A RECURRENCE MODEL FOR THE PREDICTION OF DDT FLUX IN ATLANTIC MENHADEN[a]

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Abstract: A simple recurrence model is developed for the prediction of DDT flux through Atlantic menhaden (*Brevoortia tyrannus*). The DDT body burden in young-of-the-year menhaden at any time is equal to the body burden on the previous day plus the DDT accumulated on the current day minus the DDT turnover. Accumulation of DDT is simulated and compared with field observations. Estimations of DDT ingestion, assimilation, turnover, and egestion are made on both per fish and population bases. It is estimated that emigrating juvenile menhaden export 20 g DDT year^{-1} from the Newport River estuary in North Carolina.

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The insecticide DDT has probably received the greatest usage, stirred the most controversy over its continued use, and been the subject of more research than any other synthetic pesticide. Despite all of the research on DDT, relatively little is known about its movement within the estuarine ecosystem.

Estuaries receive insecticide residues from a variety of agricultural, silvicultural and domestic sources. These residues cycle in the estuary and can be accumulated by the biota. Thus, to better understand the role of the biota in determining the pathways of residue movement within the estuaries, I have studied DDT concentration and turnover in young-of-the-year ($\leq$ 9 months old) Atlantic menhaden, a dominant fish in many Atlantic coast estuaries.

Menhaden accumulate ΣDDT (DDD + DDE + DDT) insecticide residues during their estuarine residency (Warlen 1974). Warlen et al. (1971) constructed a model that estimated feeding rate, DDT food concentration, the fraction of ingested DDT that was assimilated, and the fractional DDT accumulation and turnover rates in young-of-the-year Atlantic menhaden. However, the model did not predict the concentration of DDT in menhaden at any given time and given level of DDT in their food.

The purposes of this paper are to (1) describe a simple model of the recurrence type that can generate estimates of the DDT body burden in menhaden over time, (2) use the model to estimate the flux of DDT in menhaden in the Newport River estuary in North Carolina, and (3) estimate the export of DDT out of the system through menhaden emigration.

MODEL

The model contains a recurrence relation which enables the estimation of DDT body burden in young-of-the-year menhaden at any day given the fish's DDT body burden on the previous day. The pattern of change in body burden over time, for a given set of values for the parameters, is obtained by successive calculation of the daily values.

In the model I assume that the DDT body burden in young-of-the-year menhaden at any time (t) is equal to the body burden on the previous day (t-1) plus the DDT accumulated minus the amount of DDT lost (turned over):

$$B_{(t)} = B_{(+.1)} + FCAW_{(t)} - \lambda B_{(t-1)}$$

where B is the DDT body burden in picograms (pg), FCAW is the accumulation rate of new DDT in pg, and λ is the fraction of DDT turned over per day. I assume no loss of the current day's accumulation, and that growth rate, assimilation rate, and turnover rate are constant. The model is assumed to apply to ΣDDT as well as to DDT alone. I could estimate DDT body burden in young-of-the-year menhaden at any desired age with these assumptions, an initial DDT body burden value, and successive numerical iteration of the model on a day-by-day basis.

Body Burden (B)

Body burden is the total amount of DDT in all tissues of a fish. DDT in young-of-the-year menhaden was considered to be 4.8 x 10^2 pg ($\bar{x}$, n = 2) when fish immigrated as larvae (6 mg dry weight) to the Newport River estuary in North Carolina and

7.2×10^5 to 1.8×10^6 pg when they emigrated as large juveniles (4.3 g dry weight) about 250 days later (Warlen 1974). The immigration value was used as the body burden for time = 0 in testing this model. Estimates of body burden were calculated where time was $\geq$ 1 day and time increments were discrete steps of 1 day.

Accumulation Rate [$FCAW_{(t)}$]

The DDT accumulation rate is the product of the daily feeding rate (F) in mg dry food/mg of dry fish weight, the DDT concentration in food (C) in pg/mg dry food, the fraction of DDT assimilated (A), and the dry weight of fish [$W_{(t)}$] calculated assuming an exponential growth rate.

