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The Effects of Temperature and Organism Size on the Feeding Rate and Modeled Chemical Accumulation in *Diporeia* spp. for Lake Michigan Sediments

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ABSTRACT. Diporeia *spp. are one of the most important benthic organisms in the Great Lakes. These amphipods represent a major prey item for most fish at some stage in the fish life cycle. Understanding of the physiology, energetics, and exposure to sediment-associated contaminants of* Diporeia *requires studies of their feeding behavior. This work examined the role of temperature and organism size on the feeding rate, measured as fecal pellet output, for lake sediments. The feeding rate was measured at 2, 4, 8, and 12°C after 3- and 7-d exposure in sieved Lake Michigan sediment. Amphipod feeding rates declined exponentially with increasing mass and increased exponentially with temperature. The relationship between feeding rate, temperature (∞C), and size (mg) is described by the following equation:*

$$FR_{t,s} = 10^{-1.22\,(\pm\,0.08)} \cdot T^{0.83\,(\pm\,0.09)} \cdot W^{-0.84\,(\pm\,0.08)},\ r^2 = 0.63$$

where FR = feeding rate, T = temperature (°C), W = size (mg), and standard errors in parentheses. The relationship between feeding rate, temperature, and size allowed for improved parameterization of a contaminants uptake model for Diporeia. *Model results show that the concentration of a contaminant in* Diporeia *biomass was lowest in April at 100 m and highest in June at 15 m and 45 m. The concentration was 2.3 and 2.9 times greater at 15 m and 45 m compared to the concentration at 100 m.*

INDEX WORDS: *Feeding rate, uptake rate, temperature, organism size,* Diporeia *spp.*

INTRODUCTION

Diporeia spp. are an important benthic species in the Great Lakes and represent a major prey item to most Great Lakes fish at some stage in their life (Wells and Beeton 1963, Elrod 1983, Wojcik *et al.* 1986, Fratt *et al.* 1997). This organism also represents an important source of contaminants to the food web. For instance, food web modeling suggests that *Diporeia* account for up to 40% of PCB in alewife (Breck and Bartell 1988). Other efforts have also identified that the sediment pathway is critical to the transfer of contaminants up the aquatic food chain (Morrison *et al.* 1996, Thomann *et al.* 1992).

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The ingestion route is considered to be the dominant route for accumulation of sediment-associated contaminants by *Diporeia* (Landrum and Robbins 1990). To assess the extent of contamination from this route, both the rate of ingestion and the assimilation efficiency of food are required to evaluate the extent of exposure. A recent review of the factors affecting the ecotoxicology of *Diporeia* identified feeding behavior as one aspect that requires additional study (Landrum and Nalepa 1998).

Diporeia are intermittent feeders (Quigley 1988). At shallower depths, they feed heavily during the spring and fall diatom blooms and infrequently at other times of the year. The feeding rate also depends on the size of the amphipods, with the smaller organisms having fuller guts, indicating more continuous feeding, while the larger animals feed very infrequently (Quigley 1988). Feeding rates of *Diporeia* also depend on the type of food supply. When *Diporeia* fed on sediment particles, the gut turnover was greater by a factor of 10 compared to feeding on the diatom *Melosira varians* (Quigley and Vanderploeg 1991). It was postulated that the energetic requirements of *Diporeia* were met by a smaller quantity of the diatom compared to sediment organic carbon. Furthermore, the feeding rate for *Diporeia* in Lake Michigan was reported to be similar to measurements in Lake Ontario (Quigley and Vanderploeg 1991). Thus, it is expected that food type, organism size, and environmental temperatures would affect the observed feeding behavior of *Diporeia*.

If possible, feeding rate should measure the amount of material ingested per size of organism per time. However, with small organisms this is often impossible to determine. Several studies indicate that for sediment dwelling organisms, a maximum of 20% of the total organic carbon ingested is assimilated (Hargrave 1970, 1972; Lopez and Levinton 1978; Cammen 1980). Because the sediment fed to the *Diporeia* in this study contained about 1% carbon, and because most of that is probably not assimilated based on the studies cited above, then the bulk of the material ingested would also be egested as fecal material. Therefore, an estimate of the feeding rate can be determined through the measure of the egestion rate for sediment. Assuming that the egestion rate is approximately equal to the ingestion rate based on the above arguments, the feeding rate for *Diporeia* of differing sizes and at different temperatures can be compared.

