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Mercury accumulation in bats near hydroelectric reservoirs in Peninsular Malaysia

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Abstract In large man-made reservoirs such as those resulting from hydroelectric dam construction, bacteria transform the relatively harmless inorganic mercury naturally present in soil and the submerged plant matter into toxic methylmercury. Methylmercury then enters food webs and can accumulate in organisms at higher trophic levels. Bats feeding on insects emerging from aquatic systems can show accumulation of mercury consumed through their insect prey. In this study, we investigated whether the concentration of mercury in the fur of insectivorous bat species was significantly higher than that in the fur of frugivorous bat species, sampled near hydroelectric reservoirs in Peninsular Malaysia. Bats were sampled at Temenggor Lake and Kenyir Lake and fur samples from the most abundant genera of the two feeding guilds—insectivorous (*Hipposideros* and *Rhinolophus*) and frugivorous (*Cynopterus* and *Megaerops*) were collected for mercury analysis. We found significantly higher concentrations of total mercury in the fur of insectivorous bats. Mercury concentrations also differed significantly between insectivorous bats sampled at the two sites, with bats from Kenyir Lake, the younger reservoir, showing higher mercury concentrations, and between the insectivorous genera, with *Hipposideros* bats showing higher mercury concentrations. Ten bats (*H.* cf. *larvatus*) sampled at Kenyir Lake had mercury concentrations approaching or exceeding 10 mg/kg, which is the threshold at which detrimental effects occur in humans, bats and mice.

Keywords Mercury · *Hipposideros* · *Rhinolophus* · *Megaerops* · *Cynopterus* · Hydroelectric reservoirs

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Introduction

Mercury (Hg) contamination has become a well-known global issue (Pacyna et al. 2006; Selin et al. 2007) as the burning of coal, creation of hydroelectric dams, metal mining and municipal waste incineration have increased and augmented the amount of inorganic mercury entering the atmosphere and water sources (Chan et al. 2003). Extensive deforestation and agricultural land use also release mercury from soils creating point sources of local, acute contamination (Barbosa et al. 2003). Lake-sediment records suggest locations distant from point source contamination can also receive significant inputs of anthropogenically released mercury due to transcontinental and global distribution of highly volatile, atmospheric mercury (Fitzgerald et al. 1998; Chan et al. 2003).

In aquatic systems, relatively harmless inorganic mercuric (Hg^{2+}) or mercurous (Hg^{+}) forms of mercury are naturally present in the substrate, but can be transformed by sulphate-reducing and iron-reducing bacteria to methylmercury

(MeHg) (Chan et al. 2003; Poulain and Barkay 2013). Significant amounts of mercury can be introduced into aquatic food webs during the flooding of forests (Barbosa et al. 2003), such as during the construction of hydroelectric dams (Bodaly et al. 1984; Stokes and Wren 1987; Ikingura and Akagi 2003). When a reservoir is created, submerged vegetation and organic material start to slowly decompose (Rodgers et al. 1995), leading to a rise in the dissolution rate of organic carbon, increased release of mercury bound to organic material and higher net mercury methylation rates (Chan et al. 2003). A deeper water column and increased decomposition creates anoxic conditions which are ideal for mercury methylation (Hylander et al. 2006). A study of reservoirs up to 67 years old suggested that it may take 20–30 years before mercury concentrations return to pre-dam levels (Hylander et al. 2006).

Methylmercury has been shown to be a potent neurotoxin in humans (Mergler et al. 2007) and other mammals including bats and otters (Basu et al. 2005; Nam et al. 2012). Central nervous system damage caused by methylmercury toxicity in mammals includes motor and sensory deficits and behavioral impairment (Wolfe et al. 1998). Increased levels of methylmercury in vertebrates have been shown to impair reproductive system function (Wada et al. 2010; Nam et al. 2012). Methylmercury is readily transferred across the placenta and can concentrate selectively in the fetal brain, causing developmental alterations leading to fetal death (Wolfe et al. 1998). Infants can also be exposed to methylmercury during lactation (Mergler et al. 2007).

Mercury biomagnifies as it moves up the food chain, with high trophic level species, such as top predators showing higher concentrations of mercury in their tissues than primary consumers, which absorb mercury (Barbosa et al. 2003; Stewart et al. 2008). Insects that have aquatic larval stages could act as biovectors, exporting methylmercury from aquatic systems upon emergence (Benoit et al. 2013; Mogren et al. 2013). The biomass of aquatic insects can reach 190 kg/ha per day in productive lake systems (Mogren et al. 2013).

Most studies of environmental mercury contamination have been conducted in temperate regions (e.g. Baxter 1977; Tweedy et al. 2013), have measured total mercury in fish (e.g. Barbosa et al. 2003), aquatic insects (e.g. Hall et al. 1998; Benoit et al. 2013); or fish-eating birds and mammals (see Chan et al. 2003 and references therein). In Malaysia, studies have examined mercury levels in fish and seafood (e.g. Bloom 1992; Agusa et al. 2005; Hajeb et al. 2009) and in humans living in coastal communities, or in fishing communities near lakes (e.g. Sivalingam and Sani 1980; Hajeb et al. 2008).