The product of the first 3 factors (FCA) is the daily DDT assimilation rate on a per unit dry weight basis. Feeding rates (F) for young-of-the-year menhaden may vary considerably and are probably dependent on the life stage during the menhaden's first year. In an experimental DDT uptake study, Warlen et al. (1977) used a feeding rate (mg dry food/mg dry fish weight) of 0.17 and Peters and Kjelson (1975) determined the feeding rates of larval and juvenile menhaden to be 0.05 and 0.14, respectively. Estimates of the DDT concentration in the food (C) of menhaden are difficult to obtain owing to the nature of the menhaden's diet which consists of plankton-detritus in all except the larval stages (June and Carlson 1971). Gas chromatographic measurements on 15 plankton-detritus samples taken from the study area showed a mean ΣDDT content of 113 pg/mg which varied from 11 to 250 pg/mg (Warlen 1974). The mean fraction of DDT assimilated (A) by experimental menhaden was 0.22 (Warlen et al. 1977). If values of 0.17, 113, and 0.22 are used for feeding rate, DDT concentration in food and fraction DDT assimilated respectively, the DDT assimilation rate is 3.8 pg DDT/mg of fish day^{-1}.

The assimilation rate must be multiplied by the growth rate equation to obtain the DDT accumulation rate for use in the model. The growth rate equation for wild menhaden from the Newport River estuary is mg dry body weight = $6.3149e^{0.02718t}$ (Warlen 1974).

Fractional Turnover Rate (λ)

The fractional turnover rate of DDT was estimated from experiments measuring the loss of DDT in menhaden (Warlen et al. 1977). The DDT body burden loss equation used was pg DDT = $5137.9746e^{-0.00506t}$. The absolute value of the exponential coefficient, 0.00506, is the daily fractional turnover rate, about 0.5 percent.

SIMULATION OF ACCUMULATION

The accumulation of DDT by young-of-the-year menhaden can be simulated from the model using the estimated parameter values described previously and shown in Fig. 1. Successive iteration of the model from time = 0 to time = 200 days gave the prediction curve for DDT body burden shown in Fig. 1. The exponential increase in DDT body burden is due to the great influence of the growth of the fish on body burden. In this relation I have assumed that menhaden accumulate DDT primarily from their diet and very little, if any, from the water. Macek and Korn (1970) also suggested that the food chain is the major source of DDT for fish in natural waters. The flux model was designed for young-of-the-year menhaden that are growing rapidly during their estuarine residency. The contained exponential growth model was appropriate for young-of-the-year menhaden (Warlen 1974). Other types of growth equations would probably be more useful in the flux model when estimating DDT flux in yearling or older menhaden.

Sensitivity analyses, using output from several computer runs, showed the impact of varying the values of 1 parameter at a time on estimation of DDT body burden. For example, DDT concentration in the food significantly affects the prediction of the DDT body burden in menhaden (Table 1). The accumulated DDT body burden is proportional to the DDT concentration in the menhaden's food (C), except early in the post-larval period when the starting body burden (480 pg DDT) has a proportionally greater effect on the total body burden. Macek et al. (1970) and Robinson (1967) also reported that accumulation of DDT by rainbow trout (*Salmo gairdneri*) and an organochlorine insecticide by vertebrates, respectively, was dose dependent. The form of the model shows that the change in DDT body burden with time approached proportionality with the changes in either the feeding rate (F), fraction of DDT assimilated (A), or the exponential growth rate.

