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Enhanced Mercury Accumulation in Riparian Spiders: An Evidence of Insects' Emergence Effect in Aquatic and Upland Terrestrial Crossed Habitat

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Abstract

Many studies have focused on mercury (Hg) accumulation in both aquatic and terrestrial organisms, but the effects of aquatic Hg on terrestrial organisms have rarely been documented. Here we report the accumulation of Hg in two species of spiders, *Argiope bruennichi*, inhabiting paddy fields, and *Nephila clavata*, inhabiting small forests in the riparian zones of two hydroelectric reservoirs in Guiyang, southwest China. The mean concentration of total mercury (THg) was higher in *N. clavata* (0.38 mg kg^{-1}) than in *A. bruennichi* (0.20 mg kg^{-1}). The monthly average THg in *N. clavata*, collected consecutively from May to October, and the highest values for THg in June (1.2 mg kg^{-1}) could be related to the emergence of aquatic insects during early summer, suggesting that emerging insects play a crucial role in the accumulation of Hg in riparian spiders. The high values could also be attributable to the different times of spider sampling or individual differences.

Keywords Mercury · Bioaccumulation · Riparian spider · Emergence

Transfer of pollutants in the environment is a physical process, although recent studies have shown that biological transfer is a significant factor regulating the exposure of environments or biota beyond polluted areas to pollutants (Kraus 2019). The transfer of pollutants from aquatic to terrestrial systems has been closely examined because aquatic systems bioaccumulate many contaminants from natural and anthropogenic sources (Ali et al. 2018). Aquatic insects emerging from polluted systems contain elevated concentrations of persistent pollutants (Naslund et al. 2020) and transfer significant amounts of these pollutants to terrestrial food webs (Nasri et al. 2017). Therefore, it is essential to understand the influence of these insects on the accumulation of pollutants in terrestrial systems.

Spiders are sensitive to pollutants in their habitats and can accumulate elevated levels of heavy metals, making them good indicators of pollutant accumulation in different habitats (Żmudzki et al. 2012) and of heavy metal contamination in the soil and air (Jung et al. 2012). The exposure of spiders to high levels of heavy metals causes no physiological toxicity because they synthesize metallothionein in response to metal exposure, which binds heavy metals and deposits them as intracellular granules in the midgut gland (Babczyńska et al. 2011).

Mercury (Hg) is a significant widespread contaminant in the environment, as it is transferred in its elemental form through atmospheric cycling (Tartu et al. 2013). Once Hg enters an aquatic ecosystem, it is methylated by bacteria and biomagnified in food chains, posing an exposure risk to humans and wildlife (Sandheinrich and Wiener 2011). The biogeochemical cycling of Hg in aquatic systems has been studied over several decades since the notorious Minamata disease occurred in Japan (e.g., Pack et al. 2014; Pinedo-Hernández et al. 2015). This research has confirmed that Hg can be significantly bioaccumulated and biomagnified in aquatic food chains, causing high levels of Hg in apex predators. Many studies have focused on Hg accumulation

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in terrestrial organisms and have reported the occurrence of accumulation and biomagnification in terrestrial food chains (Mallory et al. 2018; Rutkowska et al. 2019). However, few studies have reported the effects of aquatic Hg on terrestrial organisms (Cristol et al. 2008; Kraus 2019).

Riparian spiders are vital predators of insects emerging from aquatic systems, and they usually contain high levels of pollutants (Ballinger et al. 2006). Previous studies investigating Hg in spiders that feed on emergent aquatic insects have indicated that the insects have a considerable influence on Hg concentrations in spiders (Tweedy et al. 2013; Chaves-Ulloa et al. 2016). Studies have shown that spiders may be vectors by which Hg is transferred to higher trophic levels in terrestrial food chains (Abeysinghe et al. 2017; Luo et al. 2020). However, there has been little research on how spiders living in riparian areas transfer mercury from aquatic ecosystems to terrestrial ecosystems.

We hypothesized that the change of mercury exposure in riparian spiders could be explained by the spatial and temporal differences of food sources and species, with higher mercury exposure in individuals that are more dependent on aquatic insects. In this study, the spatial and temporal characteristics of total mercury (THg) accumulation in riparian spiders were investigated. Our objectives were (1) to determine THg levels and distribution in riparian spiders; and (2) to clarify the temporal trends in THg levels in riparian spiders to assess the influence of emergent aquatic insects.

