African Journal of Aquatic Science 2004, 29(1): 91–96
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AFRICAN JOURNAL OF AQUATIC SCIENCE
ISSN 1608–5914

Biomagnification of mercury in fish from Thruston Bay, Napoleon Gulf, Lake Victoria (East Africa)

Linda M Campbell[1,3,4]*, JS Balirwa[2], DG Dixon[1] and RE Hecky[1]

[1] *Department of Biology, University of Waterloo, 200 University Avenue, Waterloo, Ontario N2L-3G1, Canada*
[2] *Fisheries Resources Research Institute, PO Box 343, Jinja, Uganda*
[3] *Canada Centre for Inland Waters, 867 Lakeshore Road, Burlington, Ontario L7R 4A6, Canada*
[4] *Current address: School of Environmental Studies, Queen's University,116 Barrie Street, Kingston, Ontario K7L 3N6, Canada*
** Corresponding author, e-mail: campbelm@biology.queensu.ca*

Received 30 September 2002, accepted in revised form 8 December 2003

Total mercury concentrations (THg) were measured in fish from Thruston Bay, Napoleon Gulf in northern Lake Victoria between 1998 and 2000. Total Hg concentrations in *Lates niloticus* (Nile perch) and *Oreochromis niloticus* (Nile tilapia) ranged from 10.6 to 77.5ng g^{-1} and from 15.0 to 44.5ng g^{-1} wet weight respectively. These concentrations are lower than in the same fish species from elsewhere in Napoleon Gulf and are in the middle of the range of THg concentrations from across Lake Victoria. The rate of THg biomagnification, as indicated by the regression slope of log-THg vs stable nitrogen isotope values (0.28), is within the ranges of biomagnification rates observed in temperate and tropical lakes, suggesting that THg is biomagnifying at a similar rate in Thruston Bay as elsewhere. The low THg concentrations in fish were attributed to the storage capacity, high oxygen concentrations and high organic matter content of the wetlands surrounding Thruston Bay. However, caution is required because the storage capacity and the methylation rates present in the wetlands of Thruston Bay are unknown and the gradual accumulation of THg contamination from other sources (e.g. atmospheric THg) may result in unexpected THg increases in the biota of this system.

Keywords: Nile perch, Nile tilapia, stable carbon isotopes, stable nitrogen isotopes

Introduction

Methylmercury (MeHg) is an environmental neurotoxicant which can biomagnify up to thousand-fold through food webs (Morel *et al*. 1998). In fish, over 90% of the total mercury (THg) is MeHg (Bloom 1992), leading to human health concerns in areas such as the Great Lakes of Africa, where fisheries and fish consumption are important. The fisheries of Lake Victoria are exceedingly important to the economies of the surrounding countries, Kenya, Tanzania and Uganda, largely through their exports to the European Union. If THg concentrations in fish were to exceed the EU marketing limit of 500ng g^{-1} wet weight (European Economic Community 16 June 1993), exports would be restricted. The World Health Organization (WHO) has recommended that at-risk groups, such as frequent fish consumers, pregnant women and young children, consume fish with no more than 200ng g^{-1} THg (World Health Organization 1990). Fortunately, THg concentrations in fish from Lakes Malawi, Tanganyika, Kivu and Victoria have consistently been below human health risk and marketing limits (Sindayigaya *et al*. 1994, Ikingura and Akagi 1996, Mhlanga 2000, Van Straaten 2000, Campbell *et al*. 2003a, Kidd *et al*. 2003). However, the water and sediment THg concentrations in Lake Victoria have been found at higher-than-expected concentrations (Campbell 2001) and there have been recent reports of elevated THg concentrations in fish from Lake Albert in northwestern Uganda (Campbell *et al*. 2001). Those indicate that low THg concentrations cannot be assumed for fish, water or sediment from any African lake and should be confirmed.

