

Transfer of DDT and Metabolites from Fruit Orchard Soils to American Robins (*Turdus migratorius*) Twenty Years After Agricultural Use of DDT in Canada

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Abstract. Wildlife contamination studies found high levels of DDT and associated metabolites in bird eggs from Canadian orchard sites during the early 1990s. The present study investigated local dietary uptake of DDT and geographic variability in tissue concentrations in the same orchards. A soil–earthworm–robin food chain was chosen for study, as early surveys showed that robins contained the highest levels of DDT of several avian species and because published research indicated that earthworms were a probable dietary exposure route. Organochlorine pesticides and PCBs were measured in soil, earthworm, robin egg, and robin nestling samples collected from fruit orchards and reference sites. High average DDE (soil: 5.2 mg/kg; earthworm: 52 mg/kg; robin egg: 484 mg/kg dry weight) and DDT (soil: 9.2 mg/kg; earthworm: 21 mg/kg; robin egg: 73 mg/kg dry weight) concentrations in Okanagan (British Columbia) samples confirmed that previously recorded contamination was common in the region. Concentrations detected in Simcoe, Ontario, orchards were not as high but were still significantly elevated relative to levels in soils and robins from reference areas. Significant positive linear regressions between soil and earthworm concentrations and consistent trends in food chain accumulation suggested that robins were acquiring DDT and metabolite (DDTr) burdens locally. Low concentrations of DDT and DDTr in robin eggs collected from nests in nearby nonorchard and post-DDT orchard habitats suggested that the local sources were in orchards. Persistence of DDT in orchard food chains is likely due to a combination of retarded degradation rates for DDT in soil and its extensive use historically. DDT concentrations in some robin eggs and earthworms were at levels comparable to those observed in field studies where mortality or reproductive effects occurred.

The environmental persistence of historically applied organochlorine (OC) pesticides has been well documented in the northern hemisphere (Loganathan and Kannan 1994). In particular, routine detection of 1,1,1-trichloro-2,2-bis(*p*-chlorophenyl)ethane (DDT) and dieldrin in environmental media suggests some level of continuing risk to avian wildlife.

On the Niagara Peninsula in Ontario (Canada), the use of DDT for control of insect pests on apples was one of the few applications to food crops allowed after 1970; it was discontinued in 1973 (Ontario Ministry of the Environment 1978). In 1989, elevated levels of DDT metabolites were detected in local American kestrel (*Falco sparverius*) and Eastern bluebird (*Sialia sialis*) food chains (Hebert *et al.* 1994). Of special note, concentrations of *p,p'*-DDE ranged higher in American robin (*Turdus migratorius*) eggs (1.25 to 17.25 mg/kg wet weight) than in the predatory kestrel or any other bird, mammal, or invertebrate assessed. Similarly, American robin eggs contained up to 42 times more DDT, on average, than eggs of six other avian species collected from the Okanagan Valley, British Columbia (BC) in 1990–91 (Elliott *et al.* 1994). In pooled samples from two orchard habitats, *p,p'*-DDT ranged from 11 to 26 mg/kg in robin eggs, while *p,p'*-DDE ranged from 68 to 103 mg/kg wet weight. The latter was also 4 to 80 times higher than DDE concentrations detected in Niagara robin eggs the year before. DDT use on fruit crops in the Okanagan Valley (BC) was largely halted by 1970 (British Columbia Pollution Control Branch 1973).

Because resident Okanagan Valley species (some robins; black-billed magpie, *Pica pica*) contained greater concentrations than three neotropical migrant species (tree swallow, *Tachycineta bicolor*; barn swallow, *Hirundo rustica*; house wren, *Troglodytes aedon*), it was suggested that birds had acquired much of the *p,p'*-DDE and -DDT burdens locally, via uptake through the food chain (Elliott *et al.* 1994). Fruit orchard soils were considered the most likely environmental sink of these persistent OCs. Robins readily use orchard habitat and could uptake DDT or metabolites via earthworms, which are a dominant prey item directly before and during the breeding season (Johnson *et al.* 1976; Wheelwright 1986). A soil–

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earthworm–robin exposure scenario was assessed by several early investigators when robin die-offs proceeded DDT treatments for bark beetles and spruce budworm (Barker 1958; Dimond *et al.* 1970; Johnson *et al.* 1976). Unfortunately, in the 1990 BC study, prey were not analyzed for DDT content. Since the migrant species were insectivores and the resident species were omnivores, the contribution of diet to interspecific differences in tissue burdens was an unknown variable. Also, the regional differences in robin contamination were of interest, because use of DDT should have been comparable between the two provinces.

In 1993, a coordinated Ontario/BC study of DDT in the American robin food chain was initiated. An expansion of previous investigations was especially warranted, because of the high degree of contamination observed relative to similar post-DDT era studies (DeWeese *et al.* 1986; Blus *et al.* 1987; Clark *et al.* 1995) and also due to the importance of these orchard habitats for local bird populations (Cannings *et al.* 1987). Soils, earthworms, and robin eggs and chicks were collected for pesticide analysis. The objectives of the study were: (1) to assess local orchard soils as a potential source of DDT and metabolites (DDTr) for resident wildlife; (2) to quantify the extent of DDT and DDTr bioaccumulation in robins and their local prey; and (3) to search for differences in exposure or bioavailability among regions at two lower levels in the robin food chain. The reproductive success of local robin populations was also investigated and the results will be presented elsewhere.

Materials and Methods

Collection Sites

Selection of sampling locations was based on a regional gradient of *p,p'*-DDE contamination found in previous studies (Elliott *et al.* 1994; Hebert *et al.* 1994). Sites in the Okanagan Valley, BC, fell within a 20-km² radius of either Penticton, Kelowna, or Vaseux Lake, while those in southwestern Ontario were located near Guelph, Simcoe, or in the Niagara fruit belt (Figure 1). In the Okanagan, 15 orchards were surveyed at least once during the 3 years of study (1993–1995). In Ontario, eight orchards were surveyed in the Niagara fruit belt, and six near Simcoe in 1994 alone. To establish the relative level of contamination in old orchards compared to other local habitats, three nonorchard sites were also surveyed in the Okanagan, and five young orchards were surveyed in Guelph, Ontario. Guelph orchards were established after the ban on DDT was implemented. The majority of orchard samples were collected in apple groves, but some apricot and cherry orchards were also included in the Okanagan Valley collections. In the remainder of the text, Okanagan, Simcoe, Niagara, and Guelph were described as sampling regions, and regional comparisons describe tests done with average values for these areas. Regional groupings were distinguished as follows: Okanagan nonorchard = OREF; Okanagan orchard = OK; Guelph orchard = GO; Niagara orchard = NO; Simcoe orchard = SO.

Soil Sampling

Soil samples were collected in 5 of the 15 Okanagan sites and in all Niagara, Simcoe, and Guelph orchards ($n = 18$) in the spring of 1994. Usually, only one sample was collected from each site. In three

Okanagan orchards, samples were collected from three locations within each, because past fruit crops had varied considerably in composition and longevity. The soils in the Okanagan Valley consisted of a thin surficial layer, then a dense sand/gravel mixture below 10 cm depth. Consequently, Okanagan samples were collected by digging out a block of soil approximately 15 cm square at the surface and 10 to 15 cm deep using a garden spade. Each of these samples was placed in a Ziploc plastic bag, returned to the laboratory, and refrigerated at 4°C until chemical analysis. Just prior to extraction, soils were divided into 0–5 and 5–10 cm horizons. In Ontario orchards where a gravel bedrock was not encountered, a 60–70-cm-deep pit was dug and at least 500 g of soil were removed at depth increments of 0–5, 5–10, 10–20, and 20–40 cm. Samples were collected from one face of each pit using a carving knife and masonry trowel. Each incremental sample was placed in a Ziploc bag, returned to the laboratory, and refrigerated at 4°C until chemical analysis.

Earthworm Sampling

Earthworms were sampled on the same dates and sites as soils in 1994. Six to eight samples were collected from each site within a 5-m radius of the soil collection. A modified formalin extraction method (Raw 1959) was used to bring earthworms to the soil surface. The area within a 60 cm² wooden quadrat was cleared of surface debris with a rake and the grass, when present, was clipped to its base. A dilute formalin solution (50 ml of 37% formaldehyde in 9 L water) was sprinkled over each quadrat with a watering can, ensuring that the solution infiltrated the soil with no runoff. Surfacing worms were collected and immersed in clean water to remove surficial formalin and to keep the earthworms alive until their guts could be cleared of soil. Gut contents were cleared by placing worms on moist paper towels for 72 h in 250-ml glass preserving jars with no food. Individual earthworms were identified to species, weighed, and tallied by site. The cleaned earthworms were freeze-dried (Virtis Freezermobile-12, Gardiner, NY) and stored at –20°C until chemical analysis. Where tissue quantities were sufficient, species were segregated for residue analysis. In some cases, species could also be divided by age into groups of juveniles and adults. Species divisions were possible for most of the Ontario orchard samples, but only limited amounts of earthworm tissue were procured from several of the Okanagan sites.

American Robin Sampling

American robins follow the 3°C isotherm northward in the spring to breeding grounds (Campbell *et al.* 1997); they begin breeding in the Okanagan Valley in late February and in southern Ontario in mid-April. The robin is an “edge” species, meaning that they prefer to nest in trees or shrubs near clearings rather than in dense bush (Campbell *et al.* 1997). It is one of the most common and widely distributed breeding songbirds in Canada, adapting well to urban environments. In study orchards, robins were observed feeding on earthworms, which are reported to be the most common food item during breeding (Wheelwright 1986).

