,p'-DDE varied from 72 to 81% with slightly higher values in the unflooded plots.

It is readily apparent that flooding with or without organic amendments can be an effective method for reducing total DDTR residues in the soil even though the level of DDE was not affected immediately after the flooding (Farmer et al., 1974). However, as speculated by Farmer et al. (1974) the total DDE produced in the soil was eventually reduced by flooding since DDT was degraded to DDD rather than DDE. The fate of the DDD is unknown. It was most likely volatilized or

Table 2. Amounts of DDT isomers and metabolites within the 0 to 75 cm depth of soil sampled 28 Feb. 1994 as affected by deep plowing (P), flooding (F), and organic amendment (M) treatments applied in 1971 (kg ha^{-1}).†

	Amounts								
	o,p'-isomers				p,p'-isomers				Total
Treatment‡	DDD	DDE	DDT	Total	DDD	DDE	DDT	Total	DDTR
	kg ha^{-1}								
UP	0.14	0.56	0.95	1.66	0.25	17.83	2.87	20.95	22.61
P	0.16	0.48	0.93	1.56	0.70	24.82	3.60	29.12	30.68
PF-OM	0.23	0.23	0.59	1.05	0.29	10.77	2.56	13.61	14.66
PF-45M	0.21	0.17	0.37	0.74	0.30	7.78	1.58	9.66	10.40
PF-180M	0.25	0.18	0.41	0.84	0.58	8.59	1.93	11.10	11.94

† Calculated from soil concentrations at various depths (Table 1), assuming a uniform bulk density of 1.47.
‡ 1971 treatment designations: UP is unplowed; P is deep plowed to 60 cm; F is flooded for 7 wk; M is manure applied at 0, 45, or 180 t ha^{-1}.

degraded in the soil to DDA and other more degradable metabolites (Guenzi and Beard, 1968). In the plowed and unplowed plots that were not flooded in 1971 (UP and P), most of the DDT was degraded to DDE which accounted for the higher amount of total DDTR.

The finding that p,p' DDE was the major component of the DDTR is in agreement with data reported by Cooke and Stringer (1982) on breakdown of DDT in orchard soil in England over an 11-yr period and with data reported by Boul et al. (1994) on influence of irrigation and fertilization on levels of DDT and its residues in soil in New Zealand over a 40-yr period. Boul et al. (1994) found that irrigation resulted in lower levels of recoverable DDT residues in soil primarily because of lower levels of p,p' DDE than in nonirrigated soil. Our data indicate that greater volatilization of DDE from the irrigated soil could have contributed to this difference.

Soil Dust Concentrations

The soil dust vacuumed from the surface of the deep plowed, unflooded area (P) contained both the o,p'- and p,p'-isomers of DDD, DDE, and DDT (Table 3). Table 3 shows the average concentrations from six dust samples extracted with soxhlet and with SFE. The concentrations of all isomers are very similar to the concentrations in the surface 0 to 15 cm soil samples from which the dust was derived. p,p'-DDE was the predominant component of the DDTR residue constituting 79.4% of the DDTR by soxhlet extraction and 75.8% in the SFE-extracted samples. An average of 99.1 g of dust was collected for each composite sample of 16 screens over a total area of 0.32 m^2 or 309 g m^{-2} dust. Average pesticide mass in the mobile dust can be calculated from the dust levels and the individual isomer concentrations. For example, using the p,p'-DDE concentration of 2.719 mg kg^{-1} and the 309 g m^{-2} dust, the p,p'-DDE mass on the mobile dust was 0.840 mg m^{-2} or 8.74 g ha-'. The mass of the other isomers on the mobile dust can be calculated in a like manner.

Atmospheric Concentrations

Air concentrations at 20 and 80 cm above the soil surface for 48-h periods beginning 28 Feb. 1994 and 27 Sept. 1994 are shown in Tables 4 and 5, respectively. The air temperatures were much higher during the 27 September 1994 sampling. The concentrations of all the isomers are higher during the September sampling, with the exception of p,p'-DDT. There was little diurnal variation, and concentrations in the air were approximately the same at night as during the day. Again the p,p'-DDE is the major component of the atmospheric DDTR levels. p,p'-DDE constituted 70% of the total DDTR in the atmosphere during the February sampling and 76% of the DDTR in the September sampling. In September, the DDE levels in the atmosphere were approximately two times those during February. The DDD levels were below minimum detectable concentrations. The air concentration measurements show that DDT and its breakdown products are continually volatilizing from soils where they are present, resulting in very low concentrations of DDT components in the atmosphere.