Field studies in temperate and boreal lakes in the northern hemisphere have revealed that decaying plants and the resulting increase in organic matter can lead to elevated MeHg in fish, especially in hypoxic waters (Hecky *et al*. 1991). The presence of wetlands surrounding a lake has been associated with increased Hg concentrations in fish (St Louis *et al*. 1994), presumably because wetlands typically have high organic matter and low oxygen concentrations in the overlying waters. These factors promote the methylation of Hg by anoxic bacteria, which thrive in high-organic environments, leading to higher amounts of bioavailable Hg, especially MeHg, to biota, and hence to elevated THg concentrations in fish (Hecky *et al*. 1991). Conversely, high amounts of organic matter can chelate Hg compounds and remove them from methylation pathways, thereby reducing the bioavailable fraction of THg (Morel *et al*. 1998). Bioaccumulation of Hg can occur when fish take up Hg from their food (*biomagnification*), or from water via their gills (*bioconcentration*). Typically, nearly the entire Hg

burden in fish is from their diet (Morel *et al*. 1998), therefore food web analyses can provide insights into how Hg is being biomagnified through the food chain.

The shoreline of Lake Victoria contains many types of wetlands (Balirwa 1995, 1998), which could create ideal conditions for the transformation of inorganic Hg to more biologically active forms, including MeHg. In addition, increasing eutrophication and hypoxia in the lake may be leading to increased mercury concentrations in fish. In this study, we determined THg concentrations of several important fish species from Thruston Bay, which contains a significant proportion of wetland areas, and how it biomagnified through the food web. We also compared THg concentrations in *Lates niloticus* (Nile perch) and *Oreochromis niloticus* (Nile tilapia) with published results to determine how THg concentrations in Thruston Bay fish compare with those from other regions away from wetlands.

Study area

Thruston Bay, with an area of approximately 1 650 hectares, is located in the northeastern region of Napoleon Gulf, Lake Victoria (Figure 1). The mean depth is 5m and the maximum depth is 11m. In contrast to other nearby bays (e.g. Fielding), Thruston Bay has a large littoral wetland region dominated by the macrophytes *Cyperus papyrus* (papyrus), *Phragmites mauritianus* (reeds), *Typha domingensis* (cattails), *Vossia cuspidata* (hippo grass) and *Eichhornia crassipes* (water hyacinth). Three distinct shoreline types can be distinguished, including a papyrus-dominated sub-bay (Kafunda Bay), a forested eastern shoreline and a rocky *Phragmites–Vossia* stretch to the west. Between 1996 and 1998 about 800ha of Thruston Bay was covered with thick mats of water hyacinth. However, following the impact of biological control weevils and other environmental factors, including nutrient depletion and changes in water levels, the compacted mats collapsed and sank to the bottom of the bay (Kayanja 2002). Between 1999 and 2000, dissolved oxygen (DO) levels were between 2.5–5.5mg l^{-1} (JS Balirwa, unpublished data). In December 2000, surface water quality parameters in the shallow (<4m) littoral wetland habitats of the bay were: DO, 4.9mg l^{-1}; conductivity, 110.7µs cm^{-1}; total phosphorus, 30.6µg l^{-1}; ammonia, 0.5µg l^{-1}; and chlorophyll-*a*, 64.3µg l^{-1} (JS Balirwa, unpublished data).

Methods

Between 1998 and 2000 personnel from the Fisheries Resources Research Institute (FIRRI) in Jinja set gill nets overnight at various depths in the littoral regions of Thruston Bay. See Balirwa (1998) for site and gear descriptions. Several fish species, including Nile perch, *Lates niloticus*, and Nile tilapia, *Oreochromis niloticus*, were collected (Table 1). All fish were dissected, with a 10cm^2 sample of lateral white muscle being removed from each fish, wrapped in hydrochloric acid-cleaned aluminum (Al) foil, double-wrapped in self-sealing bags and kept on ice until they could be transferred to freezers on return to FIRRI laboratories. All fish were sub-sampled for both stable isotope and mercury analyses. Three individual *Caridina nilotica*, a freshwater