Robin nests were located using row-by-row searches of orchards. Additional nests were found incidentally in nonorchard areas in the Okanagan. Based on rudimentary observations, we assumed that robins from nests in orchards fed mainly but not exclusively in those orchards. For OC analysis, one egg was removed from each nest during the laying period, and a wooden egg was simultaneously introduced to reduce the risk of nest abandonment (Okanagan nests only). Eggs were collected from Okanagan sites in 1993, 1994, and 1995. Ontario robin populations were only sampled in 1994; both eggs and nestlings were collected, though from different nests within the

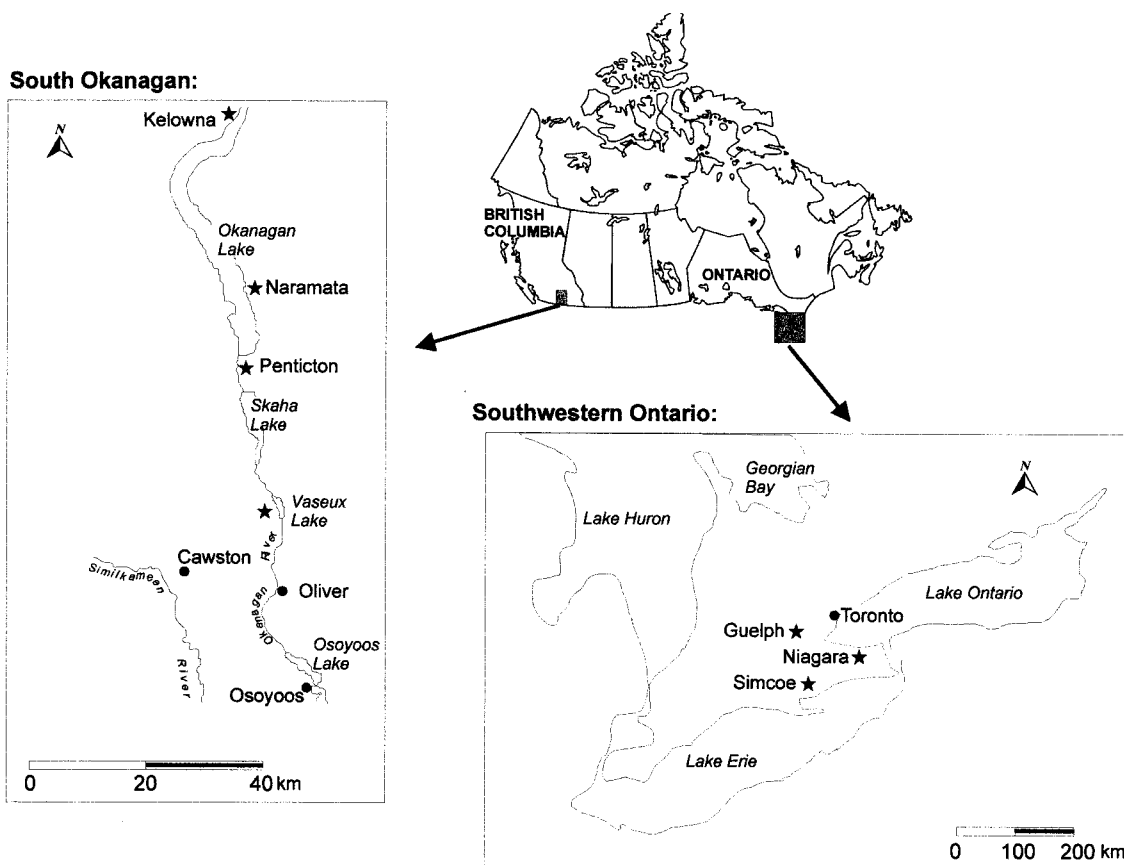


Fig. 1. Location of orchards and nonorchard reference sites in the Okanagan Valley, British Columbia and southwestern Ontario, Canada

same site. Eggs were weighed, eggshell thickness measured, and contents stored in acetone/hexane-cleaned glass jars at -20°C until analysis. Ten-day-old nestlings were asphyxiated with carbon dioxide and decapitated; after weight and length were measured, carcasses were individually stored in hexane-cleaned glass jars at -20°C .

Chemical Analyses

Soil and earthworm samples were analyzed for DDT and DDT_r at the Southern Crop Protection and Food Research Centre, Agriculture and Agri-Food Canada, London, Ontario. Soil samples were analyzed by GC-ECD after an acetone extraction process suitable for samples containing multiresidue insecticides like DDT and its congeners (Luke *et al.* 1981). No clean-up step was required due to the relatively high concentrations of DDT and DDT_r encountered in soil samples. A 200-g subsample of fresh soil was mixed with 300 ml acetone and tumbled for 1 h at 30 rpm. The mixture was transferred to a Buchner funnel containing 90 mm #1 Whatman filter paper, and the acetone collected and stored at -15°C until analysis on a Tracor 540 gas chromatograph equipped with a Ni^{63} electron capture detector (Tracor Instruments Austin, Austin, TX) and a 30-mm DB-1701 column (0.32 mm ID, 0.21 μm film thickness). Sample run time was 23 min with temperature ramping of $20^{\circ}\text{C}/\text{min}$ from 150°C to 210°C . Detection limits in soil were 0.01 mg/kg dry weight for *o,p'*- and *p,p'*-DDE, 0.02 mg/kg for *p,p'*-DDD and *o,p'*-DDT, and 0.03 mg/kg for *o,p'*-DDD and *p,p'*-DDT. All concentrations were expressed on a soil dry weight basis.

Freeze-dried earthworm samples were extracted using an acetone

step similar to that used for soil samples, except that each worm sample (≥ 1 g in 100 ml acetone) was placed in an ultrasonic bath for 15 min as a substitute for the tumbling extraction procedure. This change was necessary because only small quantities of tissue were available for some analyses. The earthworm-acetone mixture was left at room temperature overnight, filtered in a Buchner funnel containing 55 mm #1 Whatman filter paper, and stored frozen (-4°C) until fractionation. Earthworm samples required a clean-up step adapted from Miles and Harris (1971). A 75-ml acetone extract was evaporated to dryness, reconstituted to 3 ml in hexane, and fractionated on a 16-g Florisil glass column (25 mm ID, 50 cm long). Fraction A was eluted with 75 ml hexane and fraction B with 60 ml 10% acetone/hexane (v/v). Eluted fractions were analyzed using the same GC and run conditions described for soils. Dilutions of hexane solutions were made to meet the linearity range requirements of the GC-ECD. The detection limit for all isomers in earthworms was 0.3 mg/kg dry weight. All earthworm concentrations were expressed on a dry weight basis. For reporting concentrations in soil and earthworms, *o,p'*- and *p,p'*-DDE or DDT were summed and referred to as simply DDE or DDT. When ΣDDT is discussed, it refers to the sum of all measured DDD, DDE and DDT isomers.

American robin egg contents (minus shell) and nestling carcasses (minus beak, feet, and feathers) were analyzed as whole homogenates (blended for 4 to 5 min at high speed) at the National Wildlife Research Centre (NWRC), Canadian Wildlife Service, Hull, Quebec. Eggs from Ontario were pooled by region, while those from the Okanagan were analyzed individually, as were Ontario nestlings. Organochlorine (OC) pesticides and polychlorinated biphenyls (PCBs) were measured according to a multiresidue GC/MSD procedure (En-

vironment Canada 1997). Samples were submitted to neutral lipid extraction, gel permeation chromatography (GPC), and Florisil column chromatography as clean-up steps prior to GC/MSD analysis. A 1.5-g tissue sample was ground with 10 g anhydrous sodium sulfate, introduced to a glass column (1 cm ID × 24 cm) packed with 50% 1:1 methylene chloride (DCM)/hexane, and eluted with 100 ml 1:1 DCM/hexane at 5–10 ml/min. The extract was rotoevaporated to dryness, spiked with an internal standard mixture, reconstituted with 1:1 DCM/hexane, and added to a GPC glass column (3 cm ID × 60 cm; ABC Laboratories, Columbia, MO) packed with 60 g BIO-BEADS S-X3 (Analytical Biochemistry Laboratories, Columbia, MO) with a flow rate of 5 ml/min (Norstrom *et al.* 1986). The resulting eluate was rotoevaporated to dryness with hexane, submitted to a glass column (1 cm ID × 24 cm) wet packed (hexane) with 8 g 1.2% water deactivated Florisil (Floridin, Berkeley Spring, WV), and eluted with 100 ml hexane at a flow rate of 5 ml/min. The cleaned-up sample was then rotoevaporated to dryness, mixed with 20 µl PCB-154 recovery standard, and the final volume adjusted to 570 µl with hexane. Each sample was injected twice onto a HP5890 gas chromatograph equipped with a HP5970 mass selective detector (Hewlett Packard, Mississauga, ON) and a 30-m DB-5 fused silica column (0.25 mm ID, 0.25 µm film thickness). The first injection quantified OC pesticides in a total run time of 31 min and temperature ramping of 5°C/min to 300°C, and the second injection quantified PCBs in a total run time of 55 min and temperature ramping of 2.5°C/min to 300°C. Internal standards and quality control measures are described elsewhere (Environment Canada 1997). One to three diluted herring gull egg pool reference materials were analyzed each year, and results indicated residue analyses were reliable. Detection limits for *p,p'*-DDD, -DDE, and -DDT ranged between 0.0001 and 0.0003 mg/kg wet weight. The *o,p'*-isomers were not identified with this method. Robin egg and carcass values were expressed on a wet weight basis, and ΣDDT refers to the sum of *p,p'*-DDD, -DDE, and -DDT isomers. Detection limits for other OCs are described in the Appendix.

Statistical Analyses

Statistical analyses were performed on log-transformed DDT and DDT_r values using SYSTAT (Wilkinson 1990). After logarithmic transformation, residue data met assumptions of normality and homogeneity of variances. One-way analyses of variance (ANOVAs, α = 0.05) were used to test for significant differences in soil DDT and DDT_r concentrations among soil depths. They were also used to test for differences in average soil DDT contamination among regions (*e.g.*, Okanagan, Niagara, Simcoe, Guelph orchards). For soil tests, average concentrations in surface samples alone (0–10 cm) were compared among regions, because this was the common depth profile collected from all orchards. Average DDT and DDT_r for full soil profiles collected from Ontario orchards (0–40 cm) were calculated (see Table 1), but could not be used for statistical comparisons because similar soil profiles were not available for BC orchards. To obtain an accurate mean concentration of DDT and DDT_r for the full depth profile, soil density must be considered; however, since density was not measured and because analytical samples contained disproportionate (5, 10, or 20 cm) soil increments, it was necessary to estimate weighted average soil concentrations in Ontario orchards using the equation,

$$\bar{x} [] = 0.125[0-5 \text{ cm}] + 0.125[5-10 \text{ cm}] + 0.25[10-20 \text{ cm}] + 0.5[20-40 \text{ cm}] \quad (\text{Eq. 1})$$

where [] = concentration of DDD, DDE, or DDT.