With better estimates of feeding rate, improvements in modeling the uptake and bioaccumulation of sediment-associated contaminants by *Diporeia* are feasible. Thomann (1989) developed a model for calculating the concentration of organic chemicals in a simple aquatic food chain, and Thomann *et al.* (1992) expanded the equilibrium model to include a benthic invertebrate compartment, specifically *Diporeia*.

Model Development

The general equations for chemical uptakes are taken from Thomann *et al.* (1992) as follows:

$$\frac{dV_d}{dt} = \left[k_1 \cdot C_w\right] + \left[\alpha \cdot FR \cdot V_f\right] - \left[(K+G) \cdot V_d\right] \qquad (1)$$

where V_d and V_f are the chemical concentration on a lipid basis [µg/kg(lipid)] of *Diporeia* and food (both algae and sediment carbon), respectively. The coefficient k_1 is the chemical uptake rate in water for *Diporeia* [L/d/ kg(l); kg(l) = kg lipid], C_w is the water concentration of the chemical [µg/L], α is the chemical uptake efficiency from food for *Diporeia* (µg of the chemical absorbed per µg lipid normalized food ingested), FR is the specific feeding rate [g(w) of food per g(w) of *Diporeia*; where g(w) is the wet weight mass], K is the excretion rate, and G is the growth rate of *Diporeia*. Under the assumptions presented by Thomann (1989), k_1 is estimated as:

$$k_1 = 10^g \cdot \left(\frac{w^{-\gamma}}{p_d}\right) \cdot E \qquad (2)$$

where the coefficient (g) has a value of 3 (Norstrom *et al.* 1976), p_d is the fraction lipid to body size [g(lp)/g(w)] for *Diporeia*, w is wet weight of *Diporeia* [in g(w)], and E is the efficiency of transfer of the chemical from water to the organism. The respiration parameter γ has a value between 0.2 and 0.3 under normal conditions (Norstrom *et al.* 1976). Feeding rate (FR) is a function of growth and respiration and is estimated from

$$FR = \frac{(G+r)}{a} \qquad (3)$$

where the growth rate is estimated by

$$G = \delta \cdot \omega^{-\beta} \qquad (4)$$

with G in g/day. The regression parameter δ is $\approx$ 0.002 at 10°C, and β varies from 0.2 to 0.3 (Thomann 1981, Schmidt-Nielson 1970). Respiration rate is given as

$$r = \Phi\omega^{-\beta} \qquad (5)$$

where w is in g(w), and Φ varies from 0.014 to 0.05 (Norstrom *et al.* 1976). The elimination rate constant K is estimated as:

$$K = \frac{k_1}{K_{ow}} \qquad (6)$$

with K in g/day.

At steady-state conditions, i.e., $\frac{dV_d}{dt} = 0$, the concentration of a chemical in *Diporeia* is given by:

$$V_d = (k_1 \cdot C_w) + \frac{\left[\alpha \cdot FR \cdot \left(\frac{p_f}{p_d}\right) \cdot V_f\right]}{(K+G)} \quad (7)$$

where p_f is the fraction lipid/carbon to sediment mass [g(lp/c)/g(w)] for *Diporeia*.

To better understand transfer of sediment-associated contaminants to *Diporeia*, this study determined feeding rates ($FR_{t,s}$) for *Diporeia* and examined the effects of amphipod size (mass) and temperature. Contaminant uptake rates for *Diporeia* estimated using the $FR_{t,s}$ were compared to estimates using the original FR equation (3). The uptake model includes food chain effects and indicates significant elevations of concentration factors in higher trophic levels for chemicals with log K_{ow} of 5 to 7. For this study, simulations of *Diporeia* uptake for a chemical with a log K_{ow} of 6 were done for typical environmental conditions in southern Lake Michigan.

MATERIALS AND METHODS

Organism Collection

Diporeia were collected from a 35-m-deep location off the coast of Muskegon, Michigan (43° 13.12′N 86° 27.02′W) using a PONAR grab sampler. The amphipods were screened from the sediment, transferred to fresh Lake Michigan water, and placed in ice-filled coolers for transport to the laboratory. *Diporeia* were housed with 3 to 4 cm of Lake Michigan sediment and approximately 10 cm of overlying Lake Michigan water. The animals were kept in the dark and at a constant temperature of 4°C. The amphipods were fed weekly a dietary supplement of TetraMin®, a flaked fish food (approximately 0.5 to 1 g per aquarium per week). The amphipods were acclimated at 2°C per 24 h to the experimental temperature at least 1 week before any experimental use.