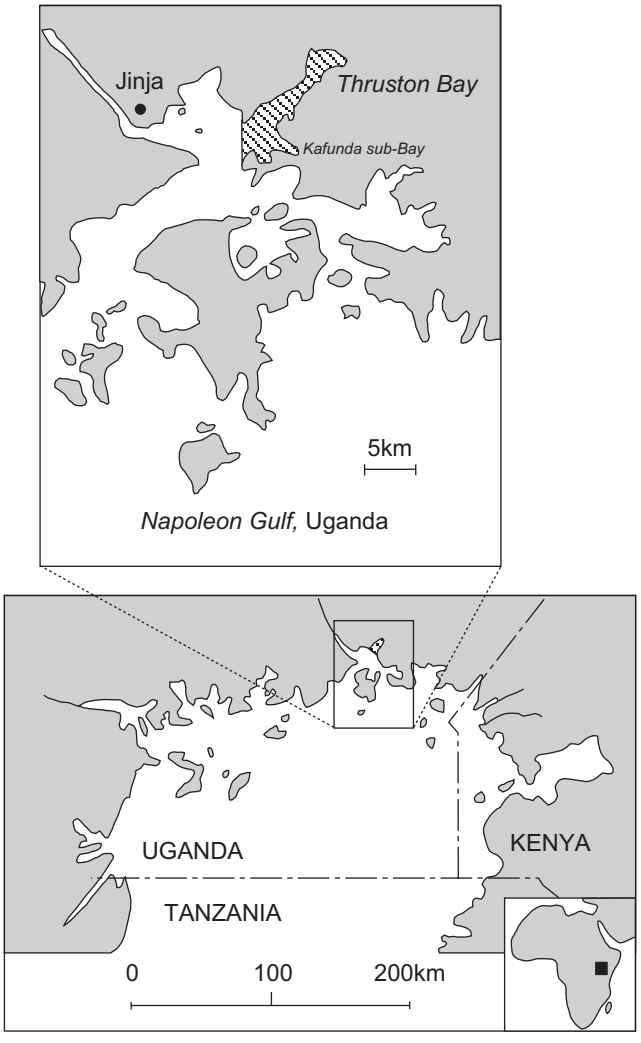

Figure 1: Map of Thruston Bay (shaded), and its location in Napoleon Gulf and Lake Victoria

atyid shrimp, were collected with dip nets and, after removing their gut contents by dissection, were pooled and wrapped in Al foil for freezing and analysis for stable isotopes.

The frozen samples were shipped to Canada. Total Hg analyses on the fish samples were performed in the clean-room laboratory of Dorset Research Centre, Ontario Ministry of the Environment, Dorset, Ontario. Dry weight samples were converted to wet-weight samples assuming 80% water (Campbell 2001). Ultra-clean protocols were employed throughout the processing (Ontario Ministry of Environment 1999) and are detailed in Campbell *et al*. (2003a*)*. The Hg concentration in each biotic sample was determined via atomic fluorescence spectroscopy using the purge-and-trap procedure (Ontario Ministry of Environment 1999). Briefly, the samples were dried, weighed and digested in 2ml of 1:4 nitric-sulphuric acid at 255°C for six hours. Also included were the National Research Council (Canada) certified reference materials, DORM-2 (4.64 ± 0.26mg Hg kg^{-1}, recovery, 110% to 125%) and DOLT-2 (2.14 ± 0.28mg Hg kg^{-1},

Table 1: Mean ± SD (with range) of total length (TL), weight (Wgt), $\delta^{15}N$, $\delta^{13}C$ and THg for fish and *Caridina nilotica* from Thruston Bay. The letter codes are used to identify the species in Figures 1 and 2. For *C. nilotica*, the n of 1 is one sample, not one organism. The subfamily (SF) Tilapiinae falls within the family Cichlidae