Sixty reservoirs have been created as the result of hydroelectric damming over the past 80 years in Malaysia (ICOLD 2014). Twelve more dams, slated for construction by 2020, have been planned for Malaysian Borneo alone (Herbertson 2013; Thin 2013). Despite the increasing concern regarding mercury contamination in this global biodiversity hotspot, no studies currently exist of methylmercury accumulation in non-human mammals.

One mammalian group showing potential as a model for the study of mercury contamination and bioaccumulation through trophic levels is bats (Chiroptera) (Nam et al. 2012; Yates et al. 2014). Bat assemblages occupy high and low trophic levels, are species rich and abundant, and represent several distinct feeding guilds including frugivorous and insectivorous species (Rojas et al. 2013). Insectivorous bats eat 20–50 % of their pre-feeding body mass in insects every night (Brunet-Rossinni and Austad 2004) including insects with an aquatic larval life stage (e.g. Megaloptera, Trichoptera, certain Diptera, certain Coleoptera, Neuroptera, Ephemeroptera, Odonata) and/or insects without an aquatic larval life stage (e.g. most Lepidoptera, certain Coleoptera) (Bogdanowicz et al. 1999; Fukui et al. 2006). The limited studies of the diet of insectivorous bat species found in Malaysia (*Hipposideros*, *Rhinolophus*) suggest 1–4 % of the insects consumed have an aquatic larval stage (Thabah et al. 2006; Jiang et al. 2008). If mercury is present in aquatic insect prey, there should be accumulation of mercury in the tissues of insectivorous bats. Hair and blood mercury concentration are closely correlated (Yates et al. 2014) and both are accepted as valid biomarkers of methylmercury exposure (US EPA 2001). Hair generally has a 250–300-fold higher mercury concentration than blood (Mergler et al. 2007; Wada et al. 2010) and mercury fixed in the hair at the time of collection is stable and can give a longitudinal history of blood mercury levels (US EPA 2001). To our knowledge no studies have compared mercury concentration in insectivorous and frugivorous bat species and there is only a single unpublished report of Hg concentrations in bats from Malaysia (Yates et al. 2011).

The overall objective of this study was to investigate whether the concentration of total mercury in the fur of insectivorous bat species was significantly higher than that in the fur of frugivorous bat species sampled near reservoirs created by hydroelectric damming in Peninsular Malaysia.

Materials and methods

Study area

Bats were sampled on the shores of two major hydroelectric reservoirs in Peninsular Malaysia: Temenggor Lake, Perak (N05°31′, E101°26′) and Kenyir Lake, Terengganu (N05°08′, E102°46′) (Fig. 1) between 16 and 25 July 2013.

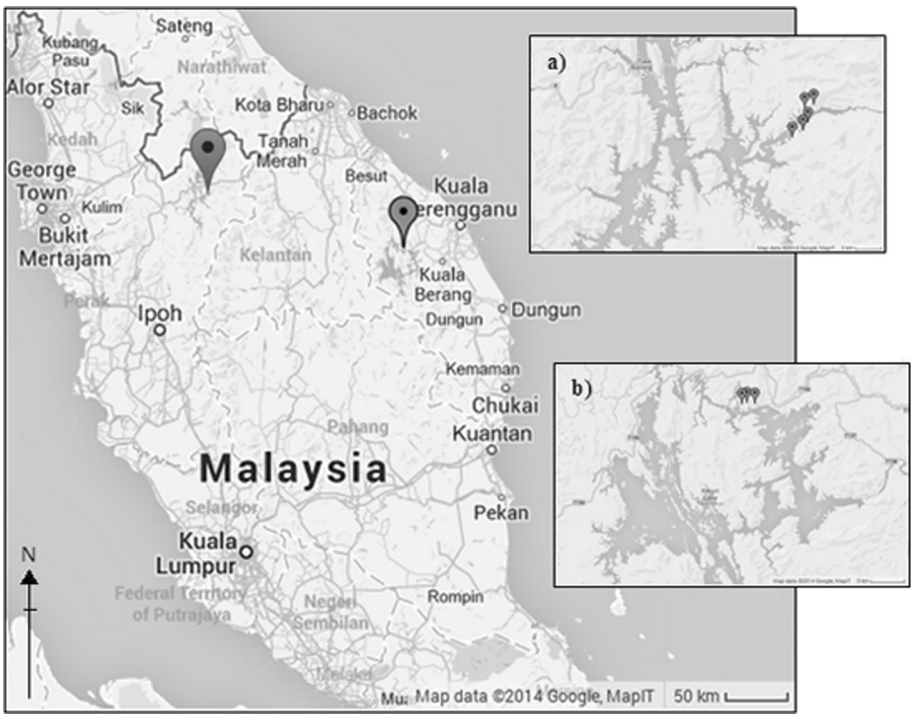

Fig. 1 Study sites in Peninsular Malaysia where bat fur was sampled for mercury analysis (2013): **a** Temenggor Lake and **b** Kenyir Lake

Temenggor Lake was created in 1979 and is the second largest man-made lake in Malaysia, covering 15,200 ha (Lin 2006) with an average depth of 127 m and average width of 537 m (Davidson et al. 1995). The reservoir is filled by two major river systems in the north, two in the east and one in the west (Norizam and Ali 2000). The lake is used as a supply for domestic water consumption (Khalik and Abdullah 2012) and is also fished by the local aboriginal community. We sampled bats along the eastern edge of Temenggor Lake (Fig. 1a). Kenyir Lake was created in 1986 and is the largest man-made lake in Malaysia covering 36,900 ha with an average depth of 37 m and a maximum depth of 145 m (Kamaruddin et al. 2011). The lake receives water from two main rivers (Rouf et al. 2010). We sampled bats along the northeastern edge of Kenyir Lake (Fig. 1b).

