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Trophic Transfer Efficiency of DDT to Lake Trout (*Salvelinus namaycush*) from Their Prey

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Buildup of dichlorodiphenyltrichloromethane (DDT) concentrations in fish-eating birds has been shown to cause shell thinning in the eggs of these birds, and consequently has led to reproductive failure in these birds (Temple and Weins 1989; Weseloh et al. 1995). DDE, a metabolite of DDT, has been specifically linked to eggshell thinning (Wiemeyer et al. 1972). The ban on DDT use in the 1960s caused a reduction in DDT concentrations in the environment (Hesselberg et al. 1990; Weseloh et al. 1995; DeVault et al. 1996), and the subsequent recovery of certain populations of fish-eating birds was partially attributable to the ban on use of DDT (Temple and Weins 1989; Weseloh et al. 1995).

Risk assessment models have been developed to predict risk to fish-eating birds under various scenarios of environmental contamination (Fordham and Reagan 1991). To exercise such models, an estimate of the trophic transfer efficiency of DDT from small fish to piscivorous fish is required. However, the efficiency with which piscivorous fish assimilate DDT from their food has rarely been measured in the laboratory. Reinert et al. (1974) fed lake trout *(Salvelinus namaycush)* pelletized commercial food spiked with DDT by soaking the pellets in the insecticide dissolved in corn oil. From their laboratory experiment, these researchers estimated that lake trout retained 20% of the DDT contained in their food. But this estimate of DDT assimilation efficiency may not be applicable to piscivorous fish in their natural environments, because assimilation efficiency of DDT from eating commercialized pellets may be substantially different than the assimilation efficiency from eating fish. Sijm et al. (1993) found that uptake efficiency of lipophilic contaminants by rainbow trout (*Oncorhynchus mykiss*) varied depending on whether the contaminants were administered to the trout via an oil or gelatin capsule. These researchers concluded that uptake efficiency of lipophilic contaminants depended on the food matrix. Additionally, these researchers recommended that natural foods be used to determine the efficiency with which fish retain contaminants from their food.

The objective of our study was to determine the efficiency with which lake trout retain DDT from their natural food. Our estimate of DDT assimilation efficiency would represent the most realistic estimate, to date, for use in risk assessment models.

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MATERIALS AND METHODS

We obtained three-year-old and six-year-old lake trout from the U. S. Fish and Wildlife Service (USFWS) Jordan River National Fish Hatchery and the USFWS Allegheny National Fish Hatchery. Both groups of fish were fed pelletized commercial feed at the hatcheries, and then we acclimated the lake trout to a diet of alewife (*Alosa pseudoharengus*) and rainbow smelt (*Osmerus mordax*) in our laboratory tanks at the Great Lakes Science Center for several months prior to the start of our experiment. Alewives and rainbow smelt have constituted the bulk of the diet of lake trout ≥ 400 mm (total length) from nearshore waters of Lake Michigan since the 1970s (Madenjian et al. 1998).

We split both of the age groups into six lots (three different rations, two replicate tanks for each ration), with 15 fish per tank for age-3 lake trout and 12 fish per tank for age-6 lake trout. Age-3 and age-6 lake trout were kept in 870-L and 2380-L circular fiberglass tanks. Each lake trout was weighed to the nearest gram at the start and end of the experiment. Lake trout were fed thawed alewife and rainbow smelt that had been caught in Lakes Michigan and Huron, frozen, and stored at -30°C. The three different feeding regimes included ad libitum, and 0.25% and 0.50% of their body weight per day. Lake trout fed the 0.25% ration were fed every fourth day, lake trout fed the 0.50% ration were fed every other day, and lake trout fed ad libitum were fed to satiation once a day. Uneaten food was retrieved, air dried for 20 min, and weighed to the nearest 0.1 g. On the average, the age-3 and age-6 lake trout fed ad libitum consumed 1.4 and 0.9% of their body weight per day. Lake trout in our laboratory tanks were subjected to an annual temperature regime similar to that experienced by Lake Michigan lake trout (Madenjian and O'Connor 1999). For more details on the laboratory experiment, refer to Madenjian et al. (2000).