Differences in average regional levels of contamination in earthworms, robin eggs, or robin nestlings were similarly assessed using

separate one-way ANOVAs. One-way ANOVAs were also used to test for differences in earthworm DDT concentrations among earthworm species in a specific region or orchard. In all substrates where nondetections were present, they were expressed as half of the detection limit in ANOVAs. Also, wherever soil or earthworm samples were collected from multiple locations within one orchard (n = 3 Okanagan orchards), ANOVAs were conducted using orchard means. Where significant differences were found, regions were distinguished using *post hoc* Tukey honestly significant difference (HSD) multiple comparisons with Tukey-Kramer adjustments for unequal sample sizes.

Linear regressions were used to estimate the dependence of earthworm contamination on surface soil concentrations (0–10 cm averages), and the dependence of robin egg contamination on earthworm concentrations. A multivariate regression was used to assess the dependence of proportion of DDT or DDE in surface soil on the potentially interacting factors, earthworm abundance, and percent soil organic matter, in Ontario orchards. In the absence of soil density values, proportion of compounds in surface soil was estimated as

$$\% []_s = \{(0.5[0-5 \text{ cm}] + 0.5[5-10 \text{ cm}]) * 10\} / \{(0.125[0-5 \text{ cm}] + 0.125[5-10 \text{ cm}] + 0.25[10-20 \text{ cm}] + 0.5[20-40 \text{ cm}]) * 40\} \quad (\text{Eq. 2})$$

where [] = concentration of DDE or DDT. Another multivariate regression was used to assess the dependence of average earthworm DDT or DDE concentrations on the following potentially interrelated characteristics of surface soil: pH, % organic matter, and soil DDT and DDT_r concentrations. To avoid bias associated with nondetectable DDT, nondetections were left out of regression calculations.

Bioaccumulation factors (as defined by Rand 1995) for DDT, DDE, and ΣDDT were calculated both by dividing the concentration in earthworms by the concentration in surface soils (0–10 cm, dry weight values), and by dividing the average concentration in robin egg contents or nestlings (converted to dry weight values) by the average concentration in earthworms. Bioaccumulation factors were compared among regions using the nonparametric Kruskal Wallis analysis of variance for ranks.

Results

Soil

Differences in the soil horizons sampled in Ontario and Okanagan orchards restricted some comparisons of DDT and DDT_r profiles. Soil samples from Okanagan sites only included the top 10 cm because sand and gravel were encountered below that depth. In Ontario, 40-cm-deep soil samples were collected. Okanagan soils tended to have slightly higher organic matter content than Ontario soils (Table 1), but the difference was significant only among surface soils (0–10 cm) of Niagara and Okanagan orchards (p = 0.009). Okanagan orchard soils were acidic, yet an Okanagan reference soil (OREF-1) was slightly basic (pH 7.9). Ontario orchard soils were highly acidic to slightly basic (Table 1); on average, Simcoe soils were significantly more acidic than Guelph soils (p = 0.031).

In regional comparisons of DDT and DDT_r in soils, significant differences were detected among Niagara and Okanagan orchards (Table 1). Okanagan orchard soils contained significantly higher concentrations of DDE (p = 0.017), DDT (p = 0.027), and ΣDDT (p = 0.022) compared to Niagara orchard soils. Simcoe soil values lay between averages for these two regions and were not different from

Table 1. DDT and DDT_r concentrations (mean ± standard error, mg/kg dry weight) in orchard surface soils (0–10 cm) and 40-cm soil profiles^a

Variable	Guelph		Niagara		Simcoe		Okanagan ^b
	0–10 cm	0–40 cm	0–10 cm	0–40 cm	0–10 cm	0–40 cm	0–10 cm
% Organic matter ^c	3.7 ± 0.4 B (2.2–5.4)	2.5 ± 0.3 (1.1–5.4)	2.3 ± 0.2 A (1.3–5.4)	1.3 ± 0.2 (0.2–5.4)	3.3 ± 0.3 B (1.8–5.2)	1.7 ± 0.2 (0.7–5.2)	3.8 ± 0.4 B (3.1–4.9)
pH ^c	7.3 ± 0.2 D (6.0–7.7)	7.5 ± 0.1 (6.0–7.9)	6.1 ± 0.3 CD (4.8–7.6)	6.1 ± 0.3 (3.3–7.9)	5.6 ± 0.5 C (3.6–6.7)	5.9 ± 0.5 (3.6–7.6)	6.4 ± 0.1 CD (6.3–6.9)
N	5	5	7	7	6	6	4
DDD	< 0.05	< 0.05	0.05 ± 0.02	0.04 ± 0.01	0.16 ± 0.07	0.13 ± 0.05	0.25 ± 0.15
DDE	< 0.02	< 0.02	0.79 ± 0.2 a	0.56 ± 0.2	3.6 ± 1.4 ab	1.7 ± 0.6	4.9 ± 1.2 b
DDT	< 0.05	< 0.05	1.0 ± 0.4 c	0.64 ± 0.26	3.4 ± 1.5 cd	1.6 ± 0.7	9.3 ± 4.8 d
ΣDDT	< 0.12	< 0.12	1.9 ± 0.6 e	1.2 ± 0.5	7.1 ± 3.0 ef	3.4 ± 1.4	14.4 ± 6.0 f
DDE:DDT	—	—	1.21	1.41	1.36	1.27	1.10

^a DDD, DDE, and DDT are the sum of *o,p'* and *p,p'* isomers, while ΣDDT is the sum of all DDD, DDE, and DDT. Regional values with the same letter (bold typeface) are not significantly different from each other ($p > 0.05$).

^b Means do not include the single nonorchard (reference) sample assayed (from OREF-1), which did not contain detectable concentrations of DDD (< 0.05 mg/kg), DDE (< 0.02 mg/kg) or DDT (< 0.05 mg/kg); soil pH at OREF-1 ranged 7.8 to 8.0, while average % organic matter was 4.7 (range 4.2 to 5.2).

^c Values in parentheses are ranges.

either. Guelph orchard soils ($n = 5$) and the single Okanagan reference soil tested (OREF-1) did not contain any forms of DDT ($\Sigma\text{DDT} < 0.12$ mg/kg). Because no DDT was detected in any Guelph soil samples, there was no variance among replicates in the region, and Guelph orchards could not be included in ANOVAs.

There were also significant changes with soil depth in DDE (NO, $p = 0.044$; SO, $p = 0.019$) and ΣDDT (NO, $p = 0.045$; SO, $p = 0.039$) concentrations in Niagara and Simcoe orchards (Figure 2). DDE concentrations fell sharply below 20 cm depth in those soils that showed elevated surface contamination. No depth differences were statistically encountered in the abbreviated soil profiles of Okanagan orchards; however, four of the nine Okanagan soils did show declines in DDE concentrations with depth between the 0–5 cm and 5–10 cm subsamples (Figure 2). The sum of *o,p'*- and *p,p'*-isomers of DDT did not vary significantly with depth in any region.

Earthworms

The species composition and density of earthworm communities differed substantially between BC and Ontario. The night-crawler, *Lumbricus terrestris*, dominated the Ontario earthworm communities in both density and biomass, but it was not found anywhere in the Okanagan Valley (Table 2). Okanagan orchard earthworm communities were dominated by *Aporrectodea turgida* and contained at least one species, *Octolasion tyrtaeum*, not found in Ontario samples. Although the mean density of *Aporrectodea* was high in Okanagan orchards (88 worms/m²), the mean biomass (29 g/m²) was still low compared to that of the much larger *L. terrestris* in Niagara (50 g/m²) orchards. Total earthworm biomass in orchard soils followed the order Niagara (58 g/m²) > Guelph (37 g/m²) > Simcoe (25 g/m²) > Okanagan (16 g/m²). The earthworm community at the only nonorchard reference site sampled (OREF-1) was far larger in density and biomass than com-

munities sampled in any of the orchard soils and corresponded with higher organic matter content (Table 1). OREF-1 earthworm samples were predominantly *A. turgida*, and total density and biomass were 219 worms/m² and 87 g/m², respectively.

To establish whether the presence of different species could contribute to varying earthworm residue concentrations among regions, three comparisons of species differences within orchards were made. In Niagara orchards, concentrations of DDT or DDE were not different ($p > 0.05$) among samples of *Aporrectodea* sp. and *L. terrestris*. In Simcoe orchards, concentrations in *Aporrectodea* sp., *A. turgida*, *L. terrestris*, and *L. rubellus* were also not different, and, within Okanagan orchard OK-14, concentrations in *Eisenia rosea* and *Octolasion tyrtaeum* were not different. The intraspecies variances in DDT and DDT_r concentrations were just as great as those among species (Table 2), which diminished the importance of species as a variable. Earthworm age (juvenile versus adult) was also tested as a covariate with regional DDT and DDT_r concentrations and was an insignificant factor ($p > 0.05$).

When average concentrations in all earthworm samples were compared by region (*e.g.*, averaging species samples and assuming negligible variance contribution of species), earthworms collected from Niagara orchards had significantly lower DDE, DDT, and ΣDDT burdens ($p < 0.001$) than earthworms from Simcoe and Okanagan orchards (Table 2). Simcoe and Okanagan populations only differed from each other in mean DDT concentration. When one species, *L. terrestris*, was tested independently, the differences between Niagara and Simcoe populations were maintained (DDE, $p = 0.004$; DDT, $p = 0.012$; ΣDDT, $p = 0.008$). No forms of DDT could be detected in earthworms from Guelph ($n = 3$) or from the single Okanagan reference site tested (OREF-1). As there was no variance among orchards in the Guelph region (*e.g.*, no detections), it could not be included in the ANOVA comparing regions.

