Science of the Total Environment 493 (2014) 342–354

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Mercury biomagnification in three geothermally-influenced lakes differing in chemistry and algal biomass

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HIGHLIGHTS

- Relationships between Hg biomagnification and 11 variables in 3 lakes.
- Hg in trout too high for consumption in two geothermally-influenced lakes.
- Hg biomagnification was highest in the most eutrophic lake.
- First study to compare Hg biomagnification in lakes ranging from oligo to eutrophic.

ARTICLE INFO

Article history:
Received 28 February 2014
Received in revised form 30 April 2014
Accepted 22 May 2014
Available online xxxx

Editor: C.E.W. Steinberg

Keywords:
Hg biomagnification
Lake trophic state
Geothermal
Stable isotopes of nitrogen and carbon
Trophic position
Rainbow trout

ABSTRACT

Accumulation of Hg in aquatic organisms is influenced not only by the contaminant load but also by various environmental variables. We compared biomagnification of Hg in aquatic organisms, i.e., the rate at which Hg accumulates with increasing trophic position, in three lakes differing in trophic state. Total Hg (THg) concentrations in food webs were compared in an oligotrophic, a mesotrophic and a eutrophic lake with naturally elevated levels of Hg associated with geothermal water inputs. We explored relationships of physico-chemistry attributes of lakes with Hg concentrations in fish and biomagnification in the food web. Trophic positions of biota and food chain length were distinguished by stable isotope ^{15}N. As expected, THg in phytoplankton decreased with increasing eutrophication, suggesting the effect of biomass dilution. In contrast, THg biomagnification and THg concentrations in trout were controlled by environmental physico-chemistry and were highest in the eutrophic lake. In the more eutrophic lake frequent anoxia occurred, resulting in favorable conditions for Hg transfer into and up the food chain. The average concentration of THg in the top predator (rainbow trout) exceeded the maximum recommended level for consumption by up to 440%. While there were differences between lakes in food chain length between plankton and trout, THg concentration in trout did not increase with food chain length, suggesting other factors were more important. Differences between the lakes in biomagnification and THg concentration in trout correlated as expected from previous studies with eight physicochemical variables, resulting in enhanced biomagnification of THg in the eutrophic lake.

1. Introduction

The lakes in the Bay of Plenty region in the North Island of New Zealand (Fig. 1) are an important resource for local Māori, the indigenous people of New Zealand. For centuries the lakes and their margins were and continue to be an important source of fish, crayfish, waterfowl and plants (Hiroa, 1921; Kusabs and Quinn, 2009). The introduced rainbow trout (*Oncorhynchus mykiss*) is also the basis of a significant recreational fishery in the Rotorua district (Unwin and Image, 2003). However, these lakes are within the Taupo Volcanic Zone (TVZ) and many have elevated mercury (Hg) concentrations associated with geothermal inputs (Timperley and Vigor-Brown, 1986). Total Hg (THg) concentrations in geothermal waters in the region range from about 100 ng L^{-1} up to more than 2000 ng L^{-1} (references in Kim, 1995). The relatively high natural sources of Hg call for an improved understanding of the factors affecting accumulation and biomagnification of Hg in the food chain, to assess the risk associated with dietary consumption of fish, such as trout and smelt, and other aquatic organisms such as mussels and crayfish. We examined Hg concentrations in the food webs of three lakes with inputs of Hg from geothermal sources, Lake Rotorua, Lake Rotomahana and Lake Tarawera (Fig. 1).

While most chemicals bioaccumulate (i.e., are at higher concentrations in organisms than their surroundings), Hg biomagnifies, meaning that concentrations in tissues of biota increase as trophic position in food chains increases (Kidd et al., 1995) and also generally as organisms

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http://dx.doi.org/10.1016/j.scitotenv.2014.05.097
0048-9697/

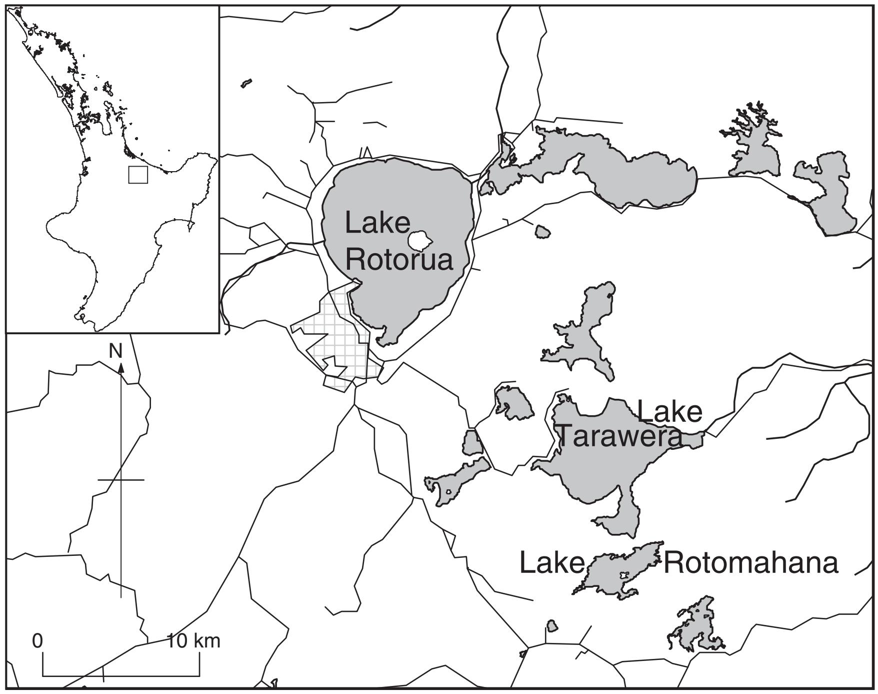

Fig. 1. The position of the lakes in the region of Bay of Plenty, with inset showing the location on the North Island, New Zealand.