Volatilization Flux

Flux chambers placed on the surface of the deep plowed, unflooded area (P) were used to measure volatilization flux of the various DDT components over 48-h periods, beginning on 28 Feb. 1994 and 27 Sept. 1994. During the February sampling, data were collected from two chambers similarly placed on relatively dry soil. Table 6 shows the average flux in February from the two chambers for 4- or 12-h periods (4-h periods during the day and 12-h periods during the night). Again, p,p'-DDE was the major component volatilizing from the soil surface comprising an average of 73% of the total volatilizing DDTR. o,p'-DDE also appeared to be a significant component of the volatilization flux.

During the September sampling, the soil under one of the chambers was irrigated with approximately 20 mm water prior to the initiation of the flux measurements. Table 7 shows the volatilization flux during 4- or 12-h periods from the irrigated and nonirrigated chambers. Wetting the soil with a small amount of water dramatically increased the volatilization flux of all the DDT components. For example, during the first period of measurement from 1045 to 1445 h on 27 Sept. 1994, the p,p'-DDE volatilization flux increased from 0.417 $\mu g\ m^{-2}\ h^{-1}$ from the dry soil to 16.1 $\mu g\ m^{-2}\ h^{-1}$ from the irrigated soil. The overall volatilization flux of DDTR was more than 10 times greater from the irrigated chamber than from the nonirrigated one. This effect of soil moisture is consistent with Spencer and Cliath's (1972) observation that vapor density of all DDT isomers are much greater in moist soil than in dry soil. The ratio of

Table 3. Concentrations of DDT isomers and metabolites in soil dust from the deep plowed, unflooded area (P), as extracted by soxhlet or SFE. me kg^{-1}.

	Dust concentrations								
	o,p'-isomers				p,p'-isomers				Total
Extn method	DDD	DDE	DDT	Total	DDD	DDE	DDT	Total	DDTR
	mg kg-'								
Soxhlet	0.043†	0.118	0.106	0.267	0.159	2.825	0.337	3.321	3.558
c v	0.468	0.504	0.364		0.543	0.300	0.247		
SFE	0.021†	0.125	0.120	0.266	0.050	2.612	0.516	3.178	3.444
c v	0.199	1.00	0.297		0.278	0.235	0.346		
Mean	0.032	0.122	0.113	0.266	0.105	2.719	0.427	3.250	3.516

t Each value is an average of six composite samples.

Table 4. Atmospheric concentrations of DDE and DDT isomers at 20 and 80 cm above the deep plowed, unflooded area (P) over a 48-h period beginning 28 Feb. 1995 at 1400 h.

Time (PST)			Atmospheric concentrations				
Start	End	Height	o,p'-DDE	o,p'-DDT	p,p'-DDE	p,p'-DDT	DDTR
h		cm	ng m^{-3}				
1400	1800	20	**0.63**†	0.49	7.66	2.34	11.12
		80	0.29	0.22	5.58	2.66	8.14
1800	2200	20	0.21	0.15	8.08	2.11	10.55
		80	0.29	0.12	6.56	3.02	9.99
2200	**1000**	**20**	**0.12**	**0.05**	5.12	0.77	6.06
		80	0.12	0.06	5.34	0.83	6.35
1000	1400	20	0.40	0.21	5.63	3.59	9.84
		80	0.48	0.14	4.43	3.77	8.81
1400	1800	20	0.35	0.17	5.51	2.51	8.53
		80	0.67	0.08	3.74	2.32	6.81
1800	2200	20	0.85	0.21	11.50	2.66	15.22
		80	0.69	0.07	8.43	2.49	11.68
2200	**1000**	**20**	0.25	0.09	8.07	0.83	9.23
		80	0.20	0.06	6.93	0.82	8.02
1000	1400	20	0.36	0.17	5.12	2.05	7.70
		80	0.57	0.24	4.67	2.51	8.00
All		20 (avg.)	0.40	0.19	**7.09**	2.11	9.78
		c v	0.56	0.65	**0.29**	0.42	
		80 (avg.)	0.41	0.12	5.71	2.30	8.55
		c v	0.49	0.53	0.25	0.41	
		Mean	0.40	0.16	6.40	2.20	9.17