Materials and Methods

Baihua Reservoir (BHR, 26°35′–26°42′ N, 106°27′–106°34′ E) and Hongfeng Reservoir (HFR, 26°24′–26°34′ N, 106°20′–106°26′ E) in Guiyang city, capital of Guizhou Province, southwest China, were selected as the study areas. Both are water sources for the residents of the city. The study region is a karst area that is characterized mainly by limestone and dolomite, and it has intricate geography with different land uses including intensive agriculture, industrial facilities, residential buildings, and decentralized seminatural forests (Yan et al. 2013; Tao 2017). The region has a subtropical humid climate with cloudy and rainy weather throughout the year and an average annual air temperature of 13.8°C (He et al. 2008; Long et al. 2018).

BHR covers a surface area of 14.5 km^2, with a maximum depth of 45 m and a capacity of 1.82×10^8 m^3 (Tian et al. 2012). It is a multifunctional reservoir, supplying drinking water and controlling flooding, with developing fisheries, sightseeing tours, and hydroelectric generation. It has four annual hydrological periods: a low water period from December to March, a storage period from April to May, a flood period from June to August, and a fluctuation period from September to November (Wang et al. 2012; Tao 2017). At one point, BHR was affected by Hg-contaminated discharge from the Guizhou Organic Chemical Plant (GOCP), which used an Hg catalyst to produce acetic acid. Approximately 140 tonnes of metal Hg were released into the reservoir from GOCP (Horvat et al. 2003; Zhou et al. 2009), causing the sediments to be heavily contaminated with Hg (Yan et al. 2008).

HFR lies upstream from BHR and has similar climatic and hydrological conditions. It covers a surface area of 57.2 km^2, with a maximum depth of 45 m and a capacity of 7.53×10^8 m^3 (Zheng et al. 2019). HFR was once affected by the Qingzhen coal-fired power plant, the Guizhou Chemical Fertilizer Plant, an iron mine, a coal mine, and cement plants (Zhou et al. 2009). The main sources of Hg supplied to HFR were industrial discharge and atmospheric deposition (He et al. 2008). Like BHR, HFR has multiple functions: supplying drinking water and controlling flooding, developing fisheries, sightseeing tours, and hydroelectric generation.

Spatial sampling campaigns in the riparian regions of both BHR and HFR and a successive temporal sampling campaign at a small riparian forest at BHR were conducted in 2018 (Fig. 1). The samples consisted of spiders (n = 143), surface soils (n = 101), plant leaves (n = 101) and surface water (n = 124) from each sampling site, and all sites are set randomly and located on the shore of the lake. Spatial sampling was conducted at 14 sites:11 rice paddy fields and 3 forests. Two riparian spider species were collected, *Nephila clavata* (n = 87) from forests and *Argiope bruennichi* (n = 56) from rice paddy fields. Surface soil samples and leaves of rice, *Alternanthera philoxeroides*, and *Pteris nervosa* were collected at each spider sampling site. Surface water samples were collected from the two reservoirs, with 2 ~ 3 water samples collected at each site.

After collection, all spider samples were transported to the laboratory, and their weights were recorded. Then washed with deionized water and placed in a freezer at − 80°C until further process. The soil samples were dried at room temperature, ground to a homogenous powder with a mortar and pestle, passed through a 200-mesh nylon sieve, and stored in polythene bags. The leaves were rinsed with deionized water, dried in a freeze dryer at − 50°C, ground to a homogenous powder, and stored in polythene bags. The water samples were collected in borosilicate glass bottles and ultrapure concentrated HCl (0.4%, v/v) was added in situ; then the samples were stored in a refrigerator at 4°C before Hg analysis.

Successive temporal sampling was conducted from May to October 2018 at the end of each month to better understand the effect of the emergence of aquatic insects on Hg accumulation in spiders. In total, 60 spiders (*N. clavata*) were collected in May (n = 8), June (n = 12), July (n = 13), August (n = 12), September (n = 8), and October (n = 7).

