RESEARCH ARTICLE

Bioaccumulation and tissue distribution of organochlorine pesticides (OCPs) in freshwater fishes: a case study performed in Poyang Lake, China's largest lake

Zhonghua Zhao · Yuyu Wang · Lu Zhang · Yongjiu Cai · Yuwei Chen

Abstract Concentrations and tissue distribution of organochlorine pesticides (OCPs) in different tissues of freshwater fish, silver carp (*Hypophthalmichthys molitrix*) and bighead carp (*Aristichthys nobilis*), collected from Poyang Lake, China's largest shallow lake, and were studied. OCPs were detected with the observed concentrations ranging from 280.67 to 1,006.58 ng/g wet weight (ww) for bighead carp and from 67.28 to 930.06 ng/g ww for silver carp. Composition analysis demonstrated OCPs in both fish were from the same polluted environment, and then, the species-specific bioaccumulation might be mainly due to the different fish age as well as the different feeding habits elucidating from the stable carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotope analysis. Tissue distribution indicated that dietary intake was the major exposure route of OCPs for both fish and higher accumulation potency of OCPs by the hepatobiliary-related tissues (such as liver, kidney, bile, and heart). The higher metabolic activities of these tissues elucidating from the higher values of $\delta^{15}N$ might be the potential-determined factor responsible for the tissue-specific accumulation.

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Z. Zhao · L. Zhang (✉) · Y. Cai · Y. Chen
State Key Laboratory of Lake Science and Environment Research, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing 210008, China
e-mail: luzhang@niglas.ac.cn

Y. Wang
College of Nature Conservation, Beijing Forestry University, Beijing 100083, China

Introduction

Toxic chemicals like heavy metals and persistent organic pollutants are ubiquitous contaminants in aquatic ecosystems. Most of them are lipophilic and thus can be bioaccumulated in organisms of higher trophic levels and transfer through the food chain to induce harmful effects for humans at last (Dallinger et al. 1987; Borgå et al. 2001; Rashed 2001; Corsolini et al. 2005; Elia et al. 2006). The contaminant loading in fish can be reflective of the pollution state of surrounding environment since fish are often at the top of the aquatic food chain and may concentrate large amounts of these contaminants from the water and also through their diet (Al-Yousuf et al. 2000; van der Oost et al. 2003; Lanfranchi et al. 2006; Blocksom et al. 2010). Previous studies mainly focused on contaminant residues among different fish species as well as the potential food chain effects (Deribe et al. 2011; Sakizadeh et al. 2012; He et al. 2012). Some studies have pointed out the tissue distribution and potential bioaccumulation routes of heavy metals in fish (Dallinger et al. 1987; Karadede et al. 2004; Yilmaz et al. 2007). However, as for the tissue distribution of persistent organic pollutants (POPs), related studies only focused on the residual levels in such tissues as muscle, liver, and gill (John and Prakash 2003; Zhou et al. 2007; Guo et al. 2008a, b). Tissue-specific bioaccumulation as well as the potential affecting factors resulting in the final storage and elimination of contaminants in fish received little attention. Additionally, studies on tissue distribution of contaminants could provide more clues about the pathways along which contamination bioaccumulation occurs, and then elucidate the target organs to evaluate the potential toxic effects of these pollutants on fishes.

Organochlorine pesticides (OCPs) were produced and used widely in the past decades. They can enter the water environments by runoff from non-point sources, discharge of industrial wastewater, wet or dry deposition, and other ways and

persist for a long period. Although their application has been banned or restricted in many countries since the early 1970s, especially in developed ones, some developing countries are still using them because of the low cost and versatility in industry, agriculture, and public health (Zhou et al. 2006). As an agriculturally well-developed nation, between the 1950s and 1980s, China applied 4.9 million tons of hexachlorocyclohexanes (HCHs) and 0.4 million tons of dichlorodiphenyltrichloroethanes (DDTs), respectively, accounting for 33 and 20 % of the total world production (Nakata et al. 2002; Jin et al. 2010). Although their production was prohibited in 1983 in China, 3,200 t of lindane (almost pure γ-HCH) was still in use between 1991 and 2000, and DDT production also continues due to the export demand and dicofol production (Qiu et al. 2004; Tao et al. 2005; Zhou et al. 2006). Furthermore, OCPs are lipophilic and thus, may be accumulated in fatty tissues of fish after entering the aquatic environments. Human exposure to such toxic chemicals may occur through numerous routes of which contaminated fish is an important pathway (Kalyoncu et al. 2009). It is therefore critical not only from the ecologic perspective, but also from human health perspective, to continue monitoring OCP residues in aquatic ecosystems, especially in edible fishes concerning human consumption.