Capture, sample collection and handling

Bats were captured using 4 four-bank harp traps positioned across flight paths (trails, logging skids or streams) and ten mist nets set near the lake edge. Traps were set at 19:00 until 07:30 and were checked at 30 min intervals with sampling continuing until morning unless it rained. A small wing punch was collected from each captured bat into a 1.5 ml microcentrifuge tube following AMNH (2013). Hair samples were taken from each captured bat by snipping a small amount of hair (0.02 g) from the upper part of the body using stainless steel scissors. Hair was stored in a 1.5 ml microcentrifuge tube. Scissors and forceps were cleaned with alcohol and sterile tissues between bats to avoid cross-contamination. If a bat with a wing punch was captured it was treated as a re-capture (Faure et al. 2009) and not subjected to another wing punch or further hair sampling. Sex and lifestage of the captured bats were recorded. Bats were identified in the field using morphological guides (Kingston et al. 2006; Francis 2008), but given the prevalence of cryptic bat species in Malaysia (Sing et al. 2013; Wilson et al. 2014) species identification was confirmed using DNA barcoding (Francis et al. 2010), following standard methods used in previous studies (see Sing et al. 2013; Wilson et al. 2014).

Mercury analysis

Hair samples from adults of the most abundant genera of the two feeding guilds—insectivorous (*Hipposideros*, *Rhinolophus*) and frugivorous (*Cynopterus*, *Megaerops*) were selected for analysis of total mercury. We measured total mercury concentration in fur which is a standard approach, and is directly proportional to the concentration of methylmercury in the fur (Yates et al. 2014). Total mercury concentration was measured using a Milestone Direct Mercury Analyzer (DMA-80) following US EPA Method 7473 (US EPA 2007). The total mercury detection limit is 0.001 mg/kg.

Quality control included the use of standard reference materials DORM-3 (percentage recovery = 89.2–101.1 %)

and DOLT-4 (percentage recovery = 96.1–106.2 %), running method blanks, sample blanks, and sample duplicates (percentage recovery = 83.5–103.6 %), initially and then every 20 samples. The percentage recovery of spiked material was 92.7 %.

Statistical analysis

Mercury concentration was compared between bats of different genera and species (with singleton species omitted from the test) using one-way ANOVA with a post hoc Tukey HSD test; and between feeding guilds (frugivorous vs. insectivorous), sites (Temenggor Lake vs. Kenyir Lake) and sexes using two-way ANOVA with a post hoc Tukey HSD test. All statistical analyses were performed using JMP 11.1.1 (SAS Institute Inc.).

Results

Forty-one samples (nine frugivorous bats and 32 insectivorous bats) from Temenggor Lake and 87 samples (22 frugivorous bats and 65 insectivorous bats) from Kenyir Lake were analysed for mercury concentration, comprising 12 species (two genera) of insectivorous bats and three species (two genera) of frugivorous bats. Note that bat species in Malaysia are often "dark taxa", species which have been recognized and recorded previously but which have not yet been formally described (Sing et al. 2013; Wilson et al. 2014), so a few of the species are referred to using non-Linnaean species names.

Insectivorous genera (5.13 ± 3.10 SD mg/kg) had significantly higher concentrations of mercury than frugivorous genera (0.02 ± 0.01 SD mg/kg) ($F_{(3,124)} = 48.64$, $p < 00001$). The post hoc Tukey HSD test indicated that the genera *Hipposideros* (6.26 ± 2.98 SD mg/kg) and *Rhinolophus* (3.14 ± 2.22 SD mg/kg) had significantly higher concentrations of mercury than the two genera, *Megaerops* (0.023 ± 0.009 SD mg/kg) and *Cynopterus* (0.013 ± 0.006 SD mg/kg) (Fig. 2).

Hipposideros cf. *larvatus* (7.136 ± 2.546 SD mg/kg) and *Rhinolophus chiewkweeae* (7.393 ± 1.793 SD mg/kg) both had significantly higher mercury concentrations than the other insectivorous species (with singleton species omitted). There were no significant differences in mercury concentration among the frugivorous bat species (($F_{(7,113)} = 40.29$, $p < 0.0001$); Table 1).

Mercury concentrations in insectivorous bats at Kenyir were significantly higher than insectivorous bats at Temenggor ($F_{(1,124)} = 10.41$, $p = 0.0016$). Grouped separately by site, mercury concentrations in insectivorous bats were significantly higher than frugivorous bats at both sites. The interaction between guild and site was significant ($F_{(1,124)} = 10.50$, $p = 0.0015$) (Fig. 3).