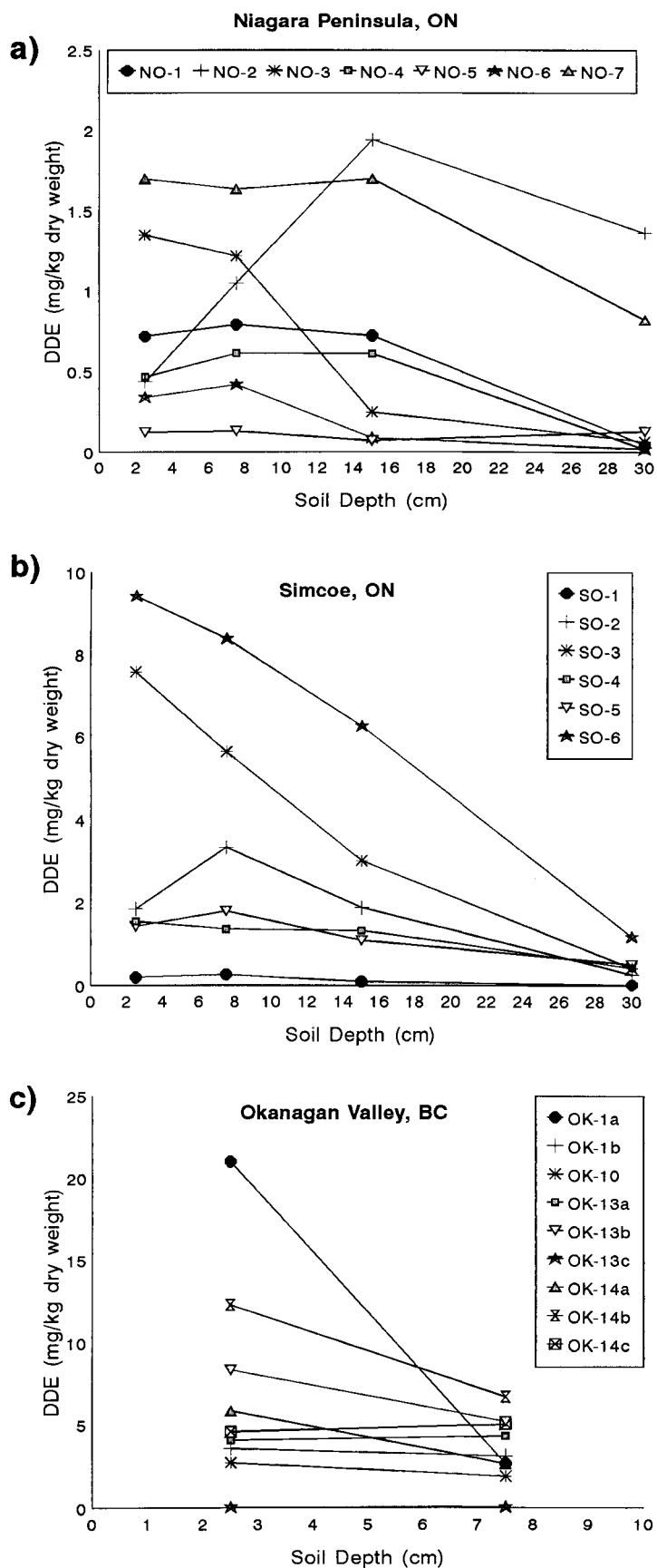


Fig. 2. Concentrations of *p,p'*- and *o,p'*-DDE in orchard soils in (a) Niagara, (b) Simcoe, and (c) Okanagan regions. Each point represents a value for a soil increment—0–5 cm, 5–10 cm, 10–20 cm, or 20–40 cm (placed midpoint within the increment on the x axis)

Table 2. A comparison of earthworm abundance and contamination (mg/kg dry weight) by species and region (all means \pm standard error)^a

Species	Region	P ^b	Density (#/m ²)	Biomass (g/m ²)	n	DDD	DDE	DDT	Σ DDT	DDE:DDT
<i>Aporrectodea</i> sp. ^c	Guelph	5/5	48 \pm 18	10 \pm 3	1	< 0.6	< 0.6	< 0.6	< 1.8	NC
	Niagara	5/6	15 \pm 4	7 \pm 2	7	0.4 \pm 0.3	3.5 \pm 0.9	1.4 \pm 0.6	4.8 \pm 1.4	2.48
	Simcoe	6/6	15 \pm 7	6 \pm 3	5	4.4 \pm 0.5	31.1 \pm 17.2	18.0 \pm 9.7	50.8 \pm 25.6	2.11
<i>Aporrectodea turgida</i>	Okanagan	2/3	39 \pm 33	8 \pm 7	1	< 0.6	0.41	< 0.6	0.41	NC
	OREF-1	1/1	131	69	1	< 0.6	< 0.6	< 0.6	< 0.12	NC
<i>Eisenia rosea</i>	Guelph	2/5	23 \pm 11	5 \pm 1	1	< 0.6	< 0.6	< 0.6	< 1.8	NC
	Okanagan	1/3	4	3	2	< 0.6	67.6 \pm 7.9	30.3 \pm 1.8	97.9 \pm 6.1	2.25
<i>Lumbricus rubellus</i>	Niagara	2/6	3 \pm 1	3 \pm 1	2	0.1	2.5 \pm 1.6	0.7 \pm 0.4	3.1 \pm 2.2	3.98
	Okanagan	2/3	15 \pm 12	6 \pm 5	—	—	—	—	—	—
	Simcoe	2/6	3 \pm 3	3 \pm 3	3	1.3 \pm 0.6	15.8 \pm 7.9	3.2 \pm 1.0	19.8 \pm 9.1	4.89
<i>Lumbricus terrestris</i>	Guelph	5/5	24 \pm 8	25 \pm 7	2	< 0.6	< 0.6	< 0.6	< 1.8	NC
	Niagara	6/6	41 \pm 12	51 \pm 12	13	0.6 \pm 0.3	2.1 \pm 0.4 A	0.7 \pm 0.2 C	2.8 \pm 0.6 E	4.94
	Simcoe	5/6	15 \pm 5	21 \pm 10	10	2.1 \pm 0.8	11.5 \pm 3.7 B	4.7 \pm 2.1 D	17.0 \pm 5.7 F	3.17
<i>Octolasion tyrtaeum</i>	Okanagan	1/3	10	8	2	1.6 \pm 1.6	61.4 \pm 53.5	17.6 \pm 17.6	80.7 \pm 72.7	2.6
Mixed species ^d	Okanagan	3/3	16 \pm 10	3 \pm 1	3	4.9 \pm 2.9	29.8 \pm 16.2	13.8 \pm 11.2	48.4 \pm 27.9	2.85
All species ^e	Guelph	5/5	81 \pm 24	37 \pm 8	3	< 0.6	< 0.6	< 0.6	< 1.8	NC
	Niagara	6/6	54 \pm 13	58 \pm 13	22	0.4 \pm 0.2	2.6 \pm 0.4 a	0.9 \pm 0.2 c	3.5 \pm 0.6 f	4.04
	Okanagan	3/3	57 \pm 25	16 \pm 7	8	2.2 \pm 1.3	43.5 \pm 14.4 b	17.2 \pm 6.1 e	62.9 \pm 20.2 g	2.56
	OREF-1	1/1	219	87	1	< 0.6	< 0.6	< 0.6	< 1.8	NC
	Simcoe	6/6	28 \pm 12	25 \pm 12	18	2.5 \pm 0.6	17.7 \pm 5.4 b	8.1 \pm 3.1 d	26.8 \pm 8.2 g	3.24

^a The single, non-orchard reference site sampled (OREF-1) is considered independently of the Okanagan orchard samples. Concentrations are the sum of *o,p'*- and *p,p'*-isomers. n = sample size (No. site + age pools) for chemistry. DDT or DDT_r concentrations in regions with the same letter (in bold typeface) are not different at $\alpha = 0.05$ (values for *L. terrestris* were considered independently and included in species averages). — = not assessed; NC = not derivable.

^b Presence of species in orchards in the region; density and biomass values are based on values from orchards in which the species was present (e.g., they do not include zero values for orchards where they were completely absent).

^c Abundance and residue data include mostly *A. turgida* and a small number of other unidentified or juvenile *A.* species.

^d Contains all individuals from species not present in sufficient numbers to enable separate chemical analyses.

^e Abundance values are totals for all species, while DDT and DDT_r concentrations are averages.

American Robins

Statistical tests of regional differences in robin egg DDT and DDT_r levels could not be completed, because eggs from Ontario were pooled by region for chemical analyses. However, the same trend seen in soils and earthworms was present (Figure 3): DDE and DDT concentrations were lowest in eggs collected near Guelph, followed by those from the Niagara fruit belt and Simcoe, and highest in eggs collected from the Okanagan Valley. The variance among orchards within the Okanagan region was high, and most of the 16 sites (n = 45 samples) were not statistically different (Table 3). Eggs from seven of nine tested orchards contained significantly more Σ DDT than eggs from reference site OREF-2 ($p < 0.05$). One egg collected from nonorchard site OREF-3 showed an elevated DDE concentration (Table 3). Soil or earthworms were not obtained from this reference area for comparison.

Absolute values for Σ DDT in robin nestlings from Ontario were much lower than those in eggs (Table 3), but an identical relative trend could still be seen among regions. DDE, DDT, and Σ DDT were significantly lower in Guelph nestlings relative to Niagara and Simcoe nestlings ($p < 0.001$).

Several other organochlorines were detected in eggs and nestlings at very low levels (see Appendix). Dieldrin and PCBs were present in most samples, but never exceeded 0.3 mg/kg wet weight. No regional trends in overall OC pesticide or PCB contamination were shown.

Relationships Among Soil, Earthworms, and Robins

The ratio of DDE to DDT increased up the food chain, with the most substantial jump in relative magnitude occurring between earthworms and robins (Tables 1, 2, 3). Average ratios for soil ranged from 1.18 to 1.41, whereas those for nestlings were two orders of magnitude higher, ranging from 40 to 95. Nestling ratios were approximately one order of magnitude greater than corresponding egg ratios. In soil and earthworms, average ratios for Okanagan samples (1.1, 2.56) were slightly but consistently lower than those for Niagara (1.21, 4.04) and Simcoe (1.36, 3.24) samples (Tables 1 and 2). The same trend was not evident in robin eggs, but the influence of pooling samples on Ontario ratios cannot be quantified and invalidates the comparison.