Poyang Lake (28° 04′–29° 46′ N, 115° 49′–116° 46′ E), the largest freshwater lake in China, is located in the north of Jiangxi province and lies on the southern bank of the Yangtze River. It is suffering from drastic changes caused by agricultural and industrial developments as well as increase in population, which thus have substantially increased contamination in the surrounding areas. To our best knowledge, most previous studies have been conducted on the heavy metal pollution around this area because Jiangxi province is famous for its nonferrous metal resources; especially copper (Chen et al. 1989; Zhang and Selinus 1997; Luo et al. 2008; Yuan et al. 2011). Few studies are available for understanding the residual levels of OCPs and other POPs in different environmental compartments including water, sediment, as well as aquatic organisms around this area. Since Poyang Lake is one of the only two lakes still freely connected to the mid-lower portion of the Yangtze River Basin, the specific environment induced by river–lake conjunction provided abundant resources for fish spawning and growing, and thus performed as an important supply base of aquatic product for its surrounding cities. It was reported that Poyang Lake supported diverse species of fish (136 species, 25 families) (Wang et al. 2011), with taxa representing a wide range of ecological attributes and life history strategies. Therefore, studies on OCP residues in aquatic organisms, especially in edible fishes, are urgently needed for further ecological risk assessment of OCPs to both Poyang Lake and the Yangtze River basin.

The primary objective of this study was to investigate the present pollution status of OCPs and their tissue-specific accumulation in edible fishes collected from Poyang Lake. The silver carp (*Hypophthalmichthys molitrix*) and bighead carp (*Aristichthys nobilis*), belong to the Cyprinid, are the most important phytoplanktivorous fish in China, and have been introduced worldwide for aquaculture, comprising as much as 18 % (silver carp 12 %) of the total freshwater fish production of the world (Xie et al. 2004). In addition, both species migrated between rivers and lakes, and thus were selected as the target fish species in terms of their ubiquitous distribution and importance for human consumption. The stable nitrogen isotope (δ^{15}N) signatures in fish were also determined to define their relative trophic position, and stable carbon isotope (δ^{13}C) signatures were used for the determination of source and flow of carbon (Sharma et al. 2009) to elucidate the bioaccumulation routes and potential factors affecting tissue distribution of OCPs in fish.

Materials and methods

Sampling

Both fish samples, bighead carp and silver carp, were collected around the northern water region located near Hukou estuary, which is the only connected area with the Yangtze River (Fig. 1). Seven individuals (with the similar length and weight) for each fish species were selected and the detailed information is listed in Table 1. Fish age was calculated according to the suggested growth model based on Von Bertalanffy equation (Ding et al. 2005) and is also shown in Table 1. All fish samples were immediately transported to the laboratory and stored at 4 °C for the following treatment.

Sample pretreatment

The fish were washed by distilled water and then were freshly dissected carefully to obtain muscle (taken from the dorsal surface of the fish), gill, liver, heart, kidney, bile, gall bladder, squama, and skin (without muscle layer and squama). Each tissue sample was dried in filter paper and weighed, packed in aluminum foil, and then kept at −20 °C until analysis.

The aluminum foil was opened and samples were stored in glass beakers with new aluminum foil covered for vacuum freeze drying. Samples were freeze-dried for about 72 h and then were divided into two parts for stable isotope analysis and OCP determination, respectively. Firstly, the dorsal muscle from each fish individuals of different species were powdered and kept in polyethylene centrifuge tubes under room temperature before stable isotope analysis. And then, the same tissue from individuals of each fish species included the rest muscle sample were pooled together to improve the sample representativeness for both stable isotope and OCP analysis. The tissues were ground in an agate mortar to obtain fine

