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# Bioaccumulation and biomagnification of mercury in African lakes: The importance of trophic status

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## HIGHLIGHTS

- We characterized Hg in water and biota from 8 East African study sites.
- Hg concentrations in fish were low and should not pose a risk to human consumers.
- Hg uptake and biomagnification rates were negatively related to trophic status.
- Growth dilution in phytoplankton and consumer trophic levels led to low fish Hg.

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## ABSTRACT

Despite the global prevalence of both mercury (Hg) contamination and anthropogenic eutrophication, relatively little is known about the behavior of Hg in eutrophic and hypereutrophic systems or the effects of lake trophic status on Hg uptake and trophodynamics. In the current study we explore Hg trophodynamics at 8 tropical East African study sites ranging from mesotrophic to hypereutrophic, in order to assess the influence of lake trophic status on Hg uptake and biomagnification. Comprehensive water, plankton and fish samples were collected for analysis of total mercury (THg) and stable carbon and nitrogen isotopic ratios. We found evidence that uptake of THg into phytoplankton tended to be lower in higher productivity systems. THg concentrations in fish were generally low, and THg trophic magnification factors (TMFs; representing the average increase in contaminant concentrations from one trophic level to the next) ranged from 1.9 to 5.6. Furthermore TMFs were significantly lower in hypereutrophic lakes than in meso- and eutrophic lakes, and were negatively related to chlorophyll *a* concentrations both across our study lakes, and across African lakes for which literature data were available. These observations suggest that THg concentrations were strongly influenced by trophic status, with year-round high phytoplankton and fish growth rates reducing the potential for high THg in fish in these productive tropical lakes.

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## 1. Introduction

Several studies over the past decade have greatly increased our understanding of mercury (Hg) concentrations and trophodynamics in arctic, temperate and tropical systems (Campbell et al., 2003a; Swanson and Kidd, 2010; Kidd et al., 2012; Clayden et al., 2013; Lavoie et al., 2013). However, it has been noted that in tropical African lakes, Hg concentrations in fish are 'anomalously' low relative to fish from temperate systems, despite total Hg (THg) concentrations in water that are often comparable (Black et al., 2011). This highlights a need for more detailed analysis of the factors that influence uptake and trophic transfer of Hg in these tropical African systems. Furthermore, the behavior of Hg in eutrophic and hypereutrophic systems (which are common in Africa), and the influence of lake trophic status on Hg trophodynamics remain poorly understood. A recent debate in the literature regarding the relationship between lake trophic status and trophic transfer of Hg (Verburg, 2014; Clayden et al., 2014) points to a clear need for robust field studies addressing this issue. Having a comprehensive understanding of the effects of trophic status on Hg uptake and biomagnification is critical, given the increasing anthropogenic eutrophication of many freshwater and coastal systems around the world, as well as ongoing recovery from eutrophication in many systems where nutrient loading has been reduced. Also, eutrophic lakes often support highly productive fisheries, which are a source of daily

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subsistence upon which riparian populations can be heavily dependent, leading to natural concern about Hg concentrations in these systems.

East Africa is home to lakes that span a wide range in trophic status, from oligotrophic (e.g. Lake Tanganyika, based on its chlorophyll concentrations; Hecky and Kling, 1981) to highly productive lakes, including both naturally hypereutrophic (e.g. Lake George) and anthropogenically eutrophied lakes (e.g. Lake Victoria). Many of these lakes can sustain perennially high standing crops of phytoplankton (Poste et al., 2013), offering a unique opportunity to explore the influence of lake trophic status on Hg uptake and trophic transfer, and in particular, to assess the potential for eutrophication-mediated biodilution (Pickhardt et al., 2002; Herendeen and Hill, 2004; Chen and Folt, 2005; Karimi et al., 2007) of Hg in tropical African lakes. Previous studies of Hg in the food webs of several sub-Saharan African lakes (including several embayments of Lake Victoria, Lake Malawi, Lake Tanganyika, Lake Chad and several smaller lakes; Table 1) have typically reported low Hg concentrations in fish (Black et al., 2011), and Hg biomagnification (Table 1) that falls within the range encountered in freshwater and marine systems worldwide (Lavoie et al., 2013).

The primary objectives of this study were two-fold: 1) to characterize bioaccumulation and biomagnification of Hg in several East African lakes spanning a range of phytoplankton biomass and productivity in the context of food web structure established through stable isotope analysis; and, in particular, 2) to explore Hg trophodynamics in tropical hypereutrophic lakes where primary productivity is high year-round. Specifically, this study will test the hypothesis that eutrophication-mediated biodilution at the base of the food web and at consumer trophic levels will lead to reduced Hg concentrations in biota from higher trophic status lakes.

In this study, we use stable carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotope analysis to characterize food web structure and trophic transfer of Hg at the study sites, using $\delta^{15}N$ as an indicator of trophic level (Minagawa and Wada, 1984; Peterson and Fry, 1987), and $\delta^{13}C$ as an indicator of primary carbon source (Cabana and Rasmussen, 1994; Hecky and Hesslein, 1995). We quantify food web biomagnification of Hg using trophic magnification factors (TMFs), defined as $10^b$, where b is the slope of the regression of log-transformed Hg concentrations against estimated trophic level (calculated based on $\delta^{15}N$ values; Borgå et al., 2012).