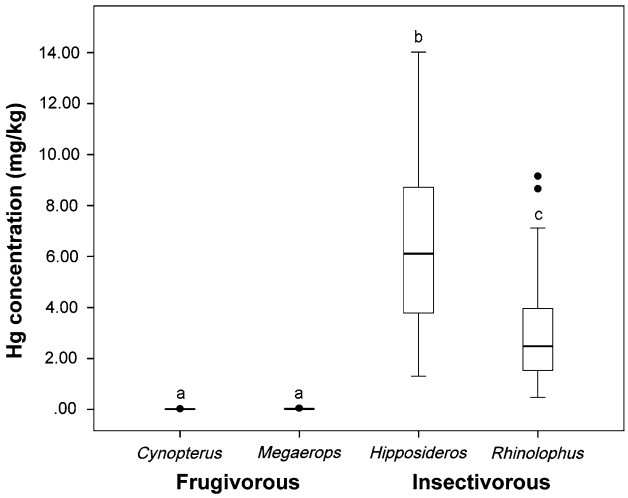

Fig. 2 Mean mercury concentration (mg/kg) in fur from bats of different feeding guilds (Frugivorous or Insectivorous) grouped by genus with standard deviation *bars*. *Different letters* above the *bars* indicate significant differences between the means based on post hoc Tukey HSD test. *Black circles* are outliers

Comparison of mercury concentrations between sex was not significant ($F_{(1,124)} = 0.0006$, $p = 0.9810$). On average, females exhibited slightly lower mercury concentrations (3.412 ± 3.669 SD mg/kg) than males (4.347 ± 3.261 SD mg/kg) (Fig. 4).

Discussion

We found that mercury concentration was significantly higher in the hair of insectivorous bats than mercury concentration in the hair of frugivorous bats sampled at two hydroelectric lakes in Peninsular Malaysia. This suggests that insectivorous bats could be accumulating methylmercury through their diet. The diet of insectivorous bats includes emergent aquatic insects (Fukui et al. 2006) that are, plausibly, contaminated with mercury from the lakes (Tremblay and Lucotte 1997; Tweedy et al. 2013). Other studies have demonstrated that aquatic insects can act as biovectors transferring sedimentary mercury from lakes into terrestrial predators on the shoreline (Haro et al. 2013; Tweedy et al. 2013). Interestingly, Reidinger (1972) argued that mercury contamination in bats probably occurred from their free water drinking source rather than through their insect prey, however, this idea has largely been abandoned (Yates et al. 2014).

Of the two insectivorous genera analyzed for mercury concentration, *Hipposideros* made up the largest proportion

Table 1 Total mercury concentrations in fur (mg/kg) for bat species sampled near Temenggor Lake and Kenyir Lake, Peninsular Malaysia

Guild	Genus	Species	*n*	Mean/ value	Standard deviation	Statistical significance[a]
Frugivorous	*Cynopterus*	*C. horsfieldii*	10	0.012	0.004	a
		C. JLE sp. A	7	0.015	0.007	a
	Megaerops	*M. ecaudatus*	14	0.023	0.009	a
Insectivorous	*Hipposideros*	*H.* cf. *bicolor*	11	2.293	0.856	a, b
		H. cf. *larvatus*	47	7.136	2.546	d
		H. cervinus	1	8.988		
		H. diadema	1	3.789		
		H. doriae	1	5.135		
		H. dyacorum	1	9.525		
	Rhinolophus	*R. affinis*	23	2.686	1.985	b
		R. chiewkweeae	2	7.393	1.793	c, d
		R. trifoliatus	7	3.969	1.987	b, c
		R. acuminatus	1	0.627		
		R. lepidus	1	1.760		
		R. luctus	1	3.132		

[a] Species that share common letters do not differ significantly. Singleton species were omitted from the post hoc Tukey HSD test

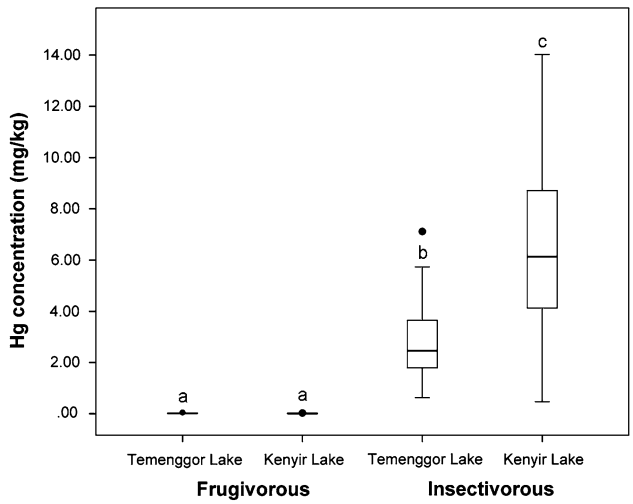

Fig. 3 Mean mercury concentration (mg/kg) in fur from bats of different feeding guilds (Frugivorous or Insectivorous) grouped by study site (Temenggor Lake or Kenyir Lake) with standard deviation bars. *Different letters above the bars* indicate significant differences between the means based on post hoc Tukey HSD test. *Black circles* are outliers