Fig. 1 Sampling locations
(the black area) of
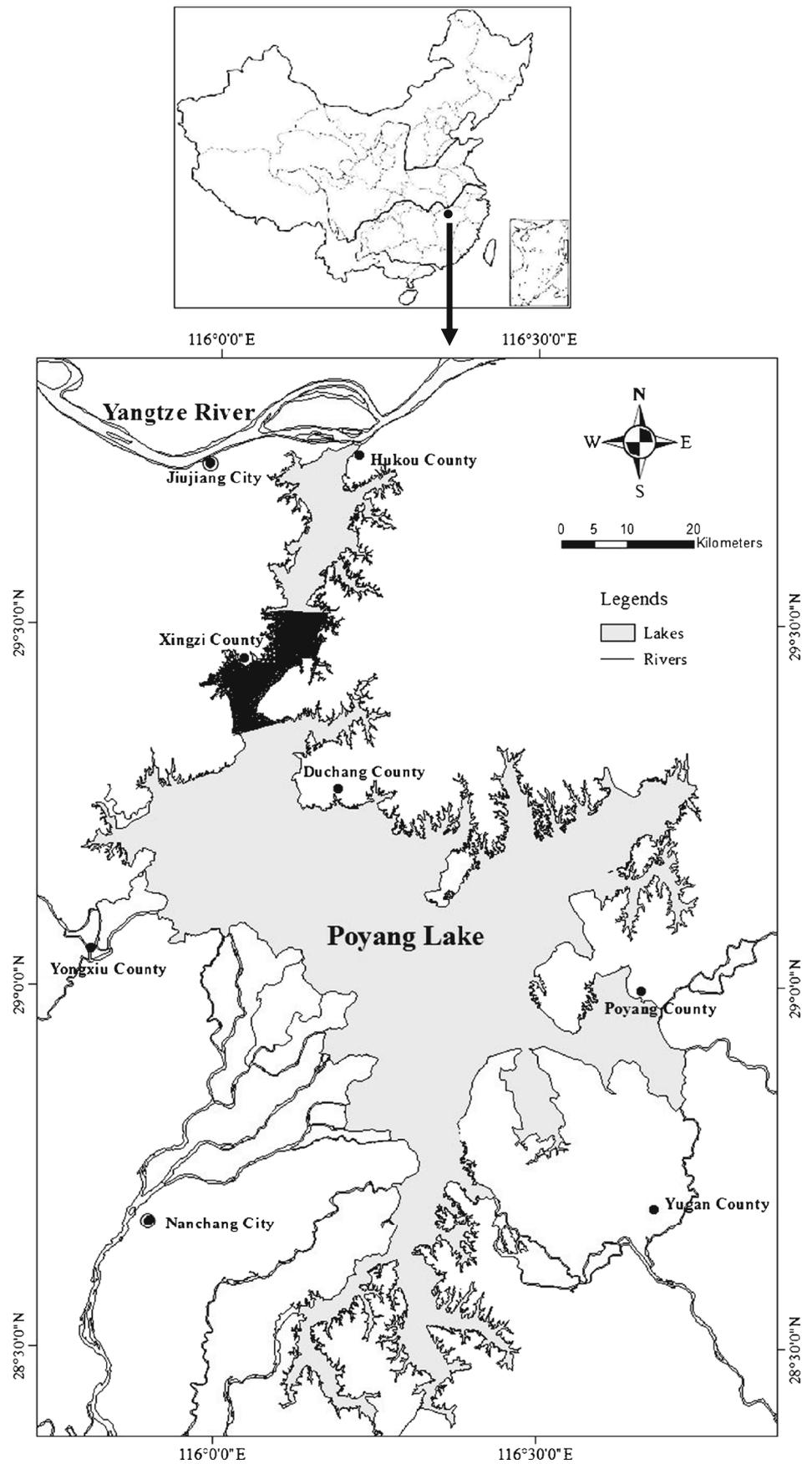freshwater fishes from
Poyang Lake

Table 1 The body length and wet weight of fish samples collected from Poyang Lake

Silver carp					Bighead carp				
Number	Length (cm)	Weight (g)	Age[a] (year)	Age[b] (year)	Number	Length (cm)	Weight (g)	Age[a] (year)	Age[b] (year)
1	35.9	788.5	1.66	1.46	1	38.4	1,015.5	1.77	2.10
2	36.5	827.1	1.69	1.49	2	34.0	771.3	1.62	1.96
3	35.9	757.1	1.66	1.43	3	35.6	904.4	1.67	2.04
4	36.5	836.3	1.69	1.50	4	36.8	1,009.6	1.72	2.10
5	37.0	840.7	1.71	1.50	5	37.5	1,016.4	1.74	2.10
6	35.2	737.6	1.62	1.41	6	37.4	918.7	1.74	2.05
7	35.2	786.6	1.62	1.46	7	38.5	1,072.9	1.78	2.13