Taxa	Family	Code	n	TL (cm)	Wgt (g)	$\delta^{5}N$ (‰)	$\delta^{13}C$ (‰)	THg (ng g^{-1} ww)
Lates niloticus	Centropomidae	N	9	44.7 ± 24.2 (10.6–77.5)	2 029 ± 2 524 (12–6 500)	8.9 ± 1.3 (7.2–11.0)	–19.0 ± 0.9 (–20.1 to –17.7)	64.1 ± 37.8 (22.9–150.2)
Protopeterus aethiopicus	Protopteridae	A	1	72.0	450	7.8	–22.0	27.2
Clarias gariepinus	Clariidae	G	1	83.3	5 042	8.2	–24.0	29.
Haplochromine spp.	Cichlidae	H	1	16.0	62	8.1	–22.2	55.5
Oreochromis leucostictus	SF Tilapiinae	L	4	17.1 ± 0.8 (16.2–18.2)	85.8 ± 12.1 (74–102)	5.4 ± 0.3 (5.0–5.7)	–21.7 ± 1.1 (–22.9 to –20.6)	1.5 ± 0.7 (0.6–2.2)
Oreochromis niloticus	SF Tilapiinae	O	8	23.5 ± 9.8 (15.0–44.5)	421.8 ± 607.9 (66–1 870)	5.7 ± 0.6 (4.9–6.5)	–19.5 ± 1.0 (–21.6 to –18.0)	12.4 ± 8.5 (1.7–25.7)
Tilapia zillii	SF Tilapiinae	Z	1	20.5	174	4.9	–23.0	3.9
Caridina nilotica	Atyidae	C	1	–	–	3.2	–24.4	–

recovery, 97% to 120%), as well as blanks (<0.5pg total). The detection limit was 10pg total Hg per sample. Replicate samples from archived Lake Victoria Nile perch and Nile tilapia were included in every run to determine between-run variation, which was 2–7%. The results reported here were not corrected for recovery. The same methods have been successfully used in studies of Hg in Lake Victoria (Campbell *et al*. 2003a).

To determine food web structure and biomagnification rates, stable nitrogen and carbon isotope ratios were determined for the fish. Stable nitrogen ($\delta^{15}N$) and carbon ($\delta^{13}C$) isotope analysis is now a standard technique in food web studies, and has been successfully applied to aquatic ecosystem research globally. Typically, $\delta^{15}N$ values have been used to characterise relative trophic position while $\delta^{13}C$ values have been used to determine the sources and flow of carbon in a food web (Cabana and Rasmussen 1996, Hecky and Hesslein 1995). The protocols for stable isotope analyses are described in detail in Campbell *et al*. (2003a). Briefly, small sub-samples of fish muscle tissue (Table 1) and the pooled *Caridina* were dried and ground into fine powder. $\delta^{15}N$ and $\delta^{13}C$ analyses were completed concurrently using a Micromass VG – Isochrom Continuous Flow Isotope Ratio Mass Spectrometer (CF–IRMS) at the Environmental Isotope Laboratory, University of Waterloo. The ratios of stable nitrogen isotopes were measured against nitrogen gas in ambient air, as a reference, while stable carbon isotope ratios are expressed relative to a PeeDee belemnite standard. The delta notation (δ) is used to indicate the parts per thousand (‰) difference in the isotopic ratio of the sample from the reference standard according to the equation:

$$\delta^{13}C \text{ or } \delta^{15}N = [R_{sample} - R_{standard}) / (R_{standard})] \times 1\,000$$

where $R = {}^{13}CO_2/{}^{12}CO_2$ in belemnite for $\delta^{13}C$ or $R = {}^{15}N/{}^{14}N$ of N_2 in air for $\delta^{15}N$.

Analytical standards were inserted in every run and included both the International Atomic Energy Agency (IAEA) and in-house walleye and cellulose standards. Replicates of an archived Lake Victoria Nile perch sample were included in every run to determine between-run variation. Standard deviations for the standards were ±0.3‰ for $\delta^{15}N$ and ±0.2‰ for $\delta^{13}C$, and standard deviations for replicate samples were ±0.16‰ for $\delta^{15}N$ and ±0.24‰ for $\delta^{13}C$.