The feeding rates are given on a *Diporeia* wet weight basis. For the laboratory studies, measured feeding rates from elimination studies were calculated for individual organisms using the equation:

$$FR = \frac{feces}{time \cdot w} \quad (8)$$

where units are feces in g (dry weight), time in days, and w is the wet weight of *Diporeia* in g. The feeding rate of amphipods is highly variable, influenced by such factors as food quality and quantity, maturation, and lipid content (Caveletto *et al.* 1996, Evans *et al.* 1990). To minimize the effect of physiological, behavioral, and other uncontrolled environmental factors that could influence feeding, values were selected from the top two quartiles within each size class for estimating maximum feeding rate.

Sediment Preparation

Sediment was collected from a 45-m station off the coast of Grand Haven, Michigan (43° 12.43′ N, 86° 18.90′W) using a PONAR grab sampler. The sediment was wet sieved beginning with a 1-mm sieve and followed sequentially by a 420-µm, 90-µm, 63-µm, and 20-µm sieve. The sediment passing through the 20-µm mesh was homogenized, and the dry-to-wet weight ratio determined.

To determine the amount of sediment that would be placed into each vial, the ingestion rate of organic matter was estimated for a mid-sized amphipod between 3 and 6 mg. Previously reported rates of sediment throughput, measured as fecal pellet output, were 0.00264 mg (dry sediment)/mg (organism)/h (Harkey *et al.* 1994). A 6-mg organism would consume 0.38 mg of sediment per day. Thus, it should only require about 11 mg of sediment to accommodate the organism for a 7-day study. The actual amount of sediment used was about 0.5 g dry weight of < 20 µm material. Thus, it was expected that there would be ample sediment organic matter to serve as food for the exposures. This is a critical assumption for calculations of *Diporeia* chemical uptake (Thomann 1981). One half gram of sediment, based on dry weight, and one amphipod were added to each vial. The organic carbon content of the < 20 µm sediment was assayed on a Perkin Elmer (Norwalk, CT) 2400 CHN elemental analyzer. TOC was determined to be 1.21% ± 0.11% (n = 44).

Water

The water used in the experiment was collected from the Huron River in Dexter, Michigan and filtered to < 1.5 µm, using a glass-fiber filter. The alkalinity averaged 180 mg $CaCO_3$/L and the total hardness of the water averaged 250 mg $CaCO_3$/L. The average pH was 8.4. This water has characteristics very similar to water from Lake Michigan (Kane Driscoll *et al.* 1997).

Design

Four experimental temperatures were examined using 72 plastic vials per temperature. Sixty vials with sediments, each with a single amphipod, were placed into an aquarium for each temperature and sampled for feces production on days 3 and 7. Twelve control vials with only sediment were used to monitor any changes in organic carbon content of the sediment over the course of the experiment. Each vial contained approximately 0.5 g sediment and one organism and was capped with a fine-meshed lid to allow water exchange but to prevent the animal from escaping. Each vial was ballasted with a 2 to 5 g rock to prevent the vials from floating or tipping in the glass aquaria. Three experimental runs were completed with one run at 4°C and 2°C, a second run at 4°C and 8°C, and a third run at 4°C and 12°C. The first experiment at 2°C and 4°C used organisms and sediment collected on 8 December 1997. Fresh sediment and amphipods had to be collected in 5 March 1998 before running the second and third experiments. After adding sediments, filtered Huron River water was added to each vial, and the sediment was allowed to settle before adding the *Diporeia*. After ensuring that the *Diporeia* was not trapped in the surface of the water, each vial was submerged into a glass aquarium filled with filtered Huron River water.

Sampling

At day three and day seven, 30 vials at each temperature were removed. The contents were emptied onto a 63-μm screen and gently rinsed. The amphipod was removed with forceps, placed in fresh water, and held for weighing. *Diporeia* were blotted dry and weighed to the nearest 0.01 mg. Once weighed, *Diporeia* were dried in 6 × 50 mm culture tubes at 70°C to determine dry to wet ratios. The pre-sieved sediment was rinsed through a 63-μm screen leaving behind the fecal pellets, which were then rinsed into a beaker or petri dish. The fecal pellets were examined before transferring them to a weighing container or filter to avoid any extraneous material that may have been retained on the screen. The samples were transferred to a tared weighing boat, dried, and dry weight determined.