[a] Fish age (t, year) of silver carp and bighead carp was calculated using the length-growth mode length (cm)=33.497lnt+18.957 and length (cm)= 49.060lnt+10.311, respectively

[b] Fish age (t, year) of silver carp and bighead carp was calculated using the weight-growth mode weight (kg)=0.369 $t^{2.0175}$ and weight (kg)= 0.048 $t^{4.1103}$, respectively

powder (100 mesh). The extraction of samples was completed using accelerated solvent extraction (ASE) (Dionex ASE 100, USA). Lipid was determined gravimetrically using 20 % of the extracts, and then the rest was in due order purified by gel permeation chromatography (GPC, J2 Scientific AccuPrep System, USA) and silica gel–alumina (2:1) power column, respectively. The detailed procedure and instrumental conditions could be found in Zhao et al. (2009 and 2013). The purified samples were rotary evaporated and made to constant volume with n-hexane, and then were stored at −20 °C before instrumental analysis.

OCP determination

The qualitative analysis and quantification of OCPs were completed by gas-chromatograph equipped with a ^{63}Ni micro-electron capture detector (GC-μECD, Agilent 7890, USA). The detailed conditions of the instruments as well as the procedure of the quality assurance and quality control tests could also be found in Zhao et al. (2013).

Stable isotope analysis

Approximately 0.1–0.2 mg of powder samples for δ^{13}C determination and 1–2 mg for δ^{15}N were weighed into a separate tin capsule for instrument analysis. Stable isotopes were measured by Thermo Scientific MAT 253 elemental analyzer at the State Key Laboratory of Lake Science and Environment at Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences. Stable isotope abundances were expressed in δ notation as the deviation from standards in parts per thousand (‰) according to the following equation (Covaci et al. 2006; Takeuchi et al. 2009):

$$\delta X = \left[\left(R_{sample}/R_{standard}\right)-1\right] \times 1000$$

where X is ^{13}C or ^{15}N and R is the corresponding ratio ^{13}C/^{12}C or ^{15}N/^{14}N. The standard values were based on the PeeDee Belemnite (PDB) for ^{13}C and atmospheric N_2 for ^{15}N. Replicate measurements of internal laboratory standards (albumen) indicated measurement errors of ±0.1 and ±0.3‰ for δ^{13}C and δ^{15}N, respectively.

Statistical analysis

OCP concentrations were expressed on the wet weight basis (ng/g wet weight, ng/g ww) and lipid basis (ng/g lipid), respectively. For samples with the concentrations below limits of detection (LODs), zero was used for calculations. The statistical analyses were performed with SPSS Microsoft version 16.0 for windows (SPSS Inc. USA). Correlations between OCP concentrations and δ^{15}N were examined by Spearman's rank correlation test. OCP concentrations were log-transformed prior to linear regression to ensure normality, a usual practice in the analysis of environmental data. Significant difference tests between fish age was completed using independent-samples t test. Statistical significance was considered for $P<0.05$ (two-tailed tests).

Results and discussion

OCP concentrations and compositions in tissues of fishes

The concentrations of total OCPs containing 20 individual compounds in different tissues of both bighead carp and silver carp are listed in Fig. 2, and the concentrations of individual compounds are shown in the supplementary material. The octanol-water partition coefficients (log Kow) of OCPs (Shen and Wania 2005; Hale et al. 2010) are also listed in the Supplementary table. OCP concentrations were detected in the range of 280.66–1006.58 ng/g ww in bighead carp, and
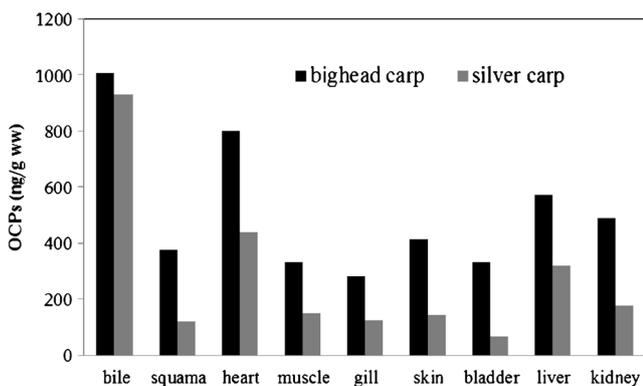
Fig. 2 Concentrations of OCPs (ng/g ww) in different tissues of silver carp and bighead carp