Results and Discussion

Total Hg concentrations ranged from 10.6–77.5ng g^{-1} in *L. niloticus*, and from 15.0–44.5ng g^{-1} in *O. niloticus* (Table 1). The lowest concentrations were generally observed for the tilapiine species (*Oreochromis leucostictus*, *Tilapia zillii*, and *O. niloticus*; Table 1). Total Hg concentrations are significantly correlated with weight for *L. niloticus* and *O. niloticus* (Table 2). The estimated total length at which THg concentrations reach the European Union marketing limit (500ng g^{-1} ww; TL_{500}) for *L. niloticus* and *O. niloticus* are much higher than seen for the same species collected in Winam or Napoleon Gulfs (Campbell *et al*. 2003a, Table 2). Since the TL_{500} values for these species exceed known maximum lengths, it is not anticipated that *L. niloticus* and *O. niloticus* from Thruston Bay would present a risk to human consumers or the commercial fisheries. Comparing the THg concentrations of these two species with other studies from across Lake Victoria, including Napoleon Gulf (Figure 2, see review by Campbell *et al*. 2003b), demonstrates that the Thruston Bay fish lie within the low to middle range of THg concentrations for the same fish species from across all of Lake Victoria.

Plotting $\delta^{15}N$ (trophic level) against $\delta^{13}C$ (carbon source) gives a visual characterisation of the food web structure (Figure 3). Nile perch usually had the highest $\delta^{15}N$ values, indicating higher trophic position than the other fish species. *P. aethiopicus* and *C. gariepinus*, both mixed piscivore/molluscivore species, and the haplochromine species had median $\delta^{15}N$ values while the tilapiine species had the lowest $\delta^{15}N$ values. *O. niloticus* and *L. niloticus* had heavier $\delta^{13}C$ values than the other species, including *P. aethiopicus*, *C. gariepinus*, *O. leucosticus* and *T. zillii*, indicating that *O. niloticus* and *L. niloticus* may rely on different carbon sources than the other fish. This has been observed in both Winam and Napoleon Gulfs, where *L. niloticus* and *O. niloticus* both tended to have heavier $\delta^{13}C$ values than other fish species (Campbell *et al*. 2003a). Both $\delta^{15}N$ and $\delta^{13}C$ are significantly correlated with total length in *L. niloticus* (Pearson correla-

Table 2: Comparisons of THg (ng g^{-1} ww) vs total length (TL) regressions for Nile perch (*L. niloticus*) and Nile tilapia (*O. niloticus*) specimens from Thruston Bay with those from Lake Victoria (Napoleon and Winam Gulfs, Campbell *et al.* 2003a). The TL_{500}, the estimated TL where the THg concentrations reach 500ng g^{-1} ww, is given

Species	Site	Slope	Intercept	r^2_{adj}	P value	TL_{500} (cm)
L. niloticus	Thruston Bay	0.002	1.481	0.51	0.029	609
L. niloticus	Winam Gulf	0.008	1.138	0.86	<0.001	195
L. niloticus	Napoleon Gulf	0.008	1.457	0.94	<0.001	155
O. niloticus	Thruston Bay	0.032	0.207	0.80	0.002	188
O. niloticus	Winam Gulf	0.020	0.393	0.99	<0.001	115
O. niloticus	Napoleon Gulf	0.020	0.920	0.94	<0.001	89