Linear regressions showed significant relationships between earthworm and soil DDT or DDE values in three of four regions (Figure 4). In the Niagara region, only regressions using DDT values were significant ($r^2 = 0.585$, $p = 0.045$), while only DDE values showed significant regressions in the Okanagan region ($r^2 = 0.838$, $p = 0.001$). In Simcoe orchards, associations were found using both DDE and DDT concentrations ($r^2 \geq 0.823$, $p \leq 0.013$). When data from all regions were combined, both regressions were strengthened (all $p < 0.001$). The Guelph region could not be included in these assessments, because no forms of DDT were detected in soils and earthworms from Guelph orchards. No significant relationships

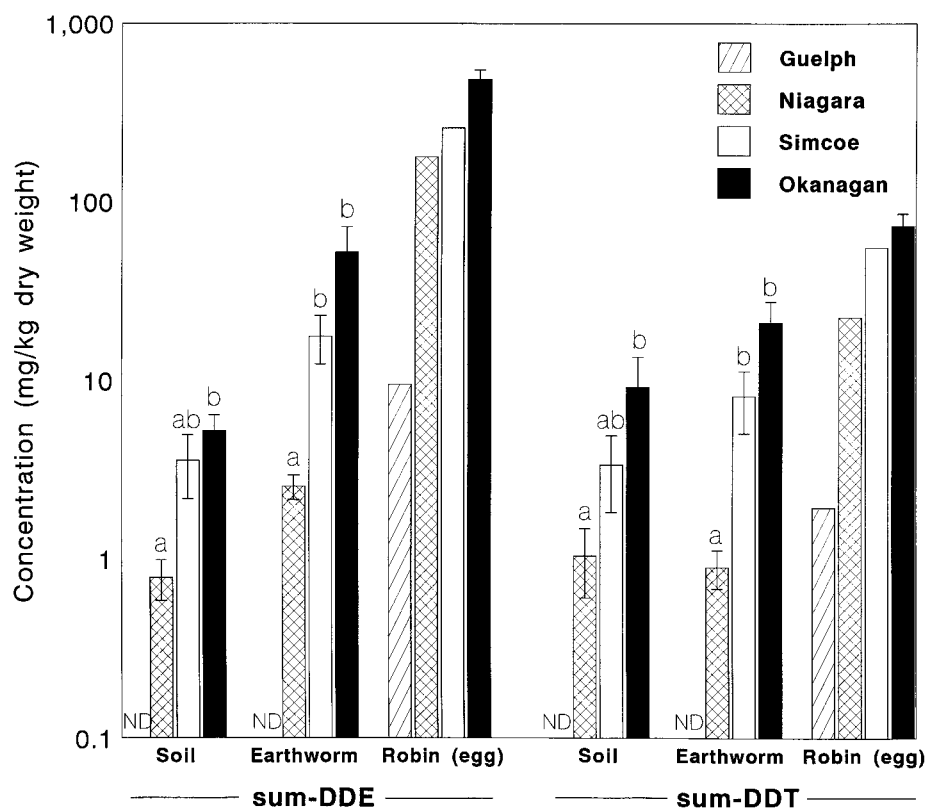


Fig. 3. Concentrations of DDE and DDT in three levels of the American robin food chain. Bars with the same letter above them are not significantly different from each other (within a substrate type, $\alpha = 0.05$). Error bars represent standard error. ND = not detected. Robin egg concentrations were converted from wet weight values for comparisons (see Table 3 for % water)

were observed between earthworm and robin egg or soil and robin egg concentrations ($p > 0.05$, $n = 6$ or 9).

Few other relationships between surface soil and earthworm characteristics were observed. Earthworm DDE values (but not DDT) increased with increasing soil percent organic matter ($p = 0.021$). Soil pH was not associated with either earthworm DDE or DDT ($p > 0.05$). The proportion of total DDT in surface soils (0–10 cm) and the abundance of earthworms showed few relationships in Niagara and Simcoe orchards. One regression suggested that the proportion of DDT in surface soils (versus the full 40-cm soil profile) increased as total density of earthworms increased ($p = 0.021$, $n = 12$) when data from both regions were combined. Regressions of earthworm biomass and surface soil contamination were not significant, and considering the percent organic matter or the absolute amount of DDT or DDE in soil as a second determinant had no effect on the results.

When soil and tissue burdens were evaluated consistently using dry weight values, proportionate increases from soil to earthworm, then from earthworm to robin were found across all regions (Figure 3). Soil to earthworm bioaccumulation factors (BAF_{s-e}) for Σ DDT ranged from 0.9 to 7.5, and those for DDE were always higher than those for DDT (Table 4). This supports the results of the regressions (Fig. 4), which found steeper slopes for DDE relationships than for DDT relationships. In 57% of Niagara orchards, BAF_{s-e} for either DDE or DDT were < 1 , implying that the process of bioaccumulation was not occurring on site. A Kruskal-Wallis test showed no differences among regions in BAF_{s-e} . On average, BAF_{s-e} were greatest in the Okanagan orchards, but substantial variability in values existed among orchards within a region.

Earthworm to robin bioaccumulation factors (BAF_{e-r}) were 6 to 145 for eggs and 0.04 to 73 for nestlings (Table 5). The worm–egg BAF_{e-r} were very high in Niagara orchards, but that should be viewed within the perspective of all-around low DDT values in this region. Also, the absolute values for DDT remained low across sample substrates (Figure 3), in sharp contrast to the increases in DDE concentrations. Once again, substantial interorchard variability existed within a region. Niagara and Simcoe worm-to-nestling BAF_{e-r} s were not different in a Kruskal-Wallis test.

Discussion

Contamination of Orchard Soils

Overall, DDE and DDT were detected in 100% of soil samples from Okanagan, Niagara, and Simcoe orchards, and in 0% of soil samples from Guelph orchards and OREF-1. The presence of DDT in only those soils where it was previously applied strongly suggests that historic inputs predominate and that atmospheric deposition of DDT and DDT_r does not contribute significantly to current soil levels. Also, continuing illegal use of DDT in orchards seems unlikely, given the absence of detectable levels in post-DDT orchards, and the observation by Harris and Sans (1971) that DDT use in Ontario orchards was already decreasing significantly without regulation by 1965, as several species of maggots and cutworms developed resistance.

DDT concentrations of < 0.004 to 28 mg/kg dry weight and DDE concentrations of 0.011 to 7 mg/kg have been recorded in

Table 3. DDT and DDT_r concentrations (means ± standard error, mg/kg wet weight) in American robin eggs collected from orchard and nonorchard sites in the Okanagan Valley, and in eggs and nestlings collected from Guelph, Niagara, and Simcoe orchards^a

Location	n ^b	%H ₂ O	%Lipid	<i>p,p'</i> -DDD	<i>p,p'</i> -DDE	<i>p,p'</i> -DDT	DDE:DDT
OREF-2	4	83.2 ± 0.2	5.4 ± 0.5	0.04 ± 0.002	4.98 ± 2.34 B	0.36 ± 0.06 A	13.6
OREF-3	1	81.4	5.5	0.14	21.2	0.53	39.9
OREF-av.	5	82.8 ± 0.4	5.4 ± 0.4	0.06 ± 0.02	8.22 ± 3.72	0.40 ± 0.06	18.9
OK-2	1	80.5	8.1	1.62	95.3	14.6	6.55
OK-3	1	84.2	5.6	1.25	82.1	13.4	6.13
OK-4	1	89.2	6.8	0.25	17.4	3.4	5.12
OK-5	1	84.8	4.5	0.21	103	6.88	15
OK-6	2	82.5 ± 1.4	5.9 ± 1.0	0.05 ± 0.03	4.96 ± 0.19 AB	0.70 ± 0.07 AB	7.09
OK-7	1	80.5	8.6	0.67	99.5	7.47	13.3
OK-8	2	83.8 ± 0.6	5.6 ± 0.4	4.88 ± 4.58	164 ± 138 C	30.6 ± 26.7 AB	5.92
OK-9	4	83.8 ± 0.5	5.5 ± 0.3	1.26 ± 1.16	73.6 ± 30.8 AC	8.23 ± 6.85 AB	32.9
OK-10	8	79.4 ± 2.0	6.0 ± 0.3	1.35 ± 0.36	106 ± 6.55 C	17.8 ± 1.13 B	6.22
OK-11	3	82.5 ± 0.5	5.1 ± 0.3	0.33 ± 0.15	93.7 ± 19.3 C	4.63 ± 2.05 AB	30.3
OK-12	2	82.4 ± 1.5	5.6 ± 0.2	1.89 ± 0.75	232 ± 61.0 C	39.3 ± 21.5 B	7.22
OK-13	5	83.4 ± 1.1	6.6 ± 0.4	1.10 ± 0.75	69.4 ± 20.1 AC	12.1 ± 6.88 AB	33.5
OK-14	5	83.0 ± 0.2	5.8 ± 0.3	0.6 ± 0.23	51.7 ± 19.6 AC	13.3 ± 5.35 B	16.6
OK-15	3	83.6 ± 0.6	5.8 ± 0.9	0.1 ± 0.02	29.0 ± 4.54 ABC	1.58 ± 0.25 AB	20.4
OK-av.	39	82.5 ± 0.5	5.9 ± 0.2	1.11 ± 0.28	85.1 ± 10.8	13.0 ± 2.3	17.2
GO-egg	1	82.1	5.7	0.01	1.7	0.34	4.95
NO-egg	1	82.7	5.2	0.16	30.7	3.89	7.9
SO-egg	1	82.7	5.2	1.01	44.61	9.58	4.66
GO-nestling	6	75.6 ± 0.5	3.7 ± 0.5	0.005 ± 0.003	0.14 ± 0.07 a	0.001 ± 0.001 a	65.4
NO-nestling	5	76.2 ± 0.3	2.9 ± 0.5	0.29 ± 0.07	9.92 ± 2.15 b	0.17 ± 0.08 b	95.4
SO-nestling	3	76.8 ± 0.3	3.2 ± 0.5	1.47 ± 0.77	19.7 ± 9.16 b	0.66 ± 0.32 b	40.3

^a Egg or nestling concentrations with the same letter (in bold typeface) are not significantly different from each other ($\alpha = 0.05$).

^b Analytical sample size; eggs from the Okanagan and nestlings from Guelph, Niagara, and Simcoe were analyzed individually, while eggs from the latter three regions were analyzed as pools, each containing five eggs.

the top 20 cm of soil in vegetable and cereal croplands where DDT has not been applied for approximately 20 years (Szeto and Price 1991; Martijn *et al.* 1993). Soil samples from the organic surface layer in a Maine forest, collected 9 and 30 years after a single DDT application contained up to 1.9 mg/kg dry weight Σ DDT (Dimond *et al.* 1970; Dimond and Owen 1996). One recent soil sample collected from the “plough layer” (assumed to be ~ 20 cm) of an apple orchard in Ontario showed 7.37 mg/kg dry weight DDE and 62.9 mg/kg DDT (Webber and Wang 1995). DDT and DDT_r concentrations in the latter orchard were higher than average concentrations in Ontario orchards in our study. In all other unmanipulated studies (*e.g.*, Martijn and associates conducted tests in experimental plots), concentrations were lower than those recorded in our study. When compared to earlier orchard studies, Σ DDT concentrations in soils from Ontario and BC fell below the range of concentrations (21–86 mg/kg dry weight) documented in surface soils (top 15 cm) of North American orchards in the late 1960s (Harris and Sans 1971; Kiigemagi and Terriere 1972), but above 1969–71 soil concentrations in British orchards (0.7–5.3 mg/kg dry weight) where DDT application rates were much lower (Bailey *et al.* 1974; Stringer *et al.* 1974).