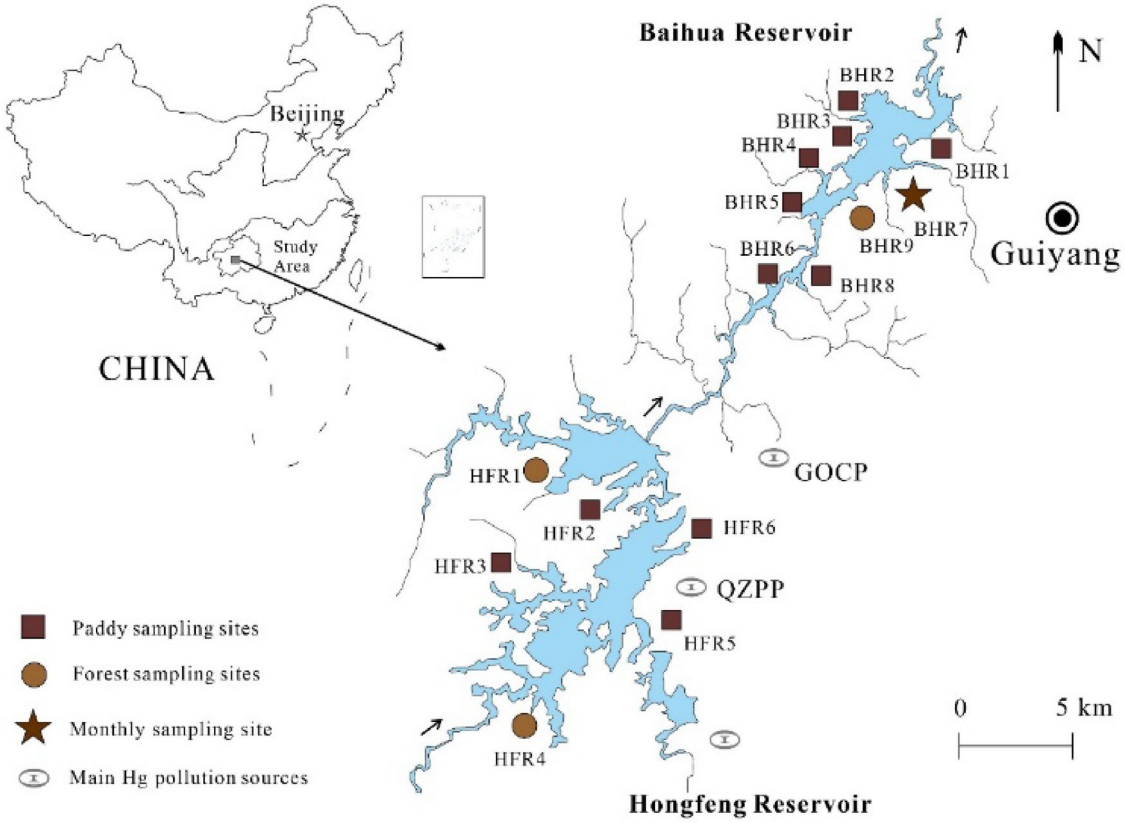

Fig. 1 Sampling sites

Each whole individual spider was digested in 5 mL of HNO_3 for 3 h at 95°C in a water bath. The THg in the samples was measured using cold vapor atomic fluorescence spectrophotometry (CVAFS, Brooks Rand Model III, USA) following Method 1631E (US EPA 2002). Approximately 0.06 g of each dry plant sample was weighed into a combustion boat and directly measured using a DMA-80 Direct Mercury Analyzer (Milestone, Italy) with a detection limit of 5×10^{-4} ng g^{-1}. Approximately 0.04 g of each soil sample was weighed and analyzed in the same way as the plant samples. The soil pH was measured using an electrode according to the national standard method (NY/T 1377–2007). After BrCl oxidation, approximately 80 mL of each water sample was reduced with $SnCl_2$, and then analyzed using CVAFS according to method 1631e of the United States Environmental Protection Agency (US EPA 2002).

Quality assurance and quality control (QA/QC) were performed using method blanks, duplicates, matrix spikes, and certified reference materials (CRMs). As CRMs, yellow-red soil (GBW07405; China Standard Material Research Center, Beijing, China), citrus leaves (GBW10020; Institute of Geophysical and Geochemical Exploration, Chinese Academy of Geological Sciences, Langfang, China), and human hair (GBW09101b; Shanghai Institute of Applied Physics, Shanghai, China) were used for the soil, leaves, and spider samples, respectively.

The relative standard deviations (RSD) of the duplicates were < 10%. The measured THg in human hair was 1.03 ± 0.03 mg kg^{-1}, which was consistent with the certified value of 1.06 ± 1.03 mg kg^{-1}. The matrix spike recoveries varied from 95% to 100% for THg in the spider samples. The THg determined in the citrus leaves and yellow–red soil (CRMs for the plant and soil samples, respectively) were 0.16 ± 0.01 mg kg^{-1} (certified value 0.15 ± 0.05 mg kg^{-1}) and 0.30 ± 0.01 mg kg^{-1} (certified value 0.29 ± 0.06 mg kg^{-1}), respectively, confirming that the Hg measurements were reliable The matrix spike recoveries ranged from 90% to 97% for THg in the water samples.