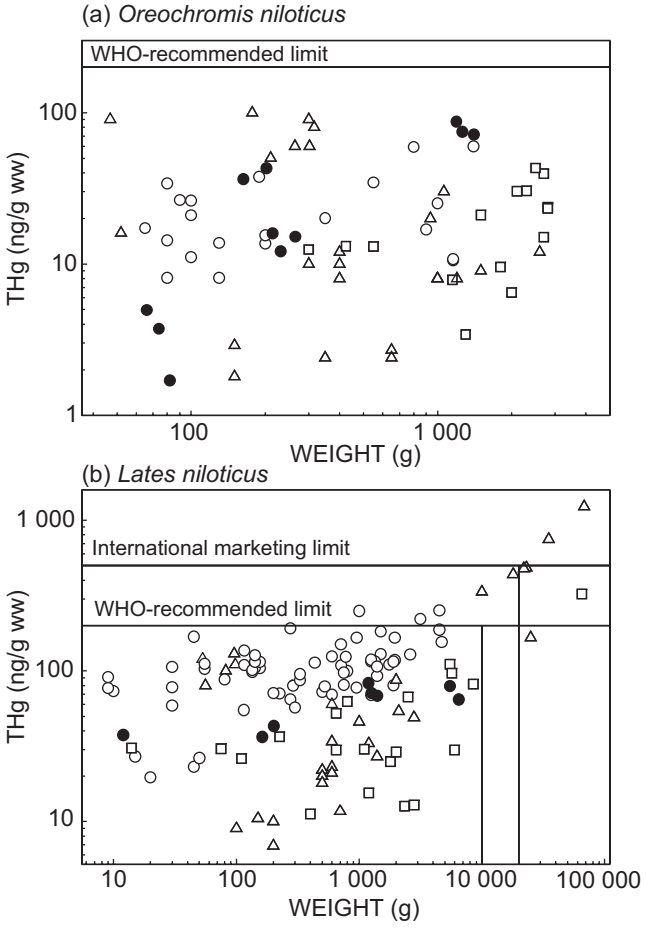

Figure 2: Total Hg in *Oreochromis niloticus* (a) and *Lates niloticus* (b) from across Lake Victoria, including fish from Thruston Bay (●), other regions in Uganda (○), Kenya (□) and Tanzania (△). Graph modified from Campbell *et al*. (2003b)

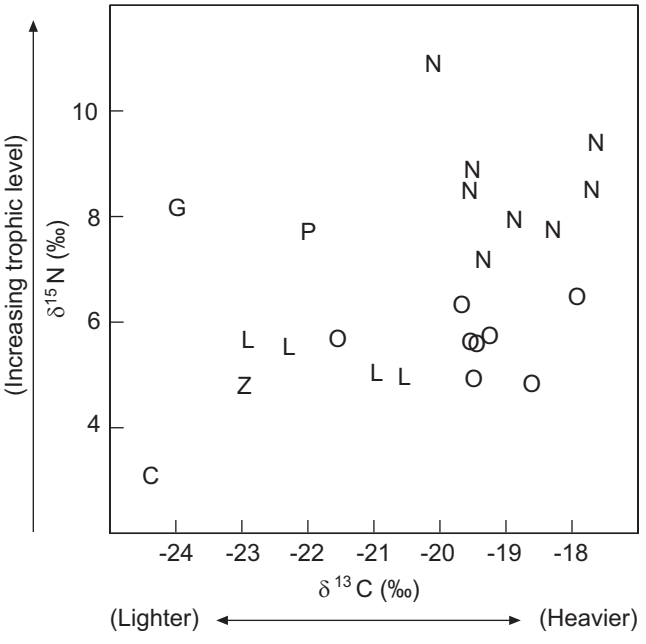

Figure 3: The relationship between $\delta^{15}N$, indicating trophic position, and $\delta^{13}C$, indicating dietary carbon source, for the fish species collected from Thruston Bay. Each taxon is represented by the code defined in Table 1

tion coefficients, 0.488 and –0.478 respectively). This is consistent with relationships seen for both Winam and Napoleon Gulfs (Campbell *et al*. 2003a) and indicates that the Thruston Bay food web structure is similar to those in other regions of Lake Victoria.