Feeding Model Development

The equation for chemical uptake was modified to include a temperature and size dependent feeding rate:

$$FR_{t,\,s} = 10^{a} \cdot T^{b} \cdot W^{c} \tag{9}$$

where T is temperature (°C), and W is wet weight of *Diporeia* (g). Exposure time (3 or 7 days) was not included in the uptake equation since this treatment effect was not found to be statistically significant by ANOVA, $p < 0.05$ (see below). To further evaluate the relative importance of the new feeding rate model, the results were compared from Thomann *et al.*'s (1992) equilibrium model (equation 7). Temporal trends of total organic chemical concentration in *Diporeia* were determined using his formulation for feeding rate (equation 3) and compared to results using the feeding rate equation (9), which is size- and temperature- dependent. For the model calculations, model coefficients and temperatures were taken from the literature and are summarized in Table 1. The size distribution of *Diporeia* was uniform, ranging in values from 0.5 to 10.0 mg.

RESULTS

Feeding rate exponentially declined with body size and exponentially increased with temperature (Table 2). An ANOVA was used to test the effects of organism size, temperature, and duration of experiment on the feeding rate data for *Diporeia*. Both organism size and temperature were significant ($p < 0.01$) with the greatest differences found at 12°C and the 0 to 2 mg size class (Table 2, Bonferroni pairwise test). Values ranged from 0.01 g (dw)/g (w)/d for > 6 mg amphipods cultured at 2°C to 0.25 g (dw)/g (w)/d for 0 to 2 mg amphipods cultured at 12°C. Feeding rate for *Diporeia* cultured at 12°C were 2 to 15 times greater than feeding rates cultured at 2°C. Similarly, feeding rates were 1.6 to 9 times greater for *Diporeia* in the size range of 0 to 2 mg compared to *Diporeia* in the size range of > 6 mg. There was no statistically significant effect from the duration of experiment on feeding rate (3 to 7 days exposure), therefore this factor was not included in the feeding uptake model.

The relationship between feeding rate, temperature, and size (Fig. 1) can be described as:

$$FR_{t,\,s} = 10^{-1.22\ (\pm\ 0.08)} \cdot T^{0.83\ (\pm\ 0.09)} \cdot W^{-0.84\ (\pm\ 0.08)}$$
$$r^2 = 0.63,\ N = 119$$

with units for FR [g (food)/g (*Diporeia*)/d], T (°C), and W (g wet weight) and with standard errors in parentheses (Table 2). These results are summarized in Figure 1 for temperatures between 1 and 10°C and for *Diporeia* with biomass between 0.005 and 0.01 g. The response changed most rapidly for

TABLE 1. Environmental and biological data at three depths and model coefficients for a bioaccumulation model (Thomann 1989) were taken from the literature for southern Lake Michigan.

	Range	Citations
15 m		
Temperature (°C)	6.8–20.0	Winnel and White (1984), McCormick and Fahnenstiel (1999)
Biomass & Size Frequency (mg)	0.5–9.0	Winnel and White (1984), Cavaletto *et al.* (1996)
45 m		
Temperature (°C)	3.8–8.0	Winnel and White (1984), Cavaletto *et al.* (1996)
Biomass & Size Frequency (mg)	1.0–9.5	Winnel and White (1984), Cavaletto *et al.* (1996)
100 m		
Temperature (°C)	3.8–4.6	Cavaletto *et al.* (1996), Evans *et al.* (1990)
Biomass & Size Frequency (mg)	1.0–10.0	Cavaletto *et al.* (1996), Evans *et al.* (1990)
Coefficient values		
a, food assimilation efficiency	0.2	Thomann (1989)
$p_{d,}$ fraction lipid in *Diporeia*	0.04–0.05	Cavaletto *et al.* (1996)
p_f fraction lipid in food	0.01	Thomann (1989), Thomann *et al.* (1992)
E, uptake efficiency for respiration	0.8	Thomann (1981)
α, chemical uptake efficiency	0.8	Thomann (1989)
β	0.2	Norstrom *et al.* (1976), Thomann (1981), Schmidt-Nielson (1970)
δ	0.01	Thomann 1981, Schmidt-Nielson 1970
γ	0.2	Thomann 1981, Schmidt-Nielson 1970
ϕ	0.01	Norstrom *et al.* (1976)