get older (Jenssen et al., 2010). Thus, the consequences for health of exposure to biomagnifying chemicals are more critical for species at the top of the food chain.

Stable nitrogen isotopic ratios ($\delta^{15}N$) are useful indicators of trophic position in food webs because $\delta^{15}N$ increases along the food chain from primary producers to the top predator, due to isotopic fractionation during assimilation of the diet (Fry, 1991). We used $\delta^{15}N$ to examine the relationship between trophic position and Hg concentration in components of the food web and to infer biomagnification of Hg in the food web. Stable carbon isotopic ratios ($\delta^{13}C$) usually increase only slightly between food sources and consumers and can therefore be used as an indicator of the source of carbon for consumers (Fry, 1991; Cabana and Rasmussen, 1994).

As noted by Borgå et al. (2012), the effects of environmental factors including biomass dilution in concert on biomagnification of Hg remain insufficiently known and warrant investigation. Much of the available information of environmental effects on Hg in fish is based on data from a large number of North American lakes where Hg is mostly derived from atmospheric inputs. Various environmental variables have been shown to correlate positively (water temperature, organic matter in the sediment) or negatively (conductivity, pH, alkalinity, and concentrations of dissolved oxygen, Ca and SO_4) with Hg in fish, possibly in part resulting from effects on biomagnification (Rodgers and Beamish, 1983; Bodaly et al., 1993; Lange et al, 1993; Regnell et al., 1997; Chen et al., 2005; Lambertsson and Nilsson, 2006; Driscoll et al., 2007; Dijkstra et al., 2013). In general, results in literature are in agreement regarding the potential effects of the eight environmental variables, mentioned above, on Hg concentrations in fish.

On the other hand, the effect of productivity of pelagic primary producers (trophic state) and particularly of plankton biomass on Hg biomagnification and concentrations in fish appears more controversial. Concentrations of THg in phytoplankton, zooplankton and fish have been shown to be lower in eutrophic lakes than in oligotrophic lakes with similar contaminant loading (D'Itri et al., 1971; Pickhardt et al., 2002; Chen and Folt, 2005). This is the result of dilution by higher plankton biomass in the more eutrophic lakes. Plankton absorbs Hg. Eutrophic lakes have higher plankton biomass resulting in a reduced concentration of Hg in plankton relative to more oligotrophic lakes. This had lead to the conclusion that biomagnification of Hg is higher in oligotrophic lakes (Chen and Folt, 2005), which was supported by a significant negative relationship between biomagnification and total nitrogen (TN) concentrations (but not with phosphorus; Clayden et al., 2013). In contrast, others have shown higher Hg concentrations in fish in a eutrophic lake compared with an oligotrophic lake (Lithner et al., 2000). In addition, Kidd et al. (2012) found a positive relationship between biomagnification of Hg and total phosphorus (TP) concentrations. A meta-analysis of literature data (Lavoie et al., 2013) showed contradictory relationships between biomagnification and chlorophyll *a* concentrations (positive for THg and negative for methylmercury).

We examined whether physical, chemical and biological variables, including phytoplankton biomass (indicated by chlorophyll *a* concentrations) and nutrient concentrations, could explain differences in Hg concentrations in the food webs of the three study lakes. In particular, we examined whether biomagnification between basal resources (phytoplankton) and the top predator (rainbow trout) differed between lakes differing in chemistry and in trophic state.

2. Methods

2.1. Taupo Volcanic Zone and geothermal inputs

The TVZ is a geothermal active region which is relatively narrow (<50 km) and geologically complex, extending 250 km northeast from Mt. Ruapehu south of Lake Taupo to White Island, in the central North Island, New Zealand (Timperley and Vigor-Brown, 1986; Boothroyd, 2009). The TVZ contains a large number of rivers and lakes which are affected by geothermal inputs, including New Zealand's largest lake, Lake Taupo (616 km^2) and longest river system, the Waikato (425 km). The lake waters range in composition from that characteristic of rainfall, to salt-rich geothermal waters, to solutions with pH down to 1.8 (Timperley and Vigor-Brown, 1986). The concentrations of sodium and potassium often exceed those of calcium and magnesium in the TVZ lakes, with other chemical characteristics differing markedly from other NZ lakes (Timperley, 1987). While extremes of temperature and pH occur in some rivers and smaller lakes, with associated limits on species present in those aquatic ecosystems (Boothroyd, 2009; Duggan