All data analyses employed Microsoft Excel 2013 (Microsoft Corporation, WA, USA) or SPSS 25 (International Business Machines Corporation, USA). All figures were plotted using Origin 2021 (OriginLab Corporation, USA) or CorelDraw X7 (Corel Corporation, Canada).

Results

The THg concentrations in all soil samples varied from 0.05 to 0.96 mg kg^{-1}, and the mean value was 0.22 ± 0.18 mg kg^{-1} (n = 101; Tables 1 and 2). Paddy soils showed an average of 0.32 ± 0.25 mg kg^{-1}, with a range of 0.11–0.96 mg kg^{-1}, which was higher than the average of 0.19 ± 0.12 mg kg^{-1} (range 0.05–0.68 mg kg^{-1}) for forest soils. HFR had an average THg of 0.48 ± 0.27 mg kg^{-1}, which was higher than the average THg of 0.18 ± 0.11 mg kg^{-1} in BHR. The peak values of THg generally occurred at sampling sites at HFR, including HFR2, HFR4, and HFR6. Soils from BHR showed a slightly higher mean pH (5.9 ± 0.38) than soils from HFR (5.2 ± 0.44).

The THg concentrations in all leaves ranged from 0.01 to 0.18 mg kg^{-1}, and the mean value was 0.04 ± 0.03 mg kg^{-1} (n = 101; Tables 1 and 2). Rice leaves had an average of 0.03 ± 0.02 mg kg^{-1} THg, with a range of 0.02–0.07 mg kg^{-1}, which was lower than the average of 0.05 ± 0.03 mg kg^{-1} (range 0.01–0.18 mg kg^{-1}) for forest leaves (*Alt. philoxeroides* and ferns). Leaves from HFR had an average THg of 0.06 ± 0.03 mg kg^{-1}, higher than that of leaves from BHR (0.04 ± 0.02 mg kg^{-1}). The peak concentrations of THg were sampled at HFR1 and HFR4 and the lowest concentrations were sampled at BHR, including BHR9, BHR3, and BHR4.

The THg concentrations in the surface water samples varied from 1.8 to 56 ng L^{-1}, and the mean value was 8.4 ± 8.0 ng L^{-1} (n = 124; Tables 1 and 2). Water from BHR showed an average of 9.1 ± 8.9 ng L^{-1}, with a range of 1.8–56 ng L^{-1}, which was higher than the average at HFR (6.1 ± 2.7 ng L^{-1}, range 2.6–18 ng L^{-1}). The highest values of THg were observed at BHR8 and BHR9.

The THg concentrations in *N. clavata* were in the range of 0.07–1.3 mg kg^{-1}, with an average of 0.38 ± 0.27 mg kg^{-1} (n = 27). *Nephila clavata* from HFR showed average THg of 0.51 ± 0.29 mg kg^{-1}, with a range of 0.21–1.3 mg kg^{-1}, which was about two times higher than the average in spiders from BHR (0.22 ± 0.09 mg kg^{-1}, range 0.07–0.36 mg kg^{-1}; Fig. 2). The THg concentration in *N. clavata* varied spatially among the sampling sites ($p < 0.05$). The highest THg in *N. clavata* was observed at HFR1, whereas the lowest THg in *N. clavata* was observed at BHR9. Similarly, the THg concentrations in *A. bruennichi* ranged from 0.01 to 0.98 mg kg^{-1}, with an average of 0.20 ± 0.20 mg kg^{-1} (n = 56). The THg levels were higher in *A. bruennichi* from HFR (0.26 ± 0.22 mg kg^{-1}, range 0.08–0.98 mg kg^{-1}) than in those from BHR (0.16 ± 0.17 mg kg^{-1}, range 0.01–0.93 mg kg^{-1}; Fig. 2). The highest THg in *A. bruennichi* was observed at HFR2 and the lowest at BHR2. However, no significant differences in the THg concentrations

Table 1 Spider, soil, plant and water of THg on HFR

		HFR1	HFR2	HFR3	HFR4	HFR5	HFR6
Spider (mg kg^{-1})	Range	0.25–0.77	0.10–0.98	0.08–0.52	0.21–1.30	0.09–0.27	0.14–0.66
	AM ± SD	0.40 ± 0.18	0.33 ± 0.37	0.25 ± 0.15	0.69 ± 0.35	0.18 ± 0.07	0.29 ± 0.25
Soil (mg kg^{-1})	Range	0.19–0.23	0.48–0.74	0.11–0.24	0.42–0.53	0.96–0.96	0.58–0.61
	AM ± SD	0.21 ± 0.02	0.64 ± 0.14	0.17 ± 0.07	0.47 ± 0.06	0.96 ± 0.00	0.59 ± 0.02
Plant (mg kg^{-1})	Range	0.073–0.14	0.038–0.052	0.048–0.075	0.018–0.12	0.035–0.060	0.025–0.033
	AM ± SD	0.094 ± 0.04	0.043 ± 0.01	0.062 ± 0.01	0.056 ± 0.05	0.048 ± 0.14	0.029 ± 0.00
Water (ng L^{-1})	Range	5.0–5.7	6.9–9.4	4.2–6.3	5.0–8.0	3.5–7.2	5.1–5.7
	AM ± SD	5.5 ± 0.43	8.2 ± 1.7	5.3 ± 1.1	6.5 ± 2.1	6.5 ± 2.1	5.5 ± 0.36