small amphipods at higher temperatures. At higher temperatures and for large organisms, feeding rate was close to being constant. The FR for a 0.5 mg amphipod was estimated to be 0.19 g/g/day at 2°C and increased to 0.85 g /g/day at 12°C. In contrast, the FR for a 10.0 mg amphipod at 2°C was 0.02 g/g/day and increased to only 0.07 g /g/day at 12°C. In Figure 1, the estimated FR using Thomann's (1989) model is also plotted. The greatest difference between the model calculations and those made from Thomann's (1989) model is the inclusion of a temperature- and size-dependent feeding rate, $FR_{t,s}$. For amphipods greater than 3 mg, FR estimates from Thomann's model were greater than those estimated from the model presented in this study. For smaller organisms at temperatures greater than approximately 5°C, estimates of FR were greater using the new model.

Temporal trends of the uptake of chemicals using the new feeding rate formula were different compared to the results from Thomann *et al.*'s (1992) equilibrium model. For a chemical with a concentration of 0.025 µg/L and a K_{ow} of 10^6, total chemical concentrations were calculated using both feeding rate equations. The concentration pattern (µg/m^2) was similar between both models (Fig. 2). However, in May, October, and November, values from Thomann *et al.* (1992) were greater by a factor of 1.2 compared to chemical concentration values calculated using the feeding rate equation. In the summer, the reverse was true. Chemical concentrations in *Diporeia* were 1.3 times larger than those estimated using the feeding rate suggested by Thomann *et al.* (1992), reaching a peak difference of 1.5 fold in mid-August.

TABLE 2. Comparison between specific feeding rates (g(dw)/g(w)/d) of* Diporeia *cultured at four temperatures and separated into four size classes.

		Size Class (mg)			
Temperature (°C)		0-2	2.1–4	4.1–6	+6.1
2	Feeding Rate	0.078 (0.057)	0.032 (0.030)	0.032 (0.050)	0.010 (0.001)
	N	21	7	22	9
	$B_{(SC)} \rightarrow$	a	b	b	b
	$B_{(T)} \downarrow$	c	c	—	c
4	Feeding Rate	0.161 (0.205)	0.054 (0.039)	0.046 (0.053)	0.017 (0.015)
	N	18	7	26	7
	$B_{(SC)} \rightarrow$	a	ab	b	ab
	$B_{(T))} \downarrow$	cd	c	—	cd
8	Feeding Rate	0.223 (0.154)	0.058 (0.066)	0.049 (0.058)	0.046 (0.051)
	N	22	10	14	11
	$B_{(SC)} \rightarrow$	a	b	b	B
	$B_{(T))} \downarrow$	de	c	—	Cd
12	Feeding Rate	0.246 (0.122)	0.198 (0.143)	0.042 (0.033)	0.153 (0.119)
	N	18	27	7	3
	$B_{(SC)} \rightarrow$	a	a	b	ab
	$B_{(T))} \downarrow$	e	d	—	d

Note: Values are means and S.D. (in parentheses). Values followed by the same letter identify a significant grouping while values with a different letter indicate significant difference (ANOVA, Bonferroni pairwise comparison, $p < 0.05$ on log transformed data).
$B_{(SC)}$: Bonferroni pairwise comparison between size classes within each temperature.
$B_{(T):}$ Bonferroni pairwise comparison between temperatures classes within each size class.

DISCUSSION

The feeding rate measured for *Diporeia* was highly variable and often had a range that included values of zero for some of the organisms at each of the sampling times. This is consistent with other field observations that *Diporeia* is an intermittent feeder (Dermott and Corning 1988, Quigley 1988). It has been suggested that part of the life history strategy for this amphipod is to feed on fresh diatom deposits to maximize production during the spring diatom bloom (Gardner *et al.* 1990). Moreover, such variability also may occur because of selectivity of feeding by the organism. *Diporeia* are selective feeders on sediment particles when presented with bulk sediment (Harkey *et al.* 1994). However, this should have been minimized in this study since the *Diporeia* were presented with only the fine fraction of sediment. The need to feed in a short-term study such as this may well be superceded by the feeding preferences of the organisms for diatoms over sediment particles.