the highest concentration was found in bile while the lowest concentration was in gill. Higher concentrations of OCPs were also found in heart, liver, and kidney with the values of 801.56, 570.62, and 489.46 ng/g ww, respectively. While for other tissues such as skin, squama, muscle, and gall bladder, OCP residues were determined to be 413.85, 374.61, 333.39, and 333.06 ng/g ww, respectively. Among OCPs, chlordanes (α-, γ-chlordane, heptachlor, and heptachlor epoxide included) were the most dominant compounds followed by aldrins (aldrin, dieldrin, endrin, endrin aldehyde, and endrin ketone included), HCHs (α-, β-, γ-, δ-HCH included), endosulfans (endosulfan I, endosulfan II, and endosulfan sulfate included) and DDTs (p,p′-DDE, p,p′-DDD, and p,p′-DDT included). Chlordanes ranged from 146.25 to 504.91 ng/g ww and the highest concentration was found in bile, while the lowest concentrations were detected in skin. The highest concentration of aldrins was detected in bile (403.14 ng/g ww) followed by heart (159.22 ng/g ww), and the lowest concentration was in gill with the value of 54.70 ng/g ww. Endosulfans were detected at the concentrations of 2.37–7.77 ng/g ww with skin being the most predominant tissue and muscle being the least for OCP bioaccumulation. As for DDTs, the highest residual level was found in bile at the concentration of 7.84 ng/g ww followed by liver (4.56 ng/g ww), and the lowest residue was observed in gall bladder at the concentration of 0.58 ng/g ww.

For individual compounds, heptachlor was the primary compound accumulated in tissues of bighead carp ranging from 120.77 to 465.00 ng/g ww followed by aldrin (47.51–383.06 ng/g ww). In HCHs, β-, and δ-HCH were the major contributors with the observed concentrations of 10.56–126.57 and 6.57–52.99 ng/g ww, respectively. The highest concentration of α-HCH was found in liver (187.38 ng/g ww) followed by kidney (39.10 ng/g ww), while the lowest concentration was detected in gall bladder with the value of 2.60 ng/g ww. γ-HCH showed the lowest detection frequency among HCH isomers, which might be attributed to its higher vapor pressure than other isomers as well as its photochemical transformation and biodegradation to α-HCH in environment

(Strandberg et al. 1998). As for DDTs, p,p′-DDE was the predominant compound followed by p,p′-DDD and p,p′-DDT. p,p′-DDT was found at the lowest residual levels among OCPs and the highest concentration of 0.03 ng/g ww was observed in muscle, which is probably due to a lower half life of p,p′-DDT in fish (~8 months) compared to that of p,p′-DDD and p,p′-DDE (~7 years) (Binelli and Provini 2003; Covaci et al. 2006).

In silver carp, the highest concentration of OCPs (930.01 ng/g ww) was also found in bile; however, the lowest concentration was found in gall bladder with the value of 67.28 ng/g ww. OCPs in heart and liver were also much higher than other tissues with the observed concentrations of 440.02 and 318.86 ng/g ww, respectively. For other tissues such as kidney, muscle, skin, gill, and squama, OCPs ranged from 119.51 to 178.39 ng/g ww. Aldrins were the major contributor to total OCPs in tissues of silver carp irrespective of higher residues of chlordanes in bile (735.61 ng/g ww). The heart showed the highest residual concentration of aldrins (245.00 ng/g ww), while the gall bladder was found at the lowest level of 48.28 ng/g ww. The concentrations of chlordanes in other tissues except for bile were in the range of 5.89–156.84 ng/g ww and the lowest concentration was found in gall bladder as aldrins. As for HCH isomers, the highest concentration was detected in bile (48.92 ng/g ww) and the lowest concentration was in squama (9.85 ng/g ww). Among OCPs, endosulfans, and DDTs observed in tissues were lower with the values of 1.24–26.71 and 0.63–1.80 ng/g ww, respectively. Aldrin was the major share of individual OCP compounds and the concentrations ranged from 45.81 to 240.15 ng/g ww followed by heptachlor (4.58–147.59 ng/g ww except for 718.13 ng/g ww in bile). β- and δ-HCH were also found at higher concentrations than other individuals with the observed values of 1.66–31.25 and 6.34–33.23 ng/g ww, respectively. Similar compositions of DDTs were found as bighead carp with p,p′-DDE being the most abundant compound (0.13–1.67 ng/g ww), while p,p′-DDT was not detected in any tissues of silver carp.