To start the experiment, five lake trout were sacrificed from each of the small tanks, and two lake trout were sacrificed from each of the large tanks. Sacrificed fish were stored in plastic bags at -30°C until time of analysis. The 10 remaining fish in each of the tanks were frozen at the conclusion of the experiment, and the fish were stored at -30°C until processing. The experiment ran 335 days for the age-6 lake trout and 293 days for the age-3 lake trout. Subsamples (10-30 fish) of both alewife and rainbow smelt were stored at -30°C for later analysis. The prey fish used to feed the lake trout were caught at several locations in both Lakes Huron and Michigan. Therefore, a subsample was taken for each combination of location of capture and prey fish species (alewife or rainbow smelt).

Following the conclusion of the experiment, frozen lake trout were thawed and grouped by tank and stage of the experiment (start or end). Each fish group was then homogenized in an industrial-strength mixer. Frozen prey fish were thawed and stratified by location of capture and species (alewife or rainbow smelt). Each group of prey fish was then homogenized in a food processor.

The procedure outlined by Hesselberg et al. (1990) was followed to determine the total DDT concentration in each of the homogenates. Appropriate quality control samples (blanks, matrix spikes, and duplicates) were used to ensure the accuracy and precision of the samples. Average recovery of total DDT from spiked samples exceeded 90%. All DDT determinations were completed within 1 year after termination of the laboratory experiment.

We calculated the efficiency with which lake trout retained total DDT from their food, γ, in the same manner as calculated by Madenjian et al. (2000):

$$\gamma = \frac{\Delta\ DDT\ body\ burden}{amount\ of\ DDT\ ingested}$$

where $\Delta\ DDT\ body\ burden$ = the average increase in the total DDT body burden of lake trout in the tank during the course of the experiment (in micrograms of DDT), and *amount of DDT ingested* = the average weight of total DDT in the food eaten by lake trout in the tank during the course of the experiment (in micrograms of DDT). We shall also refer to γ as the net trophic transfer efficiency of total DDT to lake trout from their food. Increase in total DDT body burden was calculated as:

$$\Delta\ DDT\ body\ burden = ([DDT_f]\ W_f) - ([DDT_i]\ W_i)$$

where $[DDT_f]$ = average total DDT concentration of lake trout in the tank at the end of the experiment (in micrograms per gram, wet weight), W_f = average weight of lake trout in the tank at the end of the experiment (in grams, wet weight), $[DDT_i]$ = average total DDT concentration of lake trout in the tank at the start of the experiment (in micrograms per gram, wet weight), and W_i = average weight of lake trout in the tank at the start of the experiment (in grams, wet weight). To calculate the amount of total DDT ingested, we summed the products of total DDT concentration of a particular food type and the corresponding amount of that food type eaten by an average lake trout in the tank during the course of experiment, across all food types. A food type was uniquely defined by prey fish species (alewife or rainbow smelt) and location of capture.

To estimate the net trophic transfer efficiency of DDE to lake trout from their prey, we repeated the procedure described above, substituting total DDT concentration with DDE concentration.

RESULTS AND DISCUSSION

Initial total DDT concentrations of lake trout composites ranged from 0.15 to 0.59 μg/g (Table 1). Final total DDT concentrations of lake trout composites ranged from 0.27 to 1.01 μg/g. Final total DDT concentrations were generally higher for age-6 lake trout compared with age-3 lake trout (Table 1). Age-6 lake trout fed ad

libitum attained the greatest weight by the end of the experiment, whereas age-3 lake trout maintained on a low ration of 0.25% of their body weight per day showed the smallest weight at the end of the experiment. Similarly, the amount of total DDT ingested was highest for age-6 lake trout fed ad libitum and lowest for age-3 lake trout fed 0.25% of their body weight per day (Table 1).

Total DDT concentrations of the alewives fed to the lake trout averaged 0.49 μg/g, with concentrations ranging from 0.27 to 0.80 μg/g. The mean total DDT concentration for alewives was based on nine different locations of capture. Total DDT concentrations of the rainbow smelt fed to the lake trout averaged 0.28 μg/g, with concentrations ranging from 0.19 to 0.54 μg/g. The mean total DDT concentration for rainbow smelt was based on 17 different locations of capture.

Net trophic transfer efficiencies of total DDT to lake trout from their food tended to decrease with increasing ration size (Table 1). Mean γ estimates for low, medium, and high rations were 0.87, 0.82, and 0.70. Net trophic transfer efficiencies of DDE to lake trout from their food also tended to decrease with increasing ration size; mean γ estimates for low, medium, and high rations were 0.87, 0.54, and 0.76 (Table 2). We suspected that the initial DDE concentration in the four fish sacrificed from tanks 11 and 12 at the start of the experiment was not representative of the initial DDE concentration of the lake trout remaining in the tanks (see Table 2). Excluding data for tanks 11 and 12 from the calculations for DDE trophic transfer efficiencies, mean γ estimates for low, medium, and high rations were 0.87, 0.73, and 0.76.

Both for total DDT and DDE, γ tended to decrease with increasing ration size. A similar-sized decrease was observed for net trophic transfer efficiency of polychlorinated biphenyls (PCBs) to lake trout from their food as ration size increased (Madenjian et al. 2000). Thus, these results suggested that the efficiency with which contaminants (at least lipophilic contaminants) are retained by fish decreases with increasing feeding rate.

Madenjian and O'Connor (1999) estimated that lake trout in Lake Michigan fed at a rate intermediate between the medium and high feeding rates used in our experiment. Therefore, we recommend that risk assessment modelers use a value of γ intermediate between the estimates of γ for lake trout fed medium and high rations from our experiment. Averaging estimates of γ for lake trout fed medium and high rations in our experiment yields a value of 0.76 for total DDT (Table 1). Thus, our experimental results indicate that a value of 0.76 should be used to quantify the efficiency with which piscivorous fish retain total DDT from their food in risk assessment models. We would also recommend that γ be set equal to 0.76 for modeling trophic transfer of DDE in the fish component of the aquatic food chain.

Our laboratory measurement of γ of 0.76 is drastically higher than the laboratory measurement of 0.20 by Reinert et al. (1974), and we believe that this difference

Table 1. Estimation of γ, the efficiency with which lake trout retain total DDT from their food, from a laboratory experiment.

Tank number	Lake trout age-class	Ration level	Average initial weight of lake trout (g)	Average final weight of lake trout (g)	Average initial total [DDT] of lake trout (μg/g)	Average final total [DDT] of lake trout (μg/g)	Consumption (g)	Amount of total DDT ingested (μg)	γ
26	3	low	711	724	0.160	0.273	540	155	0.541
28	3	low	727	753	0.157	0.323	559	160	0.806
21	6	low	1899	1940	0.380	0.713	1635	523	1.265
22	6	low	2121	2155	0.380	0.594	1763	542	0.874
25	3	medium	718	854	0.179	0.392	1136	323	0.637
27	3	medium	766	914	0.152	0.494	1197	338	0.992
11	6	medium	1943	2372	0.591	0.732	3603	1124	0.525
12	6	medium	2212	2588	0.591	1.011	3785	1179	1.110
13	3	high	795	1458	0.174	0.661	4042	1038	0.796
15	3	high	794	1455	0.207	0.672	4159	1067	0.762
23	6	high	2245	3153	0.556	0.937	7037	1917	0.890
24	6	high	2406	3240	0.556	0.596	6729	1767	0.336

Table 2. Estimation of γ, the efficiency with which lake trout retain DDE from their food, from a laboratory experiment.

Tank number	Lake trout age-class	Ration level	Average initial weight of lake trout (g)	Average final weight of lake trout (g)	Average initial [DDE] of lake trout (μg/g)	Average final [DDE] of lake trout (μg/g)	Consumption (g)	Amount of DDE ingested (μg)	γ
26	3	low	711	724	0.096	0.182	540	107	0.595
28	3	low	727	753	0.090	0.202	559	111	0.786
21	6	low	1899	1940	0.332	0.519	1635	367	1.021
22	6	low	2121	2155	0.332	0.518	1763	379	1.086
25	3	medium	718	854	0.105	0.244	1136	222	0.600
27	3	medium	766	914	0.089	0.294	1197	231	0.866
11	6	medium	1943	2372	0.559	0.514	3603	791	0.169
12	6	medium	2212	2588	0.559	0.645	3785	831	0.520
13	3	high	795	1458	0.123	0.418	4042	696	0.736
15	3	high	794	1455	0.145	0.413	4159	719	0.674
23	6	high	2245	3153	0.410	0.635	7037	1312	0.824
24	6	high	2406	3240	0.410	0.596	6729	1182	0.799

was primarily attributable to the difference in the food matrices. Reinert et al. (1974) observed a leaching of DDT from the food pellets into the water column of the tank during their experiment, and this leaching likely contributed to the substantial difference in the γ estimates between the two experiments. We cannot overemphasize the importance of using natural foods to measure trophic transfer efficiencies of contaminants to fish from their food.

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