The feeding rates observed in this work are consistent with the feeding rates measured for *Diporeia* feeding on a silt-loam soil composite (Harkey *et al.* 1994). Feeding rates also are similar to those observed for annual ingestion rates for *Diporeia* from Lake Ontario (Dermott and Corning 1988). To make this comparison, the 4°C data were employed and the size distribution of *Diporeia* in Lake Ontario was assumed to be similar to that observed for this study. After making adjustments for dry weight, the average feeding rate at 4°C from these experiments would be 0.382 (± 0.12) g DW sediment/g DW organism/d and standard errors in parenthesis. The values reported for Lake Ontario ranged from 0.211 to 0.238 g DW sediment /g DW organism/d depending on depth (Dermott and Corning 1988). Thus, the measured values from this study were consistent with other approaches for measuring feeding.

Previous reports of the reduction in feeding with increasing size were suggested from the percent gut fullness observed for field-collected organisms (Quigley 1988). The measurements for *Diporeia* confirm that feeding rate declined in a log linear fashion with larger organisms (Fig. 1). This feeding rate decline may be explained by observed declines in respiration rates of larger organisms (Landrum

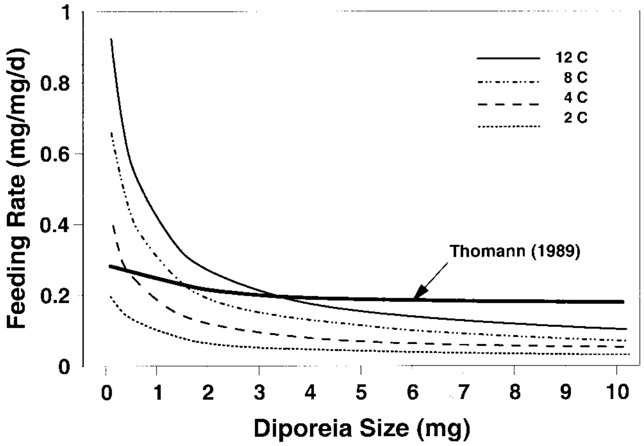

FIG. 1. The relationship between* Diporeia *feeding rates and size at four temperatures, based on equation 9 that was derived from the experimental results. Results are compared to feeding rates derived from Thomann (1989).

and Stubblefield 1991). Thus, the reduced energetic requirements for the larger organisms could result in a reduced need for feeding.

Reductions in feeding rates do need to be considered in light of the food source. It has been observed that organisms feeding on diatoms such as *Melosira* had much slower gut passage than organisms feeding on sediment (Quigley and Vanderploeg 1991). The higher food quality of diatoms met the nutritional requirements of benthic organisms faster than the organic matter in sediments. Thus, the observed feeding rates in the experiments can be considered maximal rates since organisms were feeding on sediments rather than settling diatoms in the spring and fall.

It was not surprising that feeding rates increased with increasing exposure temperature. Poikilotherms increase their metabolic rate with increasing temperature to some peak rate. Subsequent increases in temperature past peak rate generally result in reductions in metabolism and eventually death due to heat stress. Temperature related effects for uptake of contaminants from water have been observed for *Diporeia* with a Q_{10} of about 3 (Landrum 1988). The average Q_{10} for the feeding rate is a factor of 6.5. This suggests that feeding changes more rapidly than the ventilation rate over the range of temperatures from 2 to 12°C. To assess the relative importance of water versus feeding in the uptake of a chemical with a K_{ow} of 10^6, water and food inputs were estimated from the steady state models developed above (equations 5 and 7) for a chemical with a water concentration of 0.025 µg/L and water temperature of 4°C (Fig. 3). Based on model calculations, food uptake accounted for 59% (0.01 g) to 91% (0.006 g) of the total chemical concentration in *Diporeia* at steady state conditions. Similarly, Thomann *et al.* (1992) found that *Diporeia* bioconcentration of chemicals with a log K_{ow} in the range of 5.5 to 7.0 was due almost entirely to food-web transfer from the sediments as opposed to uptake from the water route.