Generally, comparison with results from other water bodies is difficult because all the relevant studies have been done with different species of different trophic positions as well as different body parts. When comparing with the surveys carried out in Taihu Lake, the third largest shallow lake in China with an area of 2,338 km², OCP residues in muscle from Poyang Lake were similar with the values found in common carp samples (228.2 ng/g ww) (Zhao et al. 2013); however, the concentrations were much higher than the grass carp (42.0 ng/g ww). As for the two typical OCPs, HCHs and DDTs, higher concentrations of DDTs were found in Taihu Lake (4.16–22.94 ng/g ww) due to the continuous inputs, while HCHs were detected at similar values of 11.01–45.22 ng/g ww. Furthermore, when comparing with the national guidelines, DDTs and HCHs in both fish did not exceed

the threshold values of 2,000 ng/g wet wt for DDTs and 5,000 ng/g wet wt for HCHs (Chen et al. 2002), thus implying the human exposure to OCPs through fish consumption from Poyang Lake at present would not induce toxic effects irrespective of the possible combined effects with heavy metal and increasing human life quality.

The compositions of OCPs in different tissues of both bighead and silver carps are shown in Fig. 3. As previously described, chlordanes were the major share in tissues of bighead carp accounting for 28.9–73.5 % of total OCPs. Aldrins contributed 11.6–40.1 % to total OCPs followed by HCHs (6.9–57.4 %), while endosulfans and DDTs only accounted for 0.6–1.9 and 0.2–1.0 %, respectively. As for silver carp, aldrins were the major contributor accounting for 14.8–71.8 % of total OCPs followed by chlordanes with the contributions of 6.8–79.1 %. Endosulfans and DDTs were the lowest contributors to OCPs and only accounted for 0.2–18.6 and 0.2–1.3 %, respectively. Correlation analysis of OCP concentrations and compositions (sum of individual OCP concentrations in all tissues being used for calculations) between bighead carp and silver carp showed extremely significant positive correlations ($R^2=0.891$, $P=0.000<0.01$, $n=20$), indicating OCPs in both fish were from the same exposure

environment. As for the residue difference among compounds, the extremely weak positive correlations were observed between Log Kow and OCP concentrations (sum of concentrations in all tissues) for both bighead carp ($R^2=0.002$, $P=0.849>0.05$, $n=20$) and silver carp ($R^2=0.022$, $P=0.534>0.05$, $n=20$), which implied that the different environmental concentrations (such as in water column or sediment) of individual OCPs could be responsible for the preferential accumulation of compounds.

Species-specific bioaccumulation of OCPs in fish

Fish can bioaccumulate contaminants that they ingest with their food or bioconcentrate chemicals directly from water via diffusion across the membrane, which is a complex phenomenon potentially controlled by a myriad of physiological and environmental factors (McIntyre and Beauchamp 2007). Since both fishes were living in the same polluted environment, the possible impacts induced by environmental concentration could be excluded at present. OCPs were lipophilic compounds and would accumulate in lipid fractions, and then the fish with a high fat content would be the most contaminated (Davis et al. 2002; Erdogrul et al. 2005). Therefore,