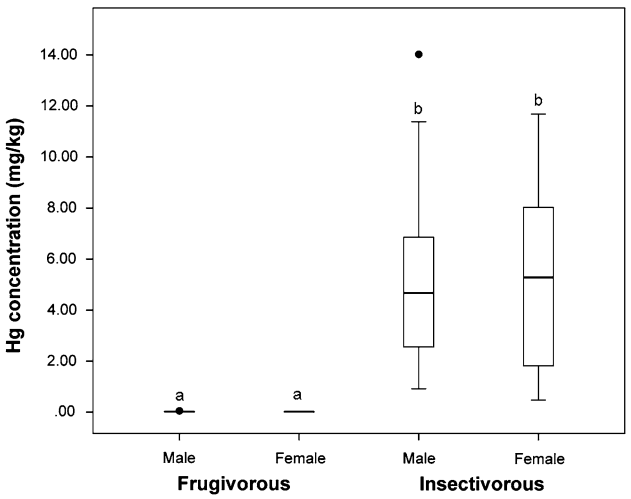

Fig. 4 Mean mercury concentration (mg/kg) in fur from bats of different feeding guilds (Frugivorous or Insectivorous) grouped by sex with standard deviation bars. *Different letters above the bars* indicate significant differences between the means based on post hoc Tukey HSD test. *Black circles* are outliers

of analyzed samples (37 %) and showed significantly higher mercury concentrations than the *Rhinolophus* bats. This could be due to a larger proportion of aquatic insects in the *Hipposideros* diet; however, records on the diet of bat species in Malaysia are limited. One study conducted in various secondary forests in Malaysia reported that 17 % of the diet of *H. larvatus s.l.* consisted of Coleoptera with the rest comprising unidentifiable insect fragments (Muda 1991). Thabah et al. (2006) reported that the diet of *H. larvatus s.l.* collected from 11 sites in the Indo-Malayan region (India, China, Myanmar, Malaysia) comprised more than 80 % coleopterans. Alternatively, the diet of *Rhinolophus affinis* from a cave in Jiangxi Province, China contained more than 50 % of Lepidoptera (Jiang et al. 2008). While the diet of insectivorous bats is likely to be opportunistic, relying on the presence and density of prey species in the bats particular foraging area, this could suggest a

larger proportion of aquatic insect species in the diet of *Hipposideros* compared to *Rhinolophus* bats, and may explain the increased exposure to mercury contamination of *Hipposideros* bats in our study areas. It is also a possibility that *Hipposideros* bats could be foraging more frequently and cover a larger area including over water bodies, but no studies have documented this yet. The use of next generation DNA sequencing (NGS) to establish the taxonomic identity of prey fragments—"DNA metabarcoding"—in feces could help resolve this question (Razgour et al. 2011). Both the frugivorous bat genera sampled, *Cynopterus* and *Megaerops*, showed significantly lower concentrations of mercury (~99 % lower than the insectivorous genera). We would expect the frugivorous bats to exhibit low concentrations of mercury because their diet likely contains little mercury. Plant roots absorb small amounts of mercury from soils and the mercury is not directly translocated from root tissues to the tissues at the top of plants (Patra and Sharma 2000) where the bats are feeding.

The comparison between the mercury concentrations in insectivorous bats collected at the two lakes showed a significantly higher concentration of mercury in bats sampled at Kenyir Lake. There was no known point source or intense agricultural activities near our study area at the lake. Kenyir Lake is shallower than Temenggor Lake, based on average depth, allowing rapid erosion of soils which increases bioavailability of mercury-rich particles to filter feeding invertebrates (Lucotte et al. 1999). Limitations on methylmercury production in Temenggor Lake might include low total mercury concentrations in the flooded soils and sediments and rapid oxidation and decay of organic matter leading to low total organic carbon in the reservoir (Ikingura and Akagi 2003). Our study area in Temenggor Lake can be considered pristine without human encroachment except for small-scale fishing and collecting of forest resources by aborigines. Ikingura and Akagi (2003) reported it was a common phenomenon for fish mercury concentration to be negatively correlated with age of reservoirs even with a difference of only 5 years. Therefore, the age of the reservoirs could potentially be a partial explanation for the differences in mercury concentration in bats from the two lakes in our study, as Kenyir Lake is 7 years younger than Temenggor Lake.

We found no significant variation in mercury concentration among sexes within each feeding guild. Similarly, no significant difference in mercury concentration between sexes was observed for both adult and juvenile bats from Oneida Lake, New York, USA (Yates et al. 2014) and Southwest England (Walker et al. 2007). Mercury contamination would not be expected to vary significantly between males and females of the same species as they live in colonies and most likely have a very similar diet.

Comparing mercury concentration in bats on a global scale, mean mercury concentrations in the fur of *Myotis lucifugus*, *M. septentrionalis*, *M. leibii* and *M. grisescens* from non point source sites in Quebec exceeded the threshold for mercury concentration in hair (10 mg/kg) (Hickey et al. 2001) at which detrimental effects occur in humans (Murata et al. 1999) and neurobehavioral disorders occurred in rodents (Burton et al. 1977). Mercury concentrations in fur from bats at point source sites in North America have been reported as 28–132 mg/kg (Wada et al. 2010; Nam et al. 2012; Yates et al. 2014) 5–30 times higher than the values for insectivorous bats in the present study. However our values are similar to the mean mercury concentration in fur from bats at 69 non-point source sites in North America (6.44 mg/kg) (Yates et al. 2014).