The comparison of chemical concentrations using feeding rate calculations from Thomann *et al.* (1992) and this study reveals several important trends. The importance of calculating the chemical concentration in *Diporeia* becomes greater up the aquatic food chain. Using the parameters and assumptions given by Burkhard (1998), the bioaccumulation factor of a benthivore fish eating mostly *Diporeia* during the

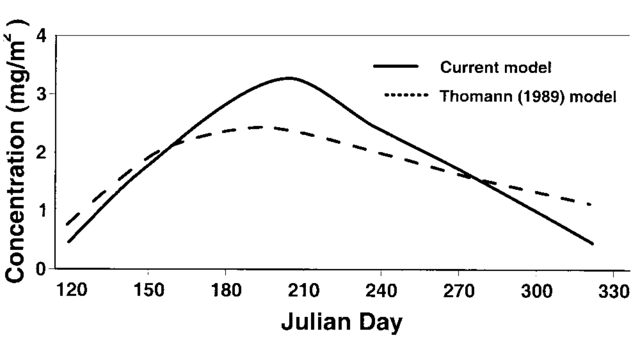

FIG. 2. Chemical concentrations based on feeding rates derived from equation 9 compared to those used by Thomann (1989).

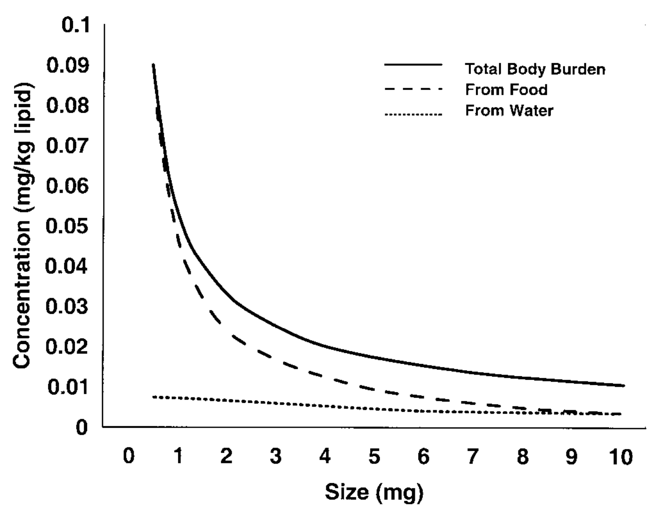

FIG. 3. The organic chemical concentrations derived from water and from food over a range of* Diporeia *sizes.

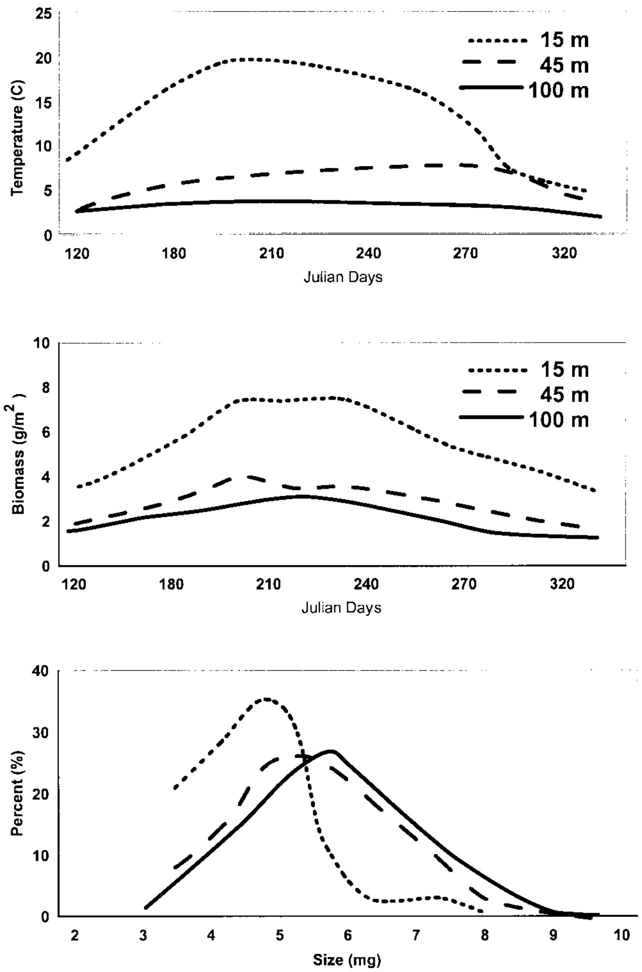

FIG. 4. Temperature, **Diporeia** *biomass, and* **Diporeia** *size distribution at three depths in Lake Michigan.*

summer would be 24 times higher based on the modified uptake model calculations compared to estimates based strictly on Thomann's (1989) model. A more complete understanding of chemical uptake in *Diporeia* emerges if these analyses are extended to more realistic environmental conditions and size distributions for *Diporeia*.