## 2. Materials and methods

### 2.1. Study sites and sample collection

Our study included several lakes in Uganda (East Africa), ranging in size from small crater lakes (Saka and Nkuruba) to the African Great Lakes Albert, Edward and Victoria (where two study sites were included); and ranging in trophic status from mesotrophic to hypereutrophic (Table 2, Fig. 1). These sites (excluding Lake Albert) are described in detail by Poste et al. (2013), and results of stable isotope and Hg analysis for Napoleon Gulf and Murchison Bay are reported in Poste et al. (2012).

Water, plankton, and fish samples were collected using trace-metal clean sampling techniques between September 2008 and February 2009 from all study sites except Lake Albert, where samples were collected in April–May 2007. In Lake Edward, water and plankton were collected from two sites (one nearshore site (EdK) near the inflow from Lake George, and one offshore site (EdO)), whereas for fish, Lake Edward was treated as a single site. Sample collection and analytical methodology for determination of chlorophyll *a* concentration are described in detail by Poste et al. (2013). Briefly, integrated euphotic zone water samples were collected on a monthly basis throughout the study period (except for in Murchison Bay and Napoleon Gulf, where samples were collected every two weeks), whole water was filtered through triplicate Whatman GF/F filters (nominal pore size of 0.7 μm), and chlorophyll *a* was determined fluorometrically after acetone extraction (Poste et al., 2013).

Water samples for analysis of total mercury (THg) were collected by lowering certified trace-metal clean glass bottles (VWR EP114-250A) to ~15 cm below surface and opening, filling and re-sealing at depth. Plankton samples were collected through vertical net hauls (20 μm net for phytoplankton; 80 and 153 μm nets for zooplankton) and were concentrated onto pre-combusted quartz fiber filters. Subsamples from net hauls were also preserved and examined microscopically to confirm general sample composition, and zooplankton samples containing appreciable amounts of phytoplankton were excluded from further analysis (this generally occurred where large colonial cyanobacteria were highly abundant). Fish ($n = 509$, representing 28 species from planktivores to top predators) were purchased from local fishermen and catch location was verified where possible. Sub-samples of skinless dorsolateral muscle tissue were removed from fish for stable isotope and THg analyses. When fish were too small to isolate dorsolateral muscle tissue, whole fillets of axial musculature were collected, and where this was not possible (for the cyprinid *Rastrineobola* spp. and two haplochromine cichlids from Lake Saka, which were <5 cm long), they were analyzed whole. Filters and fish samples were kept frozen until further processing.

### 2.2. Sample analysis

Sample processing, analytical methodology and quality assurance/quality control procedures (including SRMs used) for stable isotope and THg analyses for water, plankton and fish are presented in detail in Poste et al. (2012). Briefly, stable carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotopic ratios were determined for oven-dried (60 °C for 24 h) and homogenized fish and plankton samples at the Environmental Isotope Laboratory at the University of Waterloo. Samples were not acidified for removal of carbonates prior to analysis since we did not expect

**Table 1**
Review of log(THg) ~ $\delta^{15}N$ regression slopes, trophic magnification factors (TMFs) and mean Chl *a* concentrations for previous THg biomagnification studies in sub-Saharan African lakes.

| Site | Site code | Slope log(THg) ~ $\delta^{15}N$ | TMF[a] | Chl *a* (μg/L) | Source of data |
|---|---|---|---|---|---|
| Bosomtwe, benthic | $B_b$ | 0.21* | 5.3 | 10.3 | Hg: Poste et al. (2008); Chl *a*: Otu (2010) |
| Bosomtwe, pelagic | $B_p$ | 0.13** | 2.8 | 10.3 | "" |
| Nkuruba | $Nk_C$ | 0.14* | 3.0 | 6.2 | Hg: Campbell et al. (2006); Chl *a*, see Table 1 |
| Saka | $S_C$ | 0.14 | 2.9 | 90 | Hg: Campbell et al. (2006); Chl *a*, see Table 1 |
| Tanganyika | T | 0.22** | 5.6 | 0.66 | Hg: Campbell et al. (2008); Chl *a*, Pirlot et al. (2005) |
| Thruston Bay | TB[b] | 0.28** | 9.0 | 64.3 | Hg, Chl *a*: Campbell et al. (2004) |
| Napoleon Gulf | $NG_C$ | 0.16** | 3.6 | 24.7 | Hg: Campbell et al. (2003b); Chl *a*, see Table 1 |
| Winam Gulf | WG | 0.17** | 3.6 | 20 | Hg, Chl *a*: Campbell et al., 2003b |
| Malawi, benthic | $Ma_b$ | 0.25** | 7.1 | 1 | Hg: Kidd et al. (2003); Chl *a*: Guildford et al. (2007) |
| Malawi, pelagic | $Ma_p$ | 0.23** | 6.1 | 1 | "" |
| Chad, south basin | C | 0.21** | 5.2 | 5.5 | Hg: Kidd et al. (2004); Chl *a*: Lemoalle (1979) |
| Ziway | Z | 0.13** | 2.8 | 70.5 | Hg: Tadiso et al. (2011); Chl *a*: Hailu (2011) |

Statistical significance of log(THg) ~ $\delta^{15}N$ regressions is indicated as: "**" for $P < 0.01$, "*" for $P < 0.05$, and no asterisk where the relationship was not statistically significant.
[a] TMF was calculated from reported log(THg) ~ $\delta^{15}N$ regression slopes based on an assumed $^{15}N$ trophic enrichment factor of 3.4‰ per trophic level.
[b] This site was not included in the Fig. 2b regression.

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