This is the first study comparing mercury concentrations in frugivorous and insectivorous bats at hydroelectric reservoirs. Fur from ten bats (*H.* cf. *larvatus*) sampled at Kenyir Lake had mercury concentrations approaching or exceeding 10 mg/kg which is the threshold at which harmful effects occur in mammals (Murata et al. 1999; Burton et al. 1977). Insectivorous bats consuming large numbers of prey emerging from new reservoirs could be exposed to increased, and potentially harmful, levels of mercury as has been shown previously in insectivorous songbirds (Gerrard and St. Louis 2001). A reduction in bat populations due to neurological problems as a result of mercury toxicity could have serious consequences for the local ecosystem: insectivorous bats are important for controlling insect populations and for nutrient recycling (Jones et al. 2009). Malaysia has created 60 reservoirs as a consequence of hydroelectric damming since 1920; however, the ecological consequences of hydroelectric damming have never received serious consideration. Likewise, many other countries have embraced hydroelectricity as a renewable energy resource resulting in the creation of thousands of reservoirs around the world (Barros et al. 2011).

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Conflict of interest The authors declare that they have no conflict of interest.

References

Agusa T, Kunito T, Yasunaga G, Iwata H, Subramanian A, Ismail A, Tanabe S (2005) Concentrations of trace elements in marine fish and its risk assessment in Malaysia. Mar Pollut Bull 51:896–911

AMNH (American Museum of Natural History) (2013) Wing punch and hair sampling protocols. http://research.amnh.org/vz/mammalogy/donating-bat-tissue-and-hair-samples-genomic-and-stable-isotope-studies/wing-punch-and-hair-sampling. Accessed 1 Oct 2013

Barbosa AC, de Souza J, Dórea JG, Jardim WF, Fadini PS (2003) Mercury biomagnification in a tropical black water, Rio Negro, Brazil. Arch Environ Contam Toxicol 45:235–246. doi:10.1007/s00244-003-0207-1

Barros N, Cole JJ, Tranvik LJ, Prairie YT, Bastviken D, Huszar VL et al (2011) Carbon emission from hydroelectric reservoirs linked to reservoir age and latitude. Nat Geosci 4:593–596

Basu N, Scheuhammer A, Grochowina N, Klenavic K, Evans D, O'Brien M, Chan HM (2005) Effects of mercury on neurochemical receptors in wild river otters (*Lontra canadensis*). Environ Sci Technol 39:3585–3591

Baxter RM (1977) Environmental effects of dams and impoundments. Annu Rev Ecol Syst 8:255–283

Benoit JM, Da Cato, Denison KC, Moreira AE (2013) Seasonal mercury dynamics in a New England vernal pool. Wetlands 33:887–894. doi:10.1007/s13157-013-0447-4

Bloom NS (1992) On the chemical form of mercury in edible fish and marine invertebrate tissue. Can J Fish Aquat Sci 49:1010–1017

Bodaly RA, Hecky RE, Fudge RJP (1984) Increases in fish mercury levels in lakes flooded by the Churchill River Diversion, Northern Manitoba. Can J Fish Aquat Sci 41:682–691. doi:10.1139/f84-079

Bogdanowicz W, Fenton MB, Daleszczyk K (1999) The relationships between echolocation calls, morphology and diet in insectivorous bats. J Zool 247:381–393

Brunet-Rossinni AK, Austad SN (2004) Ageing studies on bats: a review. Biogerontology 5:211–222

Burton GV, Alley RJ, Rasmussen GL, Orton P, Cox V, Jones P, Graff D (1977) Mercury and behavior in wild mouse populations. Environ Res 14:30–34

Chan HM, Scheuhammer AM, Ferran A, Loupelle C, Holloway J, Weech S (2003) Impacts of mercury on freshwater fish-eating wildlife and humans. Hum Ecol Risk Assess 9:867–883

Davidson GWH, Soepadma E, Yap SK (1995) The Malaysian heritage and scientific expedition to Belum: Temenggor Reservoir Forest, 1993–1994. Malayan Nat J 48:133–146

Faure PA, Re DE, Clare EL (2009) Wound healing in the flight membranes of big brown bats. J Mammal 90:1148–1156

Fitzgerald WF, Engstrom DR, Mason RP, Nater EA (1998) The case for atmospheric mercury contamination in remote areas. Environ Sci Technol 32:1–7

Francis CM (2008) A field guide to the mammals of South-east Asia. New Holland, London

Francis CM, Borisenko AV, Ivanova NV et al (2010) The role of DNA barcodes in understanding and conservation of mammal diversity in Southeast Asia. PLoS ONE 5:e12575

Fukui D, Murakami M, Nakano S, Aoi T (2006) Effect of emergent aquatic insects on bat foraging in a riparian forest. J Anim Ecol 75:1252–1258