Orchards in general may be expected to retain more DDT in soil than other agricultural or silvicultural lands, partly because lack of tillage or other routine soil disturbance reduces losses from volatilization and erosion (Bailey *et al.* 1974). Early comparisons of agricultural soils also suggest that North American orchards received more DDT than tobacco, field, or veg-

etable crops (Ginsburg and Reed 1954; Harris and Sans 1971); that would further increase the relative degradation time in orchards, as concentrated DDT deposits break down more slowly (Edwards 1966; Beyer and Gish 1980). Orchards at northern latitudes might be expected to retain more DDT in soil than orchards in warmer, southern climates, because low temperature is a key delay factor in environmental degradation of DDT (Edwards 1966). Dimond and Owen (1996) suggested that the northern climate in Maine extended the half-life of DDT in forest soils to 20–30 years, from the months to a few years described in studies from tropical or sub-tropical climates. A half-life of 3.2 years for DDT in soil was suggested for pasture (Beyer and Gish 1980), but the research in forests and our data from orchards indicate that it is extended in other habitats. According to some estimates, the DDE:DDT ratio in soil should exceed 20:1 once DDT use has been stopped for 15–20 years (Elliott *et al.* 1994). However, ratios in soils of Niagara, Simcoe, and Okanagan orchards 20 years after DDT use were just above one. Our results agree with Dimond and Owen's, and we would further suggest that northern temperate DDT sinks, such as those found here in orchards, may pose more of a risk to migratory wildlife than ongoing environmental inputs in developing countries.

Stringer *et al.* (1974) found that little *p,p'*-DDT penetrated below 40 cm depth in an untilled orchard soil, and levels fell below detection limits by 50 cm depth. This suggests that our samples were a fair representation of the amount of DDT present in the soils. However, concentrations of DDE and DDT were still detectable in 100% and 70%, respectively, of the

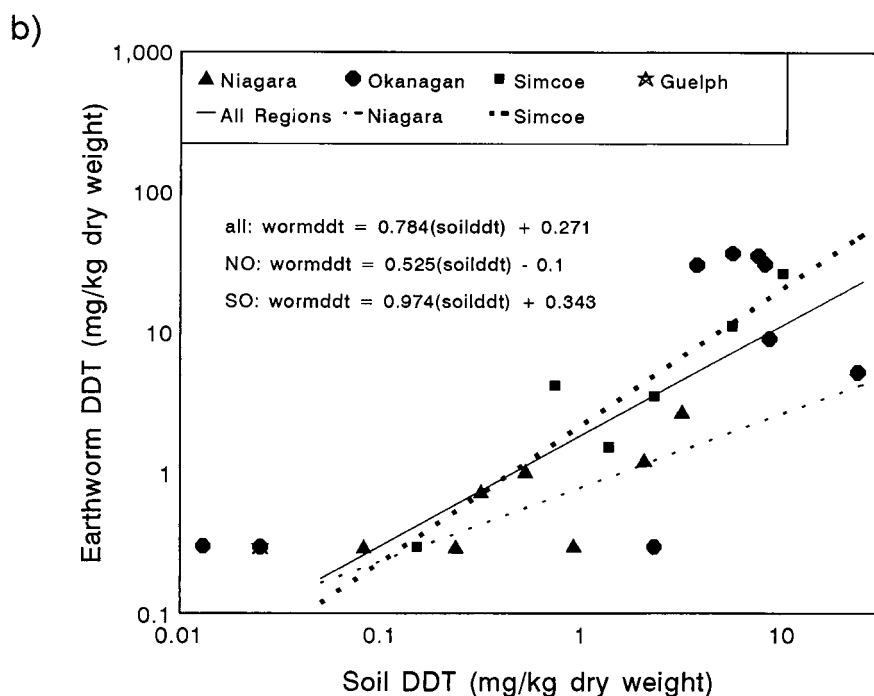
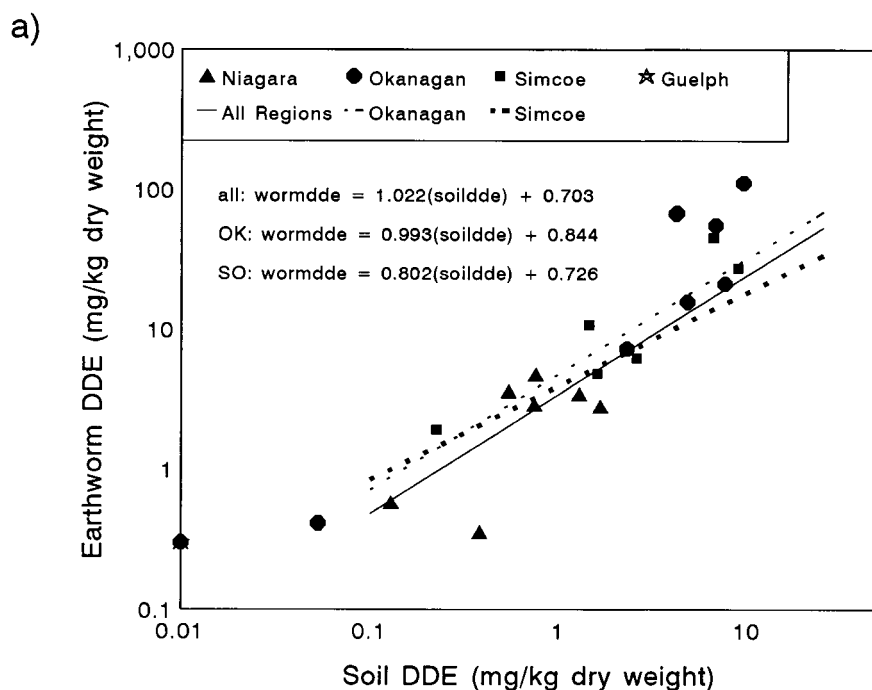


Fig. 4. Regressions of earthworm DDE (a) and DDT (b) on soil equivalents. Lines were created using y intercept and slope estimates from a linear regression. All lines represent significant logarithmic relationships; nondetections were included in each graph, but not in the regressions. Equations shown describe logarithmic relationships

20–40-cm soil increments in Ontario. Also, there was often less than previously recorded 80+% DDT and 60+% DDE sequestered in the top 10 cm of soil (Terriere *et al.* 1966; Stringer *et al.* 1974; Cooke and Stringer 1982). The proportion of Σ DDT in the surface soil ranged from 16 to 83% in Niagara and Simcoe orchards, suggesting more downward movement of compounds than was observed in early studies. This may be

related to either periodic tillage of well-established orchards when old trees were replaced with new, or transport of compounds by micro- and macroinvertebrates to depth. The proportion of Σ DDT in the surface soil was not statistically related to earthworm density or biomass, but more extensive sampling of invertebrate communities would be necessary to dismiss their influence on the soil profile of DDT.

Table 4. Bioaccumulation factors from soils to earthworms in orchard food chains. DDE and DDT represent sums of *o,p'*- and *p,p'*-isomers; Σ DDT represents the sum of all DDD, DDE, and DDT^a

Orchard	n	DDE	DDT	Σ DDT
NO-1	1	6.2	1.98	4.66
NO-2	1	3.89	0.34	1.7
NO-3	1	2.65	0.86	1.44
NO-4	1	6.57	2.36	5
NO-5	1	4.46	NC	3.43
NO-6	1	0.93	NC	0.9
NO-7	1	1.68	0.61	1.07
Niagara	7	3.77 ± 0.82	1.23 ± 0.40	2.60 ± 0.66
OK-1	1	2.77	0.22	1.14
OK-10	1	3.15	NC	1.56
OK-13	3	10.62 ± 2.68	5.62 ± 0.92	7.54 ± 1.88
OK-14	3	10.29 ± 3.73	4.32 ± 2.05	7.37 ± 3.01
Okanagan	8	8.58 ± 1.94	4.07 ± 1.25	5.93 ± 1.53
SO-1	1	8.54	NC	5.11
SO-2	1	2.4	1.13	1.92
SO-3	1	6.83	2.01	4.66
SO-4	1	7.41	5.69	6.94
SO-5	1	2.99	1.54	2.06
SO-6	1	3.07	2.65	2.96
Simcoe	6	5.21 ± 1.10	2.61 ± 0.81	3.94 ± 0.81

^a Values in bold typeface are regional means (\pm standard error); NC = not computed (one substrate did not show detectable levels of DDT).

The significant regional differences in soil concentrations are probably related to slight differences in use combined with regionally diverse climatic conditions. In Okanagan apple orchards, the BC Ministry of Agriculture and Food (1969) recommended that 3.4–6.8 kg active ingredient/ha be applied two to four times per year, which implies that 6.8–27 kg DDT/ha/year were sprayed on orchards from 1946 to 1970. The Ontario Department of Agriculture (1968) recommended that 3.4 kg active ingredient/ha be applied two to three times per year, which implies that 6.8–10 kg DDT/ha/year were sprayed on Niagara and Simcoe orchards over roughly the same time period. Growers in both provinces clearly had some flexibility when determining spray concentrations and frequencies, but Okanagan growers could potentially have applied almost three times as much DDT to trees in some years as their Ontario peers.

In addition, lower soil DDE:DDT ratios in Okanagan orchards compared to Niagara and Simcoe orchards suggest that regional differences might be partly explained by varying soil degradation rates. High organic matter content is one important delay factor for DDT degradation in soils (Edwards 1966; Szeto and Price 1991), and it was slightly higher in Okanagan orchards compared to Niagara and Simcoe orchards, possibly due to winter soil moisture limitations on organic breakdown. Although Okanagan orchards are heavily irrigated in the summer to compensate for a normally arid environment, winter soil moisture levels can become relatively low. The precipitation normals (1941–1990) for winter months (Dec to Mar) in Penticton, BC (in the Okanagan Valley), range from 20.4 to 32.1 mm, and corresponding values for Simcoe, Ontario, range from

58.3 to 92.2 mm (Environment Canada 1998). Relatively low winter levels of moisture in Okanagan soils could also limit microbial degradation of DDT.