† Each value is an average of three samples collected simultaneously.

the various isomers appearing in the atmospheric samples and from the flux chambers are in agreement with the relative vapor pressures of the compounds as reported by Spencer and Cliath (1972) and Spencer et al. (1974). The volatilization flux from the dry soil during the September sampling was much higher than in February. This could have been caused by higher temperatures in September than in February, but also could have been related to soil moisture status because of more frequent irrigations in September than February.

The finding that the DDT isomers, particularly p,p'-DDE, are continuing to volatilize from the soil surface has implications for their long-range transport (Bidleman et al., 1990) and transport of DDT and its metabolites to aboveground plant parts as well as potential exposure to animals and humans in the area of DDT-contaminated

Table 5. Atmospheric concentrations of DDE and DDT isomers at 20 and 80 cm above the deep plowed, unflooded area (P) over a 48-h period beginning 27 Sept. 1994 at 1045 h.

Time (PDT)			Atmospheric concentrations				
Start	End	Height	o,p'-DDE	o,p'-DDT	p,p'-DDE	p,p'-DDT	DDTR
h		cm	ng m^{-3}				
1045	**1445**	**20**	**2.30**†	0.42	16.01	1.92	20.65
		80	1.56	0.42	11.21	1.62	14.81
1445	1845	20	3.92	0.62	16.96	0.99	22.49
		80	3.38	1.53	12.55	1.17	18.63
1845	0645	20	4.34	0.15	17.42	1.22	23.12
		80	2.18	0.18	11.70	0.66	14.73
0645	1045	20	2.60	0.29	17.70	1.54	22.14
		80	1.57	NDS	11.54	1.34	14.45
1045	1445	20	ND	0.41	11.79	1.98	14.18
		80	ND	ND	6.76	1.59	8.35
1445	1845	20	5.13	0.44	16.48	1.16	23.81
		80	3.04	ND	10.39	2.24	15.66
1845	0645	20	1.21	0.08	11.63	0.67	13.59
		80	1.22	0.11	9.10	0.42	10.85
0645	1045	20	1.57	0.08	13.27	1.83	16.75
		80	2.02	0.26	11.95	2.32	16.56
All		20 (avg.)	2.71	0.31	15.16	1.41	19.59
		c v	0.64	0.59	0.16	0.32	
		80 (avg.)	1.87	0.31	10.65	1.42	14.26
		c v	0.53	1.54	0.17	0.44	
		Mean	2.29	0.31	12.90	1.42	16.92

† **Each value** is an average of three samples collected simultaneously.
‡ ND is below minimum detectable levels of 0.005 ng m^{-3}.

Table 6. Volatilization flux of DDE and DDT isomers from soil as measured with a flux chamber placed on the deep plowed, unflooded area (P) over a 48-h period beginning 28 Feb. 1994 at 1400 h.

Time (PST)		Flux				
start	End	o,p'-DDE	o,p'-DDT	p,p'-DDE	p,p'-DDT	DDTR
h		μg m⁻² h⁻¹				
1400	1800	0.003†	ND‡	0.066	0.038	0.107
1800	2200	0.005	0.003	0.041	0.024	0.072
2200	1000	0.002	0.001	0.037	0.008	0.048
1000	1400	0.014	ND	0.209	0.037	0.260
1400	1800	0.009	0.003	0.042	0.032	0.086
1800	2200	0.006	0.003	0.024	0.028	0.059
2200	1000	0.002	0.001	0.137	0.008	0.148
1000	1400	0.011	0.004	0.178	0.023	0.216
	Mean	0.006	0.002	0.092	0.025	0.125
	c v	0.19	0.63	0.53	0.15	

† Each value is an average from two flux chambers.
‡ ND is below minimum detectable levels of 0.001 μg m⁻² h⁻¹.

soils. The soil residues serve as a continuous source of airborne residues for long-range transport and adjacent deposition.