The kinetics for the uptake and accumulation of contaminants are not uniform throughout the year. Uptake rates are greatest during the summer and lowest in winter. To partially assess the importance of seasonal temperature and changing size distribution of *Diporeia*, literature values were used for temperature and different *Diporeia* size distributions from April to November (Table 1 and Figure 4) to simulate the uptake of a chemical with a concentration of 0.025 µg/L and a K_{ow} of 10^6. For the

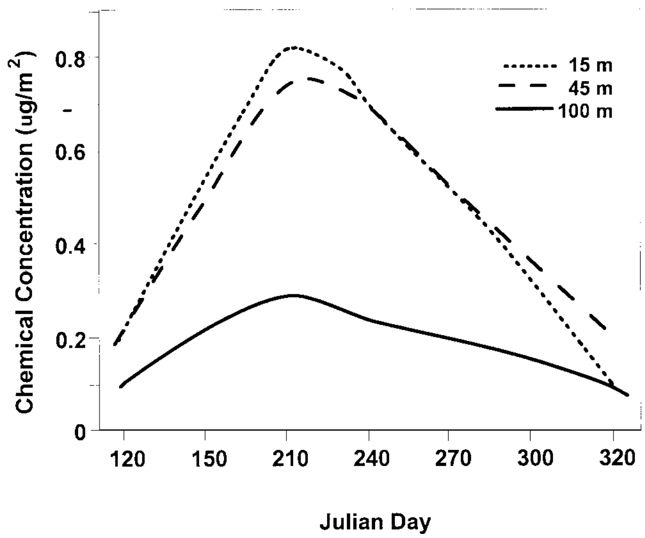

FIG. 5. **Diporeia** *chemical concentrations at three depths in southern Lake Michigan.*

simulation, densities of 3,200, 6,000, and 2,200 organisms/m^2 were used for 15, 45, and 100 m, respectively, which represents average population densities for Lake Michigan (Evans *et al.* 1990). The concentrations of contaminant in *Diporeia* biomass varied with depth. The lowest chemical concentration estimated from equation 9 was found for organisms living at 100 m (Fig. 5). Concentrations ranged from 0.1 µg/m^2 in April and October to 0.3 µg/m^2 in June. The combination of large body size, low temperatures, and low population densities would account for these values. Chemical concentrations estimated for *Diporeia* living at 45 and 15 m were approximately equal. Higher temperatures and higher frequency of smaller amphipods at 15 m compensated for the higher density of organisms at 45 m. At 15 and 45 m, concentrations were lowest in April (0.1 µg/m^2) and highest in June (0.8 µg/m^2). In June, chemical concentrations were most divergent from values found in 100 m depths. Concentrations were 2.3 and 2.9 times greater at 45 m and 15 m compared to concentrations at 100-m. These estimates of *Diporeia* concentrations would improve if other environmental factors such as depth dependent sedimentation or water movement were included in the calculations. However, even without additional enhancements to the model, these estimates provide a good indication of how different life history and environmental conditions can influence uptake of chemicals from food and water.

SUMMARY

Overall, the feeding rate on sediments was found to be consistent with other feeding studies of *Diporeia* in the Great Lakes. The feeding rates decline with increasing mass of the organism and increase with increasing temperature. These measures will allow improved parameterization of toxicokinetic models to evaluate the exposure of this organism to contaminated sediments. However, additional work on feeding behavior to account for the changes in food type will be required to fully describe the energetics from food for *Diporeia*. The incorporation of a temperature- and size-dependent model into an equilibrium model developed for benthic organisms (Thomann *et al.* 1992) is an improvement for estimating the accumulation of organic chemicals into *Diporeia*, one of the most important constituents of the Great Lakes food web. These improvements were used in this study to show the seasonal differences in chemical uptake under varying environmental conditions and life history characteristics of *Diporeia*.

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