Contamination of Earthworms

Overall, DDE was detected in 100% of earthworm samples from Okanagan, Niagara, and Simcoe orchards, while DDT was detected in > 70% of Niagara and Okanagan earthworm samples and in > 80% of Simcoe earthworm samples. No DDT or DDT_r was detected in earthworms from Guelph orchards or from OREF-1. The lack of differences in contamination among earthworms of various ages or species supports laboratory findings of Davis (1971) and Edwards and Jeffs (1974). Field studies in orchard and forest habitats also found no differences in DDT concentrations among earthworm species, but studies in pasture habitats did find interspecific variation (Thompson 1973). Thompson (1973) suggested that retention of DDT at the soil surface in orchards and forests allowed species with deep burrowing habits, like *L. terrestris*, to have equivalent access to pesticide as the smaller species that burrow horizontally in the top few cm of soil, whereas incorporation of DDT into the surface soils by cultivation in pastures and croplands increased the relative exposure of the horizontal-burrowing species to pesticide. Our study implies that equitable species exposure in orchards is maintained even many years after DDT applications have stopped.

During the period of DDT use, surveys of soil fauna in a New York apple orchard found that invertebrates were five or six times more abundant in unsprayed habitat compared to the orchard, and that earthworms forced to live in orchard soil had high mortality and weight loss (Johnson *et al.* 1976). Bailey *et al.* (1974) suggested that mortality of soil fauna at the high application rates of DDT in North American orchards actually protected avian species from the level of secondary poisoning observed in British orchards around the same time. Because past surveys of our orchards were never conducted, we cannot speculate on possible earthworm community changes since DDT applications ceased. However, the abundance of *L. terrestris* in Niagara orchards was similar to that for the species in neighboring forest soils (Tomlin *et al.* 1992). Also, the density and biomass of earthworms at our orchard sites was generally higher than the density and biomass of earthworms in pasture plots 52 weeks after a soil treatment of 5.6 kg/ha DDT (Thompson and Sans 1974). After 52 weeks, earthworm abundance was 38.7 worms/m² and 33.4 g/m², which exceeds mean total biomass values for Okanagan and mean total density and biomass values for Simcoe, but falls below all other regional averages. It is interesting that the only community values lower than those in experimentally treated plots were from the more contaminated regions. Thompson (1970) recorded an initial drop in earthworm abundance of only 33–36% in DDT-treated plots, which he considered negligible. It is difficult to compare these findings given the differences in application history and the lack of measured soil values in the earlier studies; however, it seems unlikely that earthworm abundance is still being affected by DDT, as soil values are just slightly higher than those recorded in Britain during the DDT era, when earthworm mortality was not observed (Davis 1968; Bailey *et al.* 1974).

Table 5. Bioaccumulation factors from earthworms to robins in orchard food chains. DDE and DDT represent *p,p'*-isomers in most cases (earthworm data were the sum of *o,p'*- and *p,p'*-isomers); Σ DDT represents the sum of all DDD, DDE, and DDT^a

Orchard	n	Earthworm–Robin Egg			Earthworm–Robin Nestling		
		DDE	DDT	Σ DDT	DDE	DDT	Σ DDT
NO-4	1	—	—	—	16.78	0.6	14.29
NO-5	1	—	—	—	73.27	NC	61.34
NO-6	1	—	—	—	68.64	NC	46.14
Niagara^b	1, 3	60.54	37.61	57.44	52.90 ± 18.11	0.60	40.59 ± 13.86
OK-10	2	87.87 ± 14.27	145.1 ± 98.21	85.04 ± 0.98	—	—	—
OK-13	2	22.89 ± 13.26	13.26 ± 12.03	19.57 ± 13.33	—	—	—
OK-14	2	13.78 ± 10.50	21.80 ± 21.44	14.60 ± 12.12	—	—	—
Okanagan	6	41.52 ± 15.82	60.05 ± 37.54	39.74 ± 15.09	—	—	—
SO-1	1	—	—	—	53.28	NC	61.14
SO-2	1	—	—	—	5.66	0.71	4.72
SO-5	1	—	—	—	1.89	0.04	1.14
Simcoe^b	1, 3	15.10	6.42	11.94	20.28 ± 16.54	0.37 ± 0.33	22.33 ± 19.43

^a Regional averages are in bold typeface; — = not assessed; NC = not computed (one trophic level did not show detectable levels of DDT).

^b Bioaccumulation factors for eggs calculated with an egg concentration derived from a pooled sample.

Few comparisons with DDT concentrations in earthworms from other areas can be made, because most investigators report fresh weight values, whereas worms in our study were freeze-dried before analysis. In a study conducted before DDT use was terminated, earthworms from apple orchards in Maryland contained 6.28 mg/kg (dry weight) DDT, 2.66 mg/kg DDE, and 3.57 mg/kg TDE, or 12.3 mg/kg Σ DDT (Gish 1970). Another American survey in the DDT era found 141 mg/kg dry weight Σ DDT in *L. terrestris* from sprayed forests (Hunt 1965). Twelve years after applications of DDT in a New York apple orchard, earthworms contained 106 mg/kg (dry weight) DDT, 17.6 mg/kg DDD, and 24 mg/kg DDE, or 147.6 mg/kg Σ DDT (Kuhr *et al.* 1974). These New York worms were more contaminated than worms from Maryland collected during the DDT era, which may be a reflection of inter- and intraorchard variability in contamination, changes in analytical techniques, or may also partly reflect the lag-time in maximum uptake of DDT by earthworms from contaminated soils. Beyer and Krynsky (1989) found that DDE in earthworms from experimental hay-field plots increased for 3 years after a single application of 9 kg/ha DDT, before declining exponentially. In the same plots, earthworms contained 7 mg/kg (dry weight) DDE after 11 years. Earthworms in our study orchards contained more DDT and DDT_r than those in the hay-field plots and had levels of DDE and DDT comparable to worms from the Maryland orchard. The Simcoe and Okanagan earthworms, with regional averages of 27 and 63 mg/kg Σ DDT, were less contaminated than earthworms from New York orchards in the 1970s, chiefly because they contained far less *p,p'*-DDT. The DDE:DDT ratio for earthworms in Kuhr's study was 0.23 (Kuhr *et al.* 1974), whereas we reported ratios of 2.56 and 3.24 for Okanagan and Simcoe earthworms, respectively. This suggests that DDT degradation has progressed further in our study orchards, which is not surprising considering they were sampled 22 years after the New York orchards.

The magnification of regional differences we observed from soils to earthworms may have simply been related to bioaccumulation kinetics; however, varying temperature regimes in BC and Ontario could have also influenced the absolute amount of DDT that earthworms took up annually. The number of

degree days when the temperature moves below 0°C in a year in Penticton are 244, compared with 590 for Simcoe (Environment Canada 1998), suggesting that earthworms in the Okanagan may have a shortened winter senescence period. Soil pH was not related to earthworm DDT concentrations, indicating that there was no pH-dependent differences in bioavailability of DDT to earthworms in the different regions. Organic matter, another determinant of bioavailability, was positively related to earthworm DDT concentrations, which is the opposite trend to what would be expected if organic material was influencing the binding of DDT to soil particles (Edwards 1966; Davis 1971). Hence, variable uptake of DDT by earthworms was more likely related to differences in earthworm activity, rather than differences in properties of soil.

Contamination of Robin Eggs and Chicks

DDT and DDE were detected in 100% of robin samples from Niagara, Simcoe, and Okanagan orchards. In Guelph orchards, although concentrations were low, 100% of eggs and nestlings contained DDE, while 100% of eggs and only 17% of nestlings contained DDT. The regional gradient in DDT and DDT_r concentrations, following the order Okanagan > Simcoe > Niagara > Guelph, was maintained from soil samples up through to robin eggs and nestlings, and it reflected the regional discrepancy in robin egg values detected in earlier studies. The residue data presented here suggests that the previously identified differences between Okanagan and Ontario robins was mostly a magnification of soil and possibly earthworm differences in contamination.

Absolute values for *p,p'*-DDE and -DDT in robin eggs were within the range or exceeded values measured in earlier collections from the same regions. In the Okanagan, Elliott *et al.* (1994) reported DDE concentrations in robin eggs in the range of 68–103 mg/kg and DDT in the range of 11–26 mg/kg wet weight. Corresponding values reported here were in the range of 5–302 mg/kg and 0.1–61 mg/kg, respectively; larger ranges likely reflect the expansion of sampling effort. Concentrations were higher in the one pooled robin egg sample from the

Niagara region (DDE 31 mg/kg, DDT 4 mg/kg wet weight) than in two earlier Niagara samples (DDE 17 mg/kg, DDT 1 mg/kg; Hebert *et al.* 1994; Σ DDT 1.37 to 3.29 mg/kg; Frank *et al.* 1975). With one exception, nonorchard samples remained relatively uncontaminated. The one contaminated egg from OREF-3 cannot be readily explained. Three possible scenarios are that the adult female was foraging away from the immediate nest vicinity, that an unknown soil sink of DDT existed in that nonorchard area, or that the adult acquired the DDT during migration or local wintering in orchards of the Okanagan Valley.