Table 2 Spider, soil, plant and water of THg on BHR

		BHR1	BHR2	BHR3	BHR4	BHR5	BHR6	BHR8	BHR9
Spider (mg kg^{-1})	Range	0.02–0.55	0.01–0.31	0.02–0.11	0.05–0.93	0.07–0.37	0.02–0.20	0.09–0.33	0.07–0.36
	AM ± SD	0.22 ± 0.24	0.12 ± 0.14	0.08 ± 0.04	0.23 ± 0.34	0.15 ± 0.11	0.11 ± 0.07	0.20 ± 0.08	0.22 ± 0.09
Soil (mg kg^{-1})	Range	0.22–0.25	0.11–0.25	0.16–0.19	0.29–0.31	0.13–0.15	0.13–0.17	0.14–0.18	0.05–0.41
	AM ± SD	0.24 ± 0.02	0.16 ± 0.08	0.17 ± 0.02	0.30 ± 0.01	0.14 ± 0.01	0.15 ± 0.02	0.16 ± 0.02	0.16 ± 0.10
Plant (mg kg^{-1})	Range	0.026–0.027	0.025–0.029	0.021–0.025	0.021–0.025	0.020–0.030	0.021–0.027	0.025–0.073	0.011–0.068
	AM ± SD	0.026 ± 0.01	0.027 ± 0.01	0.023 ± 0.01	0.022 ± 0.01	0.025 ± 0.01	0.023 ± 0.01	0.044 ± 0.03	0.037 ± 0.02
Water (ng L^{-1})	Range	3.8–8.4	2.8–4.2	4.6–7.7	5.9–27	4.7–5.8	4.8–5.5	4.3–4.4	5.4–37
	AM ± SD	6.1 ± 3.2	3.2 ± 0.79	6.3 ± 1.5	14 ± 11	5.2 ± 0.59	5.2 ± 0.40	4.4 ± 0.08	17 ± 10

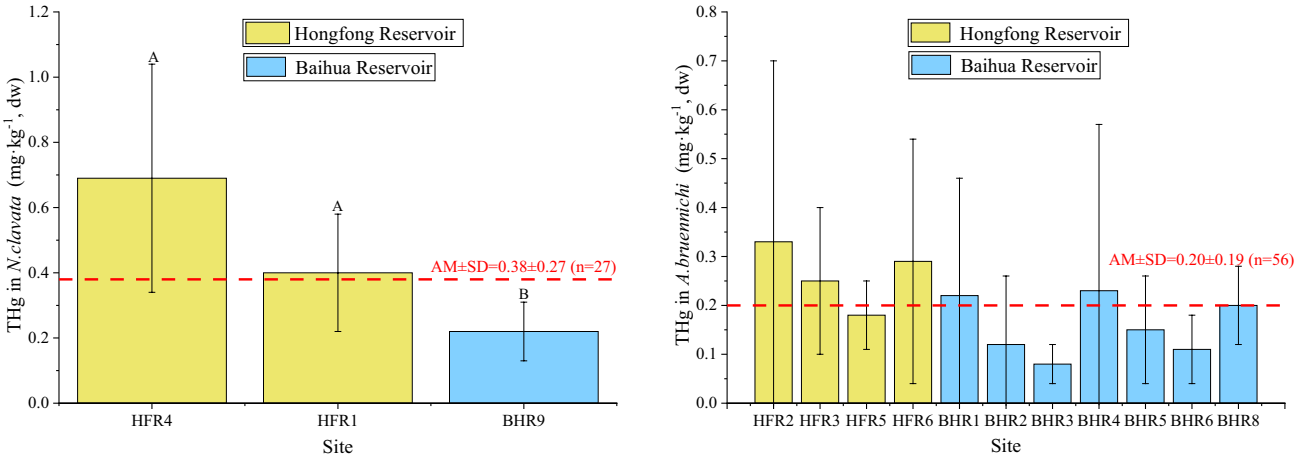

Fig. 2 Total mercury (THg) concentrations in spiders from Baihua Reservoir (BHR) and Hongfeng Reservoir (HFR). Significant differences in mean THg concentration on sites are indicated by different upper-case letters. THg concentration in *A. bruennichi* did not differ between sample locations