SUMMARY AND CONCLUSION

The data indicate that concentrations of all the DDT isomers, including p,p'-DDE, decreased with time in all plots. The soil concentrations of p,p'-DDE and total DDTR were greater in the deep plowed plot (P) than in the plot that had not been deep plowed (UP). This indicates that the deep plowing had a conservative effect on the DDT; placing it deeper into the soil profile evidently protected it somewhat from degradation and volatilization from the soil surface. The soil concentrations of p,p'-DDE and all other isomers of DDT were less in plots that had been previously flooded in 1971 than the two areas not flooded. This confirms the projection made by Farmer et al. (1974) that the total amount of DDE produced in the soil would eventually be reduced since DDT was degraded to DDD in the flooded condition rather than to DDE in the unflooded soil. Consequently, degrading the DDT by flooding lessened or prevented the formation of DDE in the soil, thus ultimately reducing its redistribution into the environment.

Air concentrations and volatilization flux indicated that small amounts of DDT isomers and metabolites, particularly p,p'-DDE, continue to be volatilized from the soils containing DDTR residues. Irrigating the soil with a small amount of water dramatically increased the volatilization flux over that from an unirrigated soil, proving that the volatilization flux will vary greatly depending on the soil water content. Air concentrations will probably be greatest immediately after rainfall or irrigation in dry climates as reported by Ware et al. (1975) and Willett et al. (1993).

Volatilization and redistribution through the atmosphere might be very important if contaminated forage or other crops are eaten by dairy cows (Bos taurus) or

Table 7. Volatilization flux of DDE and DDT isomers with (I) and without (NI) irrigation in the deep plowed, unllooded area over a 48-h period beginning 27 Sept. 1994 at 1045 h, PDT.

Time (PDT)		Water status	Volatilization flux				
Start	End		o,p'-DDE	o,p'-DDT	p,p'-DDE	p,p'-DDT	DDTR
h			μg m⁻² h⁻¹				
1045	1445	I†	0.491	ND‡	16.1	0.227	16.8
1045	1445	NI	0.059	0.005	0.417	0.016	0.496
1445	1845	I	0.379	0.081	9.22	0.151	9.84
1445	1845	NI	0.036	0.012	0.342	0.007	0.397
1845	645	I	0.121	0.029	3.81	0.059	4.02
1845	645	NI	0.046	0.007	0.536	0.005	0.594
645	1045	I	0.352	ND	2.81	0.061	3.22
645	1045	NI	0.100	ND	1.08	0.012	1.20
1045	1445	I	0.305	0.077	10.03	0.171	10.6
1045	1445	NI	0.033	ND	0.60	0.010	0.643
1445	1845	I	0.173	0.037	4.09	0.089	4.39
1445	1845	NI	0.030	0.003	0.76	0.009	0.808
1845	645	I	0.146	0.028	3.54	0.066	3.78
1845	645	NI	0.029	ND	0.607	0.005	0.641
645	1045	I	0.088	ND	2.825	0.065	2.98
645	1045	NI	0.040	ND	0.596	0.020	0.656
Mean		I	0.257	0.031	6.55	0.111	6.95
c v		I	0.53	0.98	0.68	0.54	
Mean		NI	0.046	0.003	0.618	0.010	0.679
c v		NI	0.48	1.20	0.34	0.47	

† I designates irrigated with 20 mm water; NI = no irrigation.
‡ ND is below minimum detectable levels of 0.001 μg m⁻² h⁻¹ for 4-h sampling periods and 0.0003 μg m⁻² h⁻¹ for 12-h periods.

other susceptible animals. This mechanism has been documented by Willett et al. (1993) who reported that volatilization, air transport, and deposition were the main avenues of contaminating forage with DDE and DDT eaten by cows. The health implications of exposure to humans or animals to these air concentrations are unknown.

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