Gerrard PM, St. Louis VL (2001) The effects of experimental reservoir creation on the bioaccumulation of methylmercury and reproductive success of tree swallows (*Tachycineta bicolor*). Environ Sci Technol 35:1329–1338

Hajeb P, Selamat J, Ismail A, Bakar FA, Bakar J, Lioe HN (2008) Hair mercury level of coastal communities in Malaysia: a linkage with fish consumption. Eur Food Res Technol 227:1349–1355

Hajeb P, Jinap S, Ismail A, Fatimah AB, Jamilah B, Abdul Rahim M (2009) Assessment of mercury level in commonly consumed marine fishes in Malaysia. Food Control 20:79–84

Hall BD, Rosenberg DM, Wiens AP (1998) Methyl mercury in aquatic insects from an experimental reservoir. Can J Fish Aquat Sci 55:2036–2047

Haro RJ, Bailey SW, Northwick RM, Rolfhus KR, Sandheinrich MB, Wiener JG (2013) Burrowing dragonfly larvae as biosentinels of methylmercury in freshwater food webs. Environ Sci Technol 47:8148–8156

Herbertson K (2013) Sarawak's Murum dam: What has changed since the indigenous blockade? International Rivers. http://www.internationalrivers.org/blogs/267/sarawak%E2%80%99s-murum-dam-what-has-changed-since-the-indigenous-blockade. Accessed 18 Nov 2013

Hickey MBC, Fenton MB, MacDonald KC, Soulliere C (2001) Trace elements in the fur of bats (Chiroptera: Vespertilionidae) from Ontario and Quebec, Canada. Bull Environ Contam Toxicol 66:699–706

Hylander LD, Gröhn J, Tropp M, Vikström A, Wolpher H et al (2006) Fish mercury increase in Lago Manso, a new hydroelectric reservoir in tropical Brazil. J Environ Manag 81:155–166

ICOLD (International Commission on Large Dams) (2014) Number of dams by country members. http://www.icold-cigb.org/GB/World_register/general_synthesis.asp?IDA=206. Accessed 23 Jan 2014

Ikingura JR, Akagi H (2003) Total mercury and methylmercury levels in fish from hydroelectric reservoirs in Tanzania. Sci Total Environ 304:355–368

Jiang T, Feng J, Sun K, Wang J (2008) Coexistence of two sympatric and morphologically similar bat species *Rhinolophus affinis* and *Rhinolophus pearsoni*. Prog Nat Sci 18:523–532

Jones G, Jacobs DS, Kunz TH, Willig MR, Racey PA (2009) Carpe noctem: the importance of bats as bioindicators. Endang Species Res 8:93–115

Kamaruddin IS, Kamal AM, Christianus A, Daud SK, Abit L (2011) Fish community in Pengkalan Gawi-Pulau Dula section of Kenyir Lake, Terengganu, Malaysia. J Sustain Sci Manag 6:89–97

Khalik WMAWM, Abdullah MP (2012) Seasonal influence on water quality status of Temenggor Lake, Perak. Malay J Analytic Sci 16:163–171

Kingston T, Boo Liat L, Zubaid A (2006) Bats of Krau wildlife reserve. Universiti Kebangsaan Malaysia Press, Bangi

Lin CYO (2006) Autonomy re-constituted social and gendered implications of dam resettlement on the orang asli of Peninsular Malaysia. Gend Technol Dev 10:77–99

Lucotte M, Montgomery S, Bégin M (1999) Mercury dynamics at the flooded soil–water interfacein reservoirs of Northern Quebec: in situ observations. In: Tremblay A, Lucotte M, Schetagne R, Therien N, Langlois C (eds) Mercury in the biogeochemical cycle. Springer, Berling Heidelberg, pp 165–189

Mergler D, Anderson HA, Chan LHM, Mahaffey KR, Murray M et al (2007) Methylmercury exposure and health effects in humans: a worldwide concern. Ambio 36:3–11

Mogren CL, Walton WE, Parker DR, Trumble JT (2013) Trophic transfer of arsenic from an aquatic insect to terrestrial insect predators. PLoS ONE 8:e67817. doi:10.1371/journal.pone.0067817

Muda H (1991) Diet of small mammals in the secondary tropical forest in Malaysia. J Wildl Park 11:44–52

Murata K, Weihe P, Renzoni A, Debes F, Vasconcelos R, Zino F et al (1999) Delayed evoked potentials in children exposed to methylmercury from seafood. Neurotoxicol Teratol 21:343–348

Nam DH, Yates D, Ardapple P, Evers DC, Schmerfeld J, Basu N (2012) Elevated mercury exposure and neurochemical alterations in little brown bats (*Myotis lucifugus*) from a site with historical mercury contamination. Ecotoxicology 21:1094–1101

Norizam MM, Ali A (2000) A comparative study on the secondary productivity of the littoral and limnetic zone of Temenggor Reservoir, Perak, Malaysia. J Bioscience 11:1–10

Pacyna EG, Pacyna JM, Steenhuisen F, Wilson S (2006) Global anthropogenic mercury emission inventory for 2000. Atmos Environ 40:4048–4063