Table 3 Weight and THg concentration of *N. clavata*

		May	June	July	August	September	October
Body weight	Range	0.025–0.08	0.016–0.02	0.03–0.07	0.12–0.58	0.42–1.8	0.33–0.89
	AM ± SD	0.03 ± 0.03	0.08 ± 0.01	0.05 ± 0.02	0.24 ± 0.14	0.94 ± 0.49	0.65 ± 0.21
THg (mg kg^{-1})	Range	0.39–1.0	0.31–2.0	0.19–0.71	0.07–0.36	0.11–0.25	0.19–0.47
	AM ± SD	0.64 ± 0.23	1.2 ± 0.56	0.37 ± 0.15	0.22 ± 0.95	0.17 ± 0.05	0.33 ± 0.12

of *A. bruennichi* were detected among the sampling sites ($p > 0.05$).

The THg concentrations in *N. clavata* collected consecutively from May to October are listed in Table 3, and values ranged from 0.07 to 2.0 mg kg^{-1}. The highest average THg concentration (1.2 ± 0.56 mg kg^{-1}, range 0.31–2.0 mg kg^{-1}) was recorded in June, whereas the lowest average value (0.17 ± 0.05 mg kg^{-1}, range 0.11–0.25 mg kg^{-1}) occurred in September.

Table 4 Pearson correlations between THg concentrations in *N. clavata* and *A. bruennichi* and factors

Factor	*N. clavata*	*A. bruennichi*
Body weight	− 0.433**	− 0.358**
Soil THg	0.486*	0.202
Soil pH	− 0.130	− 0.681**
Leaves THg	0.498*	0.401*
Water THg	− 0.305	− 0.098

*Significant at the level of 0.05

**Significant at the level of 0.01

Discussion

In this study, the average THg in *N. clavata* and *A. bruennichi* from HFR was higher than that from BHR, and was perhaps due to their environmental habitats because we found that the THg average concentrations in soils and rice leaves from HFR were higher than those from BHR. The mean concentration of THg was significantly higher in *N. clavata* than in *A. bruennichi* ($p < 0.05$). Among the environmental factors tested, including soil, leaves, and water, both soil and leaf THg correlated positively with THg in *N. clavata* (Table 4). However, only leaf THg correlated with THg in *A. bruennichi*. No correlations were observed between THg in water and in spiders. In addition, we found that the average THg concentration in forest leaves where *N. clavata* was located was higher than those in rice leaves where *A. bruennichi* was located. Therefore, the concentration of THg in the leaves is considered to be the key factor affecting Hg concentration in spiders. The THg concentrations in both *N. clavata* (r = − 0.43) and *A. bruennichi* (r = − 0.34) correlated negatively with bodyweight (Fig. 3A, B).

The enrichment of Hg in spiders is controlled mainly by their food sources and environmental habitats (Zheng et al. 2018). *Nephila clavata* and *A. bruennichi* live in different habitats, in small forests and rice paddy fields, respectively. For THg in *N. clavata*, we found a significant difference between HFR4 and BHR9 ($p < 0.01$) (Fig. 2), while there was little difference in these environmental factors between