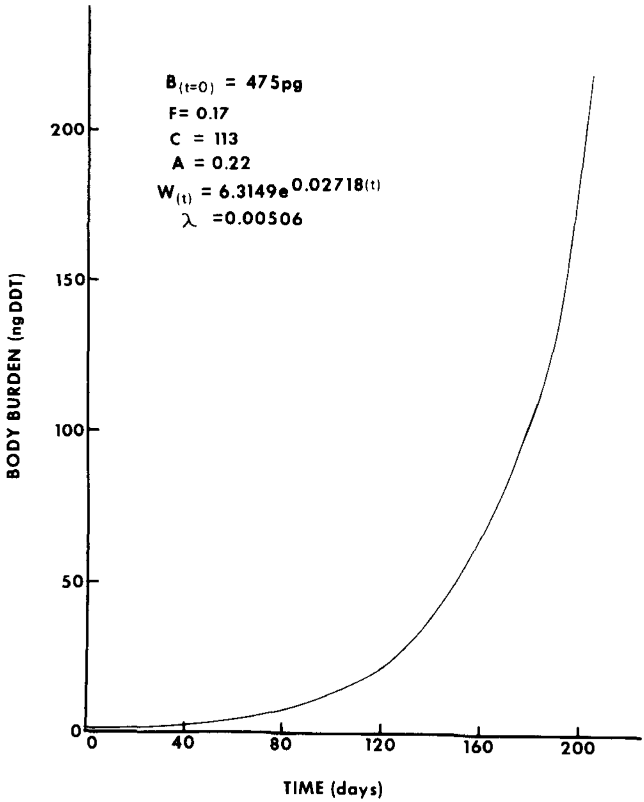

Fig. 1. Predicted DDT body burden (ng) in young-of-the-year Atlantic menhaden for 200 days. The DDT body burden (B) at day-0 is 475 pg (0.475 ng).

Table 1. Estimation of DDT body burden in menhaden using the recurrence model. Values for the DDT concentration in food (C) parameter were varied while those for the other parameters were: F = 0.17, A = 0.22, $W_{(t)} = 6.3149e^{0.02718(t)}$, and λ = 0.00506.

Time	*DDT concentration in food, C (ppb)*				
(days)	*43*	*73*	*103*	*113*	*133*
			pg DDT x 10^3		
10	0.57	0.65	0.73	0.76	0.89
50	1.4	2.1	2.8	3.0	4.1
90	3.8	6.2	8.7	9.5	13.5
130	11.0	18.6	26.1	28.6	41.1
170	32.6	55.1	77.7	85.2	122.9
210	96.4	163.6	230.8	253.2	365.1
250	285.9	485.3	684.7	751.1	1,083.4

In contrast to the above parameters concerned with DDT accumulation, the changes in the body burden were not proportional to changes in the DDT turnover rate (λ). For example, doubling of the turnover rate, from 0.00506 to 0.01012, resulted in only a 13.4 percent decrease in the DDT burden at the end of 250 days. Young-of-the-year menhaden obviously could retain a large fraction of their accumulated DDT for a considerable time even if they ceased to receive any new amounts. The biological turnover time, the reciprocal of the estimated turnover coefficient (0.00506), is 198 days. Multiplying this value by the natural log of 2 gives the biological half-life of 137 days. The DDT half-life in rainbow trout, 160 days, obtained from similar exposure conditions (Macek et al 1970), is close to our value for menhaden, which may indicate a similar DDT elimination mechanism in both freshwater and marine environments.

Surface response diagrams were constructed from these simulations. The values assigned to 1 parameter at a time were varied and the effect on the DDT body burden calculations is shown in Fig. 2. Values for the parameters were the same as those shown