Fig. 3 OCP compositions (%) in different tissues of bighead carp (**a**) and silver carp (**b**)
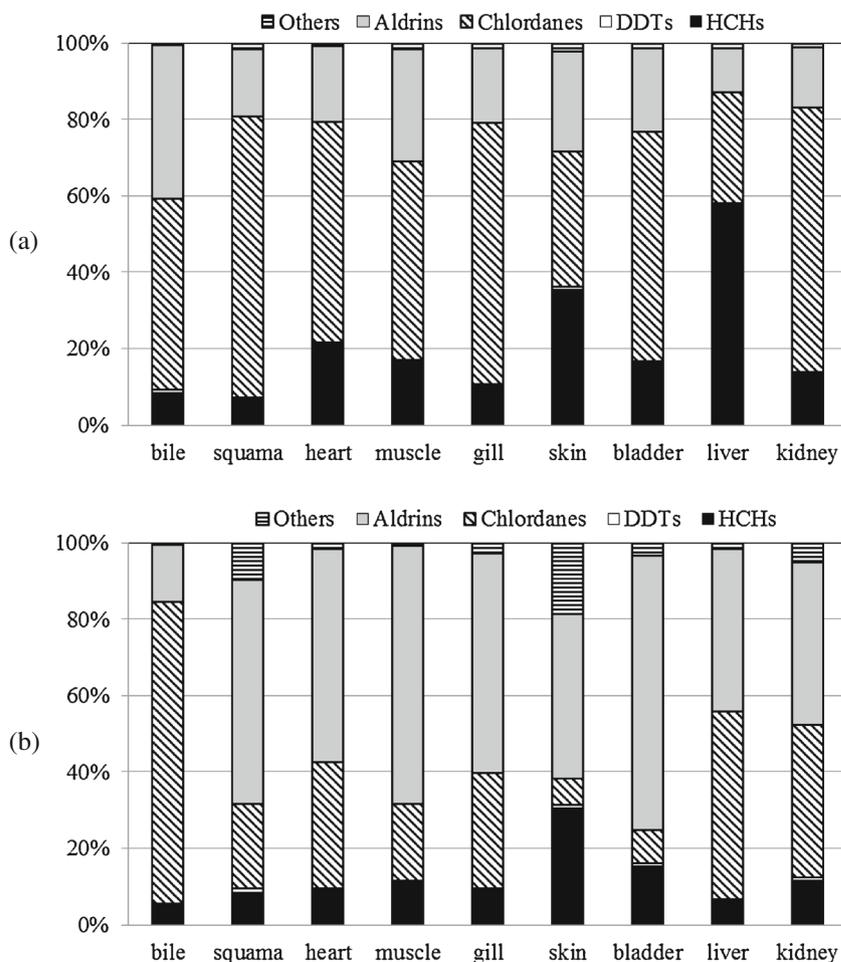
lipids are often correlated with concentrations of lipophilic contaminants such as organochlorines, but the assumption of a causal relationship between the two has been challenged, with numerous studies showing either no relationship between lipid content and organochlorine concentrations, or suggesting that such relationships are spurious (Jackson et al. 2001; Manchester-Neesvig et al. 2001; Crimmins et al. 2002). In our study, the total lipid contents in all tissues were found at 1.31 % for bighead carp and at 2.55 % for silver carp, documenting a contradictory phenomenon with the sum of OCPs detected in both fish (4,603.80 ng/g ww for bighead carp and 2,470.01 ng/g ww for silver carp). Therefore, lipid might not be the major factor responsible for the species-specific bioaccumulation of OCPs in studied fish.

Additionally, it was reported that older fish tend to accumulate more pollutants than the younger ones because of the longer exposure time, and thus elucidating that fish age is a determinant factor for the presence and level of OCPs (Vives et al. 2005; Rognerud et al. 2002). As shown in Table 1, fish age of bighead carp and silver carp calculated according to the length-growth model ranged from 1.62 to 1.78 years (arithmetic mean value of 1.72) and from 1.62 to 1.71 years (arithmetic mean value of 1.66), respectively, while according to the weight-growth model, fish age was in the range of 1.96–2.13 years (arithmetic mean value of 2.07) and 1.41–1.50 years (arithmetic mean value of 1.46), respectively. In addition, significant differences were observed between fish age of bighead carp and silver carp based on both weight-growth model ($P=0.044<0.05$, $n=7$) and length-growth model ($P=0.000<0.05$, $n=7$), thus demonstrating the longer exposure time to OCPs for bighead carp would more or less induce higher OCP accumulation.

Both bighead carp and silver carp are phytoplanktivorous filter feeders; however, analysis of intestinal contents of silver carp and bighead carp conducted by Cremer and Smitherman (1980) pointed out that silver carp consumed primarily phytoplankton while bighead carp consumed large quantities of zooplankton and detritus in addition to phytoplankton. In addition, rapid advances have been achieved recently on the modeling of the biomagnification process of environmental chemicals and trace elements using stable isotope ratios of bioelements, such as carbon and nitrogen. Stable nitrogen and carbon isotope ratios of biota can be used to characterize an organism's trophic position and carbon source, respectively. These isotopic signatures integrate dietary habits over a period of