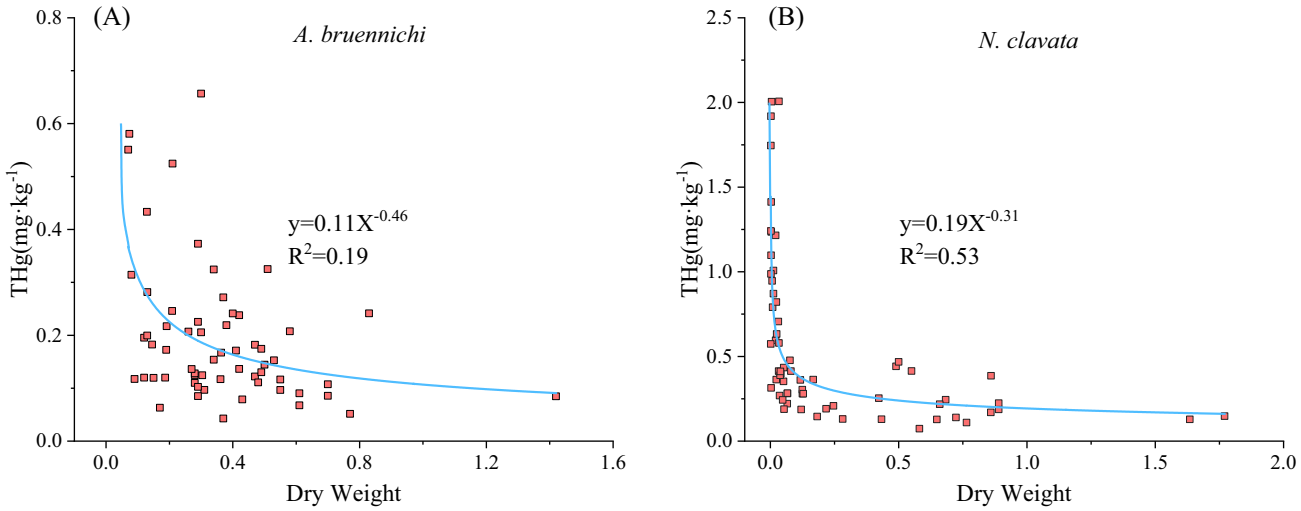

Fig. 3 Relationship between dry weight and the THg concentrations of two spider species *A. bruennichi* (**A**) and *N. clavata* (**B**)

the two sites ($p > 0.05$), suggesting that difference in food sources could affect the THg concentration in spiders. Moreover, the two sampling sites HFR1 and HFR4 from the same reservoir showed no difference in both environmental factors and THg concentrations in spiders, which indicated that the spiders in the same reservoir had the same food sources, further confirming that the difference in THg concentrations in spiders from two reservoirs of HFR4 and BHR9 attribute for different food sources. In addition, the concentrations of Hg in shoreline spiders (*A. bruennichi*) are more closely related to the proportion of emerging insects in their diet (Ortega-Rodriguez et al. 2019). Therefore, the difference in Hg enrichment in the two studied spider species may be attributable to the proportions of their prey that occupy different trophic levels. Another hypothesis is that the contaminant concentrations in riparian spiders correlate with their age or size (Pennuto and Smith 2015). Furthermore, the difference in species is also an important factor (Ortega-Rodriguez et al. 2019).

Most of the Hg in forest soils is derived from atmospheric deposition and litterfall (Zhou et al. 2013; Olsson et al. 2017). The bioavailable Hg in forest soils is usually higher than the Hg in paddy soils, which originates from agricultural activities (Yu et al. 2008; Frey et al. 2013; Frossard et al. 2017). Therefore, an alternative explanation of the difference in Hg enrichment in the two spider species is that the different levels of bioavailable Hg in forests and paddy fields influence bioaccumulation and transfer of Hg in *N. clavata* and *A. bruennichi*.

In this study, the concentration of THg in *N. clavata* increased sharply from May to June, and then decreased in July, August, and September (Fig. 4B). The highest average concentration of Hg was recorded in June, and coincided with the emergence of aquatic insects, which occurred from mid-May to July (Zhang et al. 2010). With the emergence of aquatic insects, significant quantities of aquatic invertebrates emerging from the reservoirs are caught and consumed by spiders, causing the sharp increase in the accumulation of body Hg. The significant difference in spider THg between June and the other months indicates that the riparian spiders accumulated abnormally high amounts of aquatic Hg during the emergence of their prey insects. Our results are consistent with a previous report of the positive correlation between Hg in spiders and the emergence of aquatic insects (Tweedy et al. 2013). Because spiders may be vectors by which Hg is transferred to terrestrial vertebrates (Abeysinghe et al. 2017), our findings also confirm their significant role in the linkage between aquatic and terrestrial ecosystems.

In general, the bodyweights of the spiders tended to increase gradually from May to October, with the highest bodyweights recorded in September (Fig. 4A). Moreover, the THg mass content in spiders increased with each consecutive month during the experimental period (Fig. 4C). However, the graph of THg in spiders versus spider bodyweight had a negative slope (Fig. 3A, B). More interestingly, June showed both the highest mean THg concentration and the lowest spider mass, in contrast to the obverse situation in September, suggesting that bodyweight also influences THg concentrations in spiders, according to the process of biological dilution.