The slope of the regression of the log-transformed THg concentrations and $\delta^{15}N$ values is used as a useful quantitative measure of biomagnification rate within the food web. In Thruston Bay, THg is significantly correlated ($P \leq 0.001$) with $\delta^{15}N$ values, and the slope is 0.280 (Figure 4). Published log THg: $\delta^{15}N$ slopes from other studies range between 0.17 to 0.48 for temperate lakes (Kidd 1998). In Lake Victoria, the slopes were 0.163 and 0.165 respectively for Napoleon and Winam Gulfs (Campbell *et al*. 2003a), and in Lake Malawi, the slopes ranged between 0.23 and 0.25 for benthic and pelagic food webs (Kidd *et al*. 2003). A study of the food web in Lake Murray, Papua New Guinea, resulted in a slope of 0.28 for log MeHg:$\delta^{15}N$ (Bowles *et al*. 2001). Exact comparisons of log Hg vs $\delta^{15}N$ slopes for diverse food webs are difficult, due to the variability in data and species composition, but do give an indication of biomagnification power for different ecosystems. The similar ranges of slope values in tropical and temperate lakes suggest that THg in these freshwater ecosystems (which is not lost due to volatilisation or sedimentation) is biomagnified in fish at a relatively consistent rate.

The role of sub-tropical wetlands, such as the Florida Everglades, in accumulating and methylating mercury is still

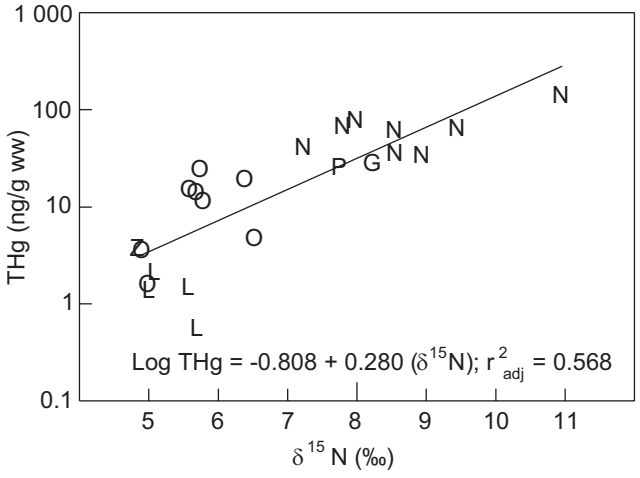

Figure 4: The relationship between THg and d^{15}N values of individual biota from Thruston Bay. Each taxon is represented by the code defined in Table 1. The regression line is indicated; the regression equation is in the text. Note the use of a log scale for THg concentrations

under extensive review (e.g. Snodgrass *et al*. 2000), and even less is known for tropical lacustrine wetlands bordering large lakes, particularly in Africa. For example, *L. niloticus* (18.9 ± 4.0THg ng g^{-1} ww) and *O. niloticus* (6.8 ± 0.5ng g^{-1} THg) from Lake Kyoga, a wetland lake surrounded by swamps, has some of the lowest measured THg concentrations measured for African fish (LM Campbell, unpublished data). The Igonzela Swamp, an important wetland feeding the Smith Arm of Mwanza Gulf in southern Lake Victoria, is situated near gold processing sites where elemental Hg is used in gold extraction (Van Straaten 2000). Upstream of the Igonzela Swamp, stream water has elevated Hg concentrations reaching 400ng l^{-1}, and THg concentrations in *C. gariepinus* and *P. aethopicus* have exceeded WHO-recommended limits of 200ng g^{-1} and international marketing limits of 500ng g^{-1}. The THg concentrations in the swamp water entering Smith Sound are ≤100ng l^{-1} and the same fish species from the vicinity are below WHO limits (Van Straaten 2000). The lower THg concentrations in fish of Thruston Bay, Lake Kyoga and Smith Sound indicate the importance of wetlands in contaminant removal.