In further comparisons, DDT contamination of robins in Okanagan and Simcoe regions generally exceeded published levels in avian eggs. During the DDT era, eggs of song thrush (*Turdus philomelos*) and blackbird (*Turdus merula*) collected in an apple orchard (coincident with several dead, poisoned adults) contained 89.2 and 77.2 mg/kg (wet weight) Σ DDT, respectively (Bailey *et al.* 1974). Robin nestlings collected in an apple orchard contained 4.7 mg/kg Σ DDT (Johnson *et al.* 1976). In a sprayed forest in Maine, robin eggs contained 4.44 ± 0.37 mg/kg Σ DDT (Knupp *et al.* 1976). In a study of persistence of DDT in Washington orchards, Blus *et al.* (1987) found that robin eggs contained more DDE (11.1 mg/kg wet weight) than eggs of seven other bird species. Although DDT levels were also relatively high in robins (1.6 mg/kg), concentrations in eggs of California quail (*Callipepla californica*, 1.8 mg/kg), wood duck (*Aix sponsa*, 2.2 mg/kg), and mallard (*Anas platyrhynchos*, 2.7 mg/kg) exceeded robin values. Concentrations of DDE in eggs of great-tailed grackle (*Quiscalus mexicanus*) from Texas ranged up to 15 mg/kg, while those in eggs of black-necked stilt (*Himantopus mexicanus*), American avocet (*Recurvirostra americana*), northern harrier (*Circus cyaneus*), American bittern (*Botaurus lentiginosus*), kildeer (*Charadrius vociferus*), cinnamon teal (*Anas cyanoptera*), and mallard from California ranged up to 9.6 mg/kg (Clark *et al.* 1995). Mean concentrations of DDE in eggs of red-necked grebe (*Podiceps grisegena*), western grebe (*Aechmophorus occidentalis*), and black-crowned night heron (*Nycticorax nycticorax*) from various locations in Canada were 4.0, 1.7, and 3.2 mg/kg wet weight, respectively (Baril *et al.* 1990). With Σ DDT concentrations of 99 ± 13 mg/kg in Okanagan eggs, 55.2 mg/kg in Simcoe eggs, and 34.8 mg/kg in Niagara eggs, robin contamination in our study orchards was far greater than that documented in any recent avian studies and was comparable to values for eggs of the closely related blackbird measured during years of DDT applications in Britain.

Local Food Chain Transfer of DDT and Potential Hazards to Robins

One objective of this study was to establish whether local orchard soils could be a major source of DDT for American robins in BC and Ontario; the weight of evidence suggests that they are. The transfer of DDT from soil to earthworms was implied by strong positive regressions. Also, bioaccumulation factors indicated that accumulation in worms was occurring in almost all Simcoe and Okanagan orchards and in roughly half of Niagara orchards. In the remaining Niagara orchards, DDT concentrations in both substrates were uniformly low, and

calculation of analytically dependent BAFs was likely inaccurate.

Bioaccumulation factors have been calculated for some experiments in the past, although not always in a consistent manner. For instance, Romijn *et al.* (1994) suggest a "bioconcentration factor" for DDT from soil to earthworms of 3.29 based on available literature, but they use wet weight values for worms and dry weight values for soil. In an early orchard study, dry weight concentrations measured in soil and earthworms suggest that the following bioaccumulation factors applied: 10.6 for DDT, 7.4 for DDE, and 9.3 for Σ DDT (Gish 1970). Beyer and Gish (1980) suggest an average "storage ratio" of 5 for Σ DDT and 16 to 6 for DDE, depending on the time following treatment. The latter set of values more closely resemble those reported in our study, probably because they were derived from an environment where DDT had not been applied for 11 years. The variability in estimated bioaccumulation factors is consistent with suggestions that there is a two compartment mode of uptake of DDT from soils (Rudd *et al.* 1981), and that the relationship between soil and earthworm concentrations is dynamic, dependent on soil properties (Romijn *et al.* 1994) and the DDT aging process (Beyer and Gish 1980).

Earthworm–robin regressions were not significant, lending uncertainty to the link between robin contamination and orchard soils. The poor match between earthworm and robin tissue contamination may have been an artifact of low sample size. Alternatively, it might have indicated that robins fed over an expansive area, including nonorchard habitat (thus diluting orchard DDT acquisitions) or that a large portion of their DDT was acquired on migration routes. Knupp *et al.* (1976) found that robins contaminated at wintering grounds were able to lose 87% of their DDT burden by the end of breeding, but only if they nested in an uncontaminated forest. In our study, DDT concentrations were relatively low in robin eggs and nestlings from reference Guelph orchards, suggesting that the DDT they might have acquired on wintering grounds was either negligible or mostly not retained. The retention of winter-acquired burdens of DDT by Okanagan robin populations is less certain, as it is unlikely that Ontario and Okanagan breeding birds spend their winters in the same area. Records show that substantial numbers of robins (*e.g.*, 500–1,000 birds) winter in the Okanagan Valley (Campbell *et al.* 1997), usually seen in orchards and vineyards (Cannings *et al.* 1987), but the summer locations of these birds are unknown. Given the size of winter flocks versus the breeding population (~2,000–3,000 birds), it is probable that at least some are resident. Robins may winter as far south as Mexico, Guatemala, and Bermuda, but limited banding surveys indicate that BC birds only move to Washington, Oregon, and California (Campbell *et al.* 1997). The most recent records of DDT in robins from the western United States (DeWeese *et al.* 1986; Blus *et al.* 1987) suggest that acquisitions there would be negligible compared to the tissue concentrations observed in our study.

There is substantial evidence that DDT accumulated from contaminated earthworms killed large numbers of robins and other thrushes in the 1950s to 1970s (Barker 1958; Wallace 1962; Wurster *et al.* 1965; Bailey *et al.* 1974; Beaver 1980). Lethal brain residues in several species of bird were measured at 300–400 mg/kg (Stickel *et al.* 1984). Blackbirds and song thrushes found dead in a British apple orchard contained 81–

128 mg/kg DDE in breast muscle, and the authors suggested that, based on the residues detected in other live birds, most thrushes in the orchard were carrying near lethal amounts of DDT (Bailey *et al.* 1974). The residues in eggs of blackbirds and thrushes collected from the same orchard were intermediate between concentrations detected in eggs of robins from Okanagan and Simcoe orchards in this study. Beyer and Gish (1980) suggested that a concentration in earthworms of 32 mg/kg Σ DDT could be a hazard to reproduction in some bird species. The average concentration in earthworms from the Okanagan and the concentration in some earthworms from Simcoe exceeded that threshold value. Nonetheless, there was no evidence that reproduction in robins was affected by high levels of DDT in the food chain in Okanagan and Simcoe orchards (unpublished data). This may indicate that aged DDT and DDE are not as acutely toxic as freshly sprayed compound. A disappearance of acute toxicity with DDT aging in soils has been described for invertebrates (Robertson and Alexander 1998). It may be difficult to distinguish contaminant effects on reproduction in this species, because success rates are often low, around 50% (Campbell *et al.* 1997), largely as a result of heavy losses from predation. Manipulated studies are underway to further quantify the risk to local birds posed by contaminated orchard habitats. Twelve-day-old robin chicks from nests in Okanagan orchards and a reference site are being raised in captivity, then bred to investigate the effect of *in ovo* exposure to DDE on later reproductive success.

Implications for Wildlife Using Northern Latitude Orchard Habitat

Old orchard habitat in northern locations in North America are probably some of the most contaminated environments with

respect to DDT. Extremely high past application rates, seasonally freezing temperatures, and infrequent cultivation all prolong the degradation of DDT in such soils. Recently published follow-up studies of DDT applied to pasturelands or forests 20 or more years ago in North America did not generally predict the high environmental levels we observed. Thus, wildlife using northern orchard habitats may be more at risk of showing associated reproductive effects than wildlife in southern climes, where DDT is still being applied. In tropical environments, DDT does not persist in terrestrial sinks to the same degree, because of rapid volatilization and related avenues of breakdown. The possibility that aged DDT in soils and prey does not produce the same severe effects in predators must be investigated in light of the findings presented here and additional observations of few or no effects on reproductive success of local avian populations. Further field studies in similar northern habitats are also warranted, particularly because the contaminant distribution in soils within and among orchards was quite patchy.

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Appendix. Presence of other organochlorine compounds in robin's eggs and nestlings, collected 1993–1995. For eggs from the Okanagan and nestlings from Ontario, values represent means \pm standard error (μ g/kg wet weight). % = % of Okanagan egg samples with detectable levels. 1,2,3,4-tetrachlorobenzene, *p*-mirex, octachlorostyrene, and *trans*-chlordane were not detected in any samples

	Guelph		Niagara		Simcoe		Okanagan	
	Eggs	Nestlings	Eggs	Nestlings	Eggs	Nestlings	%	Eggs
n	1 ^a	6	1 ^a	5	1 ^a	3	—	45
<i>cis</i> -Chlordane	0.8	< 0.05	2.8	6.8	< 0.3	< 0.3	2	7.7
Pentachlorobenzene	< 0.3	14	< 0.3	< 0.3	< 0.3	< 0.3	—	< 0.1
1,2,4,5-Tetrachlorobenzene	< 0.8	14	< 0.8	< 0.8	< 0.8	< 0.8	—	< 0.1
Hexachlorobenzene	< 0.2	< 0.2	5.4	2.7	< 0.2	< 0.2	20	1.1 \pm 0.4
Dieldrin	47	< 0.05	55	< 0.2	160	< 0.2	93	70 \pm 12
Heptachlor epoxide	3.6	< 0.05	6.5	< 0.1	11	< 0.1	71	5.3 \pm 1.5
α -Hexachlorocyclohexane	4.5	< 0.1	< 0.5	< 0.5	< 0.5	< 0.5	16	0.9
β -Hexachlorocyclohexane	< 0.1	< 0.1	< 0.8	< 0.8	< 0.8	< 0.8	18	3.7 \pm 1.9
γ -Hexachlorocyclohexane	0.6	< 0.05	< 0.4	< 0.4	5.6	< 0.4	—	< 0.1
Mirex	9.7	5.2 \pm 1.6	8.4	3.7	6.1	< 0.2	4	1.3
<i>cis</i> -Nonachlor	2.3	< 0.05	8.0	14 \pm 4.1	3.5	< 0.2	47	17 \pm 3.6
<i>trans</i> -Nonachlor	14	3.0 \pm 0.1	65	158 \pm 85	10.4	3.1	76	21 \pm 12
Oxychlordane	8.9	4.6 \pm 1.0	22	67 \pm 39	9.1	8.9 \pm 1.8	87	14 \pm 7.4
Tris(4-chlorophenyl)-methanol	0.5	< 0.1	18	< 0.4	24	< 0.4	82	76 \pm 11
Sum PCBs ^b	31	6.3 \pm 2.8	188	53 \pm 12	227	77 \pm 29	84	159 \pm 40

^a Value is from one pooled sample of five eggs.

^b Sum of 28 congeners (#42, 60, 70, 74, 99, 101, 105, 110, 118, 129, 138, 146, 149, 151, 153, 158, 170, 171, 172, 180, 182, 183, 185, 194, 195, 201, 203, 206); congeners assayed but not detected were #28, 31, 44, 49, 52, 64, 66, 87, 97, 128, 137, 141, 174, 200.

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