The riparian spiders *N. clavata* and *A. bruennichi* that occur near reservoirs accumulate Hg, and their average THg concentrations were 0.38 ± 0.27 mg kg^{-1} (range 0.07–1.3 mg kg^{-1}) and 0.20 ± 0.20 mg kg^{-1} (range 0.01–0.98 mg kg^{-1}), respectively. The mean concentration of THg in *N. clavata*, which inhabits small forests, was higher than that in *A. bruennichi*, which inhabits paddy fields, and this difference could be related to their community habitats,

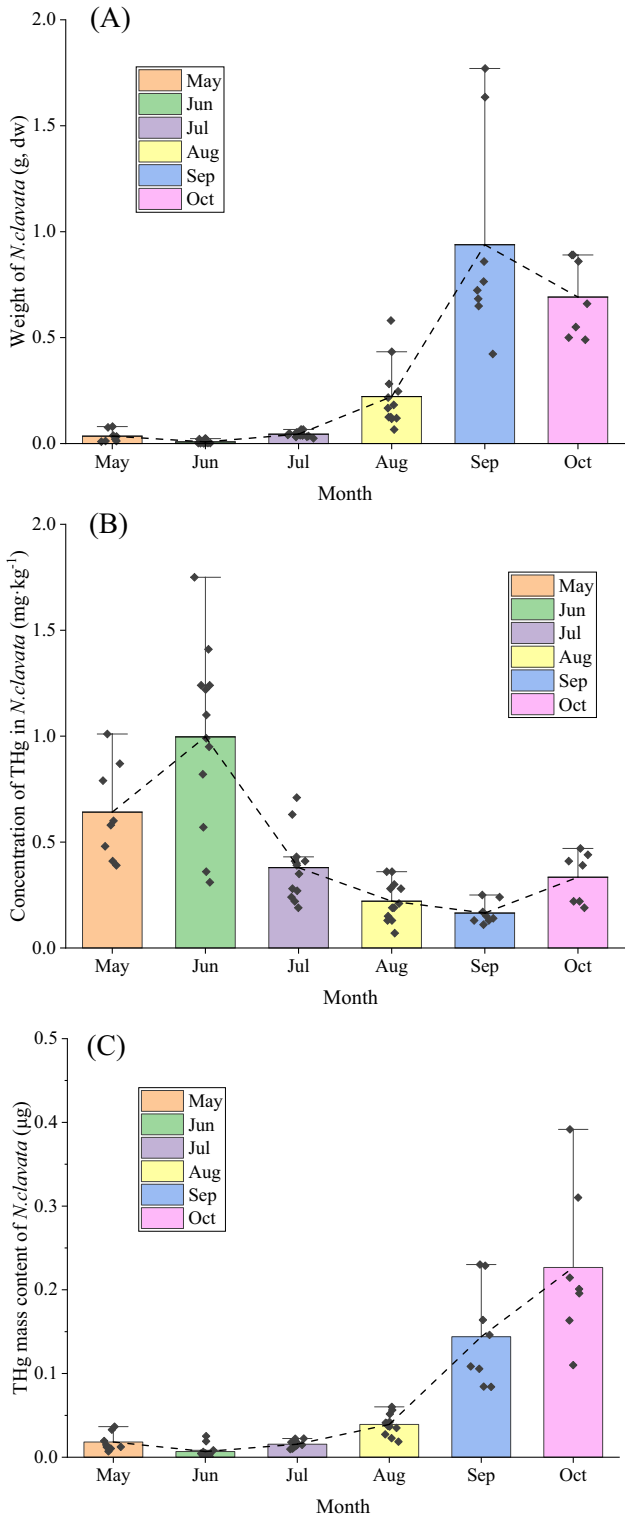

Fig. 4 The distribution and variation between THg concentration and weight in *N. clavata* among months. And the dashed line in the figure is the mean of each bar chart

diets, and/or species differences. The THg concentrations in both *N. clavata* (r = − 0.43) and *A. bruennichi* (r = − 0.34) correlated negatively with bodyweight. The sharp increase in THg in *N. clavata* from May to June and the decline from July to October were probably caused by the emergence of aquatic insects during early summer. Therefore, the emergence of aquatic insects significantly affects the Hg accumulation in riparian spiders. Riparian spiders, particularly *N. clavata*, can be considered environmental biomarkers of the transfer of Hg from aquatic to terrestrial ecosystems. More attention must be paid to the risk of Hg exposure in high-trophic organisms, such as birds, in the areas surrounding reservoirs. Further studies of the dynamics of Hg transfer during the emergence of aquatic insects are required.

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Author Contributions GQ conceived of the project and provided funding. Sampling was designed and conducted by PL, ML, and assistance of GW, ZX. THg determination were conducted by PL, with the supervision of GQ. Statistics and figures were established by DW, PL, YC and GQ. The first draft of the manuscript was written by DW and PL, with assistance from GQ, and all authors contributed to subsequent drafts.

Declarations

Conflict of interest The authors declare no conflict of interest.

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