Patra M, Sharma A (2000) Mercury toxicity in plants. Bot Rev 66:379–422

Poulain AJ, Barkay T (2013) Cracking the mercury methylation code. Science 339:1280–1281

Razgour O, Clare EL, Zeale MR, Hanmer J, Schnell IB, Rasmussen M et al (2011) High-throughput sequencing offers insight into mechanisms of resource partitioning in cryptic bat species. Ecol Evol 1:556–570

Reidinger RF (1972) Factors influencing Arizona bat population levels. Dissertation University of Arizona

Rodgers DW, Dickman M, Han X (1995) Stores from old reservoirs: sediment Hg and Hg methylation in Ontario hydroelectric developments. Water Air Soil Pollut 80:829–839

Rojas D, Mancina CA, Flores-Martínez JJ, Navarro L (2013) Phylogenetic signal, feeding behaviour and brain volume in neotropical bats. J Evol Biol 26:1925–1933

Rouf AA, Phang SM, Ambak MA (2010) Depth distribution and ecological preferences of periphytic algae in Kenyir Lake, the largest tropical reservoir of Malaysia. Chinese J Oceanol Limnol 28:856–867

Selin NE, Jacob DJ, Park RJ, Yantosca RM, Strode S, Jaeglé L, Jaffe D (2007) Chemical cycling and deposition of atmospheric mercury: global constraints from observations. Atmos, J Geophys Res. doi:10.1029/2006JD007450

Sing KW, Syaripuddin K, Wilson JJ (2013) Changing perspectives on the diversity of bats (Mammalia:Chiroptera) at Ulu Gombak since the establishment of the field study centre in 1965. Raffles Bull Zool S29:211–217

Sivalingam PM, Sani AB (1980) Mercury content in hair from fishing communities of the State of Penang, Malaysia. Mar Pollut Bul 11:188–191

Stewart AR, Saiki MK, Kuwabara JS, Alpers CN, Marvin-DiPasquale M, Krabbenhoft DP (2008) Influence of plankton mercury dynamics and trophic pathways on mercury concentrations of top predator fish of a mining-impacted reservoir. Can J Fish Aquat Sci 65:2351–2366

Stokes PM, Wren CD (1987) Bioaccumulation of mercury by aquatic biota in hydroelectric reservoirs: a review and consideration of mechanisms. Lead mercury arsenic environ. In: Hutchinson TC, Meema KM (eds) Lead mercury arsenic environ. Wiley, New York, pp 255–278

Thabah A, Rossiter SJ, Kingston T, Zhang S, Parsons S, Mya KM et al (2006) Genetic divergence and echolocation call frequency in cryptic species of *Hipposideros larvatus sl* (Chiroptera: Hipposideridae) from the Indo-Malayan region. Biol J Linn Soc 88:119–130

Thin LW (2013) Proposed Malaysia dams raise transparency, livelihood fears. Thomson Reuters Foundation. http://www.trust.org/item/20130521123410-dp5oe/?source=hptop. Accessed 3 Jan 2014

Tremblay A, Lucotte M (1997) Accumulation of total mercury and methyl mercury in insect larvae of hydroelectric reservoirs. Can J Fish Aquat Sci 54:832–841

Tweedy BN, Drenner RW, Chumchal MM, Kennedy JH (2013) Effects of fish on emergent insect-mediated flux of methyl mercury across a gradient of contamination. Environ Sci Technol 47:1614–1619

US EPA (Environmental Protection Agency) (2001). Water quality criterion for the protection of human health: methylmercury, final. EPA-823-R-01-001. Washington. http://www.epa.gov/waterscience/criteria/methylmercury/document.html. Accessed 17 Feb 2013

US EPA (Environmental Protection Agency) (2007). Mercury in solids and solutions by thermal decomposition, amalgamation, and atomic absorption spectrophotometry. EPA Method 7473. http://www.epa.gov/osw/hazard/testmethods/sw846/pdfs/7473.pdf. Accessed 2 May 2014

Wada H, Yates DE, Evers DC, Taylor RJ, Hopkins WA (2010) Tissue mercury concentrations and adrenocortical responses of female big brown bats (*Eptesicus fuscus*) near a contaminated river. Ecotoxicology 19:1277–1284

Walker LA, Simpson VR, Rockett L, Wienburg CL, Shore RF (2007) Heavy metal contamination in bats in Britain. Environ Pollut 148:483–490

Wilson JJ, Sing K-W, Halim MRA, Ramli R, Hashim R, Sofian-Azirun M (2014) Utility of DNA barcoding for rapid and accurate assessment of bat diversity in Malaysia in the absence of formally described species. Genet Mol Res 13:920–925

Wolfe MF, Schwarzbach S, Sulaiman RA (1998) Effects of mercury on wildlife: a comprehensive review. Environ Toxicol Chem 17:146–160

Yates DE, Kunz TH, Evers DC, Divoll T (2011) Assessment of mercury accumulation in bat fur from 8 countries around the world. Poster presented at The 10th international conference on mercury as a global pollutant, Halifax, Nova Scotia

Yates DE, Adams EM, Angelo SE, Evers DC, Schmerfeld J, Moore MS et al (2014) Mercury in bats from the northeastern United States. Ecotoxicology 23:45–55