The presence of wetlands near a lake environment can, however, be a two-edged sword. It has been demonstrated that metal loadings to wetlands near urban areas around Lake Victoria can exceed the storage capacity of these contaminated wetlands. Once wetlands are saturated with metals, further inputs can be flushed directly to the lake (Onyari and Wandiga 1989, Kiremire 1998, Makundi 2001). Studies in temperate regions have shown that the rich organic environments of wetlands can actually promote the methylation of THg, thereby increasing MeHg loading to lakes (St Louis *et al*. 1994). Methylation of Hg compounds occurs with microorganisms catalysing the reaction forming the covalent bonds between Hg and CH_4. The presence of chloride, organic compounds and sulfur influences the type of microorganisms and their ability to take up and methylate Hg (Morel *et al*. 1998). Sulfate concentrations and net sulfate reduction are low in Lake Victoria (Ramlal *et al*. 2003), which might ultimately be leading to the low Hg concentrations in fish from Thruston Bay, despite the rich organic environment of this wetland bay. However, there is no reason to consider that THg or MeHg will behave differently in tropical wetlands. The differences may lie in tropical fish bioenergetics, temperature-influenced methylation rates, higher UV radiation and the high amounts of organic matter and oxyhydroxides in Lake Victoria wetlands (Campbell *et al*. 2003b). More importantly, the daily exchange and circulation of water in shallow (<4m deep) wetland zones in Thruston Bay ensures oxygenated habitats. It is still unknown how these factors influence the Hg cycle in African lacustrine wetlands, and this issue should be included in future research.

The THg concentrations in the water of Lake Victoria (1–10ng l^{-1}) are higher than seen in other Great Lakes in the northern hemisphere (<1ng l^{-1}, Campbell *et al*. 2003b). The major inputs of THg to Lake Victoria have been estimated to derive from atmospheric sources, most probably biomass burnings (Campbell 2001). Biomass burnings emit large amounts of THg, both in Africa and globally (Brunke *et al*. 2001, Freidli *et al*. 2001), and a large proportion of global biomass fires (≥50%) are located in sub-Saharan Africa (Dwyer *et al*. 2000). Large-scale biomass burnings still occur in the Lake Victoria catchment, and the shifting conditions and possibly limited storage capacity of the Lake Victoria wetlands necessitate caution and require a better understanding of THg biogeochemistry in order to manage this situation.

In summary, THg is biomagnifying through the food web of Thruston Bay at the same rate as elsewhere, but concentrations in Nile perch and Nile tilapia tend to be lower than those in the same fish species from Napoleon Gulf. This indicates less bioavailable THg for uptake by biota, and may be due to the high amounts of organic matter, which can chelate THg, found in wetlands. The same pattern has been observed for the wetlands of Ingozela River near Mwanza Gulf and in Lake Kyoga, which may indicate that there is a large storage capacity for THg in East African wetland regions. However, this should not be taken for granted, as there is no knowledge of the limits of this storage capacity, and whether it could release biologically available Hg compounds into the lake when the capacity is exceeded. Given that THg concentrations in Lake Victoria water samples are relatively high compared to other northern Great Lakes, this issue needs to be examined in order to prevent any increases in the biota as the Lake Victoria environment changes to more hypoxic and eutrophic conditions.

Acknowledgements — This study would not have been possible without the whole-hearted support of the past Directors, Drs R Ogutu-Ohwayo and F Bugenyi, of the Fisheries Resources Research Institute, Jinja, Uganda. FIRRI technicians and staff (I Musana, M Nsega, G Magezi, E Muhumuza, J Luyiga) assisted with the sample collection and fish processing. Dr Greg Mierle lent laboratory space and the use of Hg analysis equipment in the clean room laboratory at Dorset Environmental Research Centre, Ontario Ministry of Environment. William Mark processed stable isotope samples at the Environmental Isotope Laboratory, University of Waterloo. Financial support was provided by two International

Development Research Council Doctorate Awards, an Ontario Provincial Graduate Sciences and Technology Scholarship and Davis Memorial Ecology Scholarship to LMC, as well as NSERC Research Grants to REH and DGD.

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