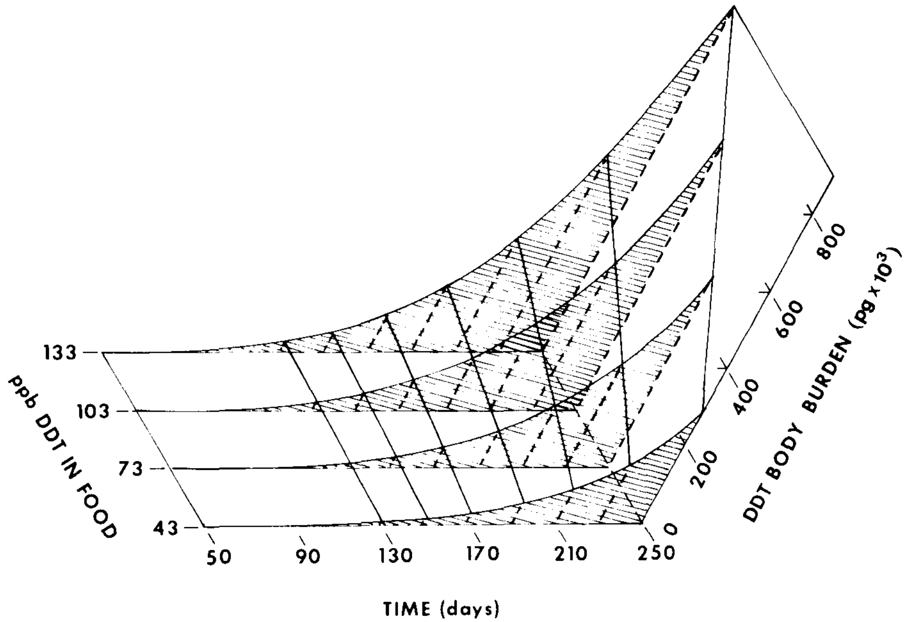

Fig. 2. Surface response diagram of DDT body burden in menhaden on time at four levels of DDT concentration in the food. Curves are generated by the recurrence model.

in Fig. 1, except that the DDT concentration in food (C) assumed values of 43, 73, 103, and 133 ppb. These response diagrams also show that changes in body burden are proportional to changes in the DDT concentration in food after about 90 days.

COMPARISON OF SIMULATED AND OBSERVED BODY BURDENS

The predictive capability of the recurrence model and its parameter values, in part, may be judged by comparing its simulation to actual values observed in a menhaden population. Linear regressions of DDT body burden data on time for 1971 and 1972 young-of-the-year menhaden (Warlen 1974) were averaged and compared (Fig. 3) with DDT body burdens provided by the recurrence model. The 2 recurrence model predictions shown were chosen from computer simulations where parameters were varied within reasonable limits and the generated curves closely bracketed the linear regression curves for the 1971 and 1972 menhaden. The close fit between the measured and predicted curves suggests that the formulation of the recurrence model may be correct and that the parameter values approximate the true values.

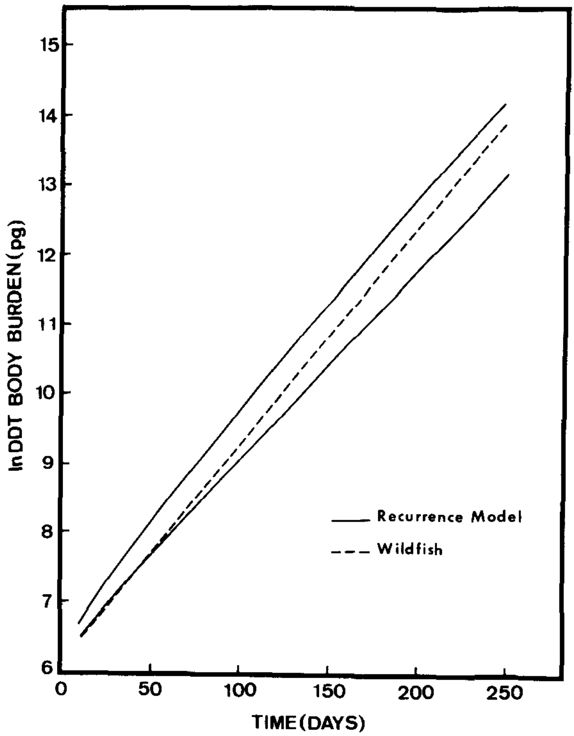

Fig. 3. Comparison of ln DDT body burden on time in menhaden, mean of 1971 and 1972 young-of-the-year menhaden (Warlen 1974), and estimates of DDT body burden from the recurrence model. The following parameter values in common for the upper and lower curves were: F = 0.17, A = 0.20, and λ = 0.00506. Values for C and the growth coefficient were, respectively, 143 and 0.03000 for the upper curve and 83 and 0.02718 for the lower curve.

DAILY DDT FLUX ESTIMATES

The daily flux of DDT through young-of-the-year menhaden (Table 2) was estimated using several of the parameters from the recurrence model. Ingestion of DDT per fish is the product of the DDT concentration in the food (C), the feeding rate (F) and the mean dry weight of fish. The mean dry weight of fish was obtained by integrating the growth model, $W = 6.3149e^{0.02718t}$. Accumulation rate is the product of ingestion, as determined above, and the fraction of DDT assimilated (A). Egestion is equal to ingestion minus accumulation. The average DDT turnover is estimated by the product of the fractional turnover rate (λ = 0.00506) and the DDT body burden of an 829 mg fish (mean dry weight). This body burden is predicted from the model, log body burden = 1.7412 + 1.1964 (log dry weight), from Warlen (1974). If any DDT is turned over on the day of its accumulation it is a relatively small amount and is ignored in this model.

The physiological flux of DDT in menhaden, i.e., the movement of a compound into and through an organism (Small, Fowler, and Keckes 1973), can be estimated for the entire population. An estimate of the size of the population of young-of-the-year menhaden for the Newport River estuary in North Carolina was taken from Cross et al. (1975). This value, 1.8 x 10^7 fish, was used to achieve the population basis estimates shown in Table 2. These estimates suggest that the filter feeding menhaden may be important in the cycling of DDT in the estuary. On the average, during their estuarine residency, they ingest almost 300 mg/day of DDT from the particulate material in the water. About 80 percent of that DDT is egested back into the environment via the feces. An unknown, but probably large, portion of such feces in a shallow estuary (mean depth $\cong$ 1 m) such as the Newport River estuary may reach the sediment where it is

Table 2. Estimated average daily flux of DDT (pg) through menhaden during their estuarine residency.

Rate Function	Per Fish Basis	Population Basis[a]
		pg DDT
Ingestion (C) (F) ($\bar{X}$ weight)	15,925	2.86×10^{11}
Accumulation (A) (ingestion)	3,185	5.73×10^{10}
Egestion (Ingestion-Accumulation)	12,740	2.29×10^{11}
Turnover[b] (λ) (x body burden)	866	1.54×10^{10}

C = 113 ppb (pg/mg)
F = 0.17 mg/mg
x weight = 829 mg dry weight
A = 0.20 pg/pg
λ = 0.00506 pg/pg

[a]Fish basis values x 1.8×10^7 fish (Cross et al. 1975).
[b]Body burden for 829 mg dry weight fish from the model: log body burden = 1.7412 + 1.1964 (log dry weight) from Warlen (1974).

available for ingestion by deposit feeders. Cross et al. (1975) have suggested the importance of this process in the cycling of several trace metals in the same estuary. It seems likely that this process may also be important in DDT cycling.

DDT EXPORT FROM THE ESTUARY

The quantity of DDT exported from the estuary in emigrating menhaden also can be estimated from aspects of this model. Export of DDT in menhaden was computed as the product of the per fish DDT body burden at 250 days (Fig. 3) and the number of fish leaving the system. The average DDT export from the Newport River estuary in 1971-1972 was 2.0×10^{13} pg (20g), the product of the average estimated DDT body burden of 1.1×10^6 pg (anti-ln of 13.95, Fig. 3) and the estimated number of fish leaving the estuary, 1.8×10^7.

CONCLUSIONS

The simple recurrence model developed in this paper can: (1) estimate the DDT body burden in young-of-the-year menhaden over time, (2) predict the flux of DDT in and through menhaden during their estuarine residency, and (3) provide estimates of the DDT exported from the Newport River estuary in emigrating menhaden. The model may also be useful in describing the flow of DDT through the estuarine ecosystem and interpreting the ecological consequences of its use to that system. This type of model may be used to describe the flux of DDT as well as other chlorinated aromatic hydrocarbons that might bioconcentrate in both marine and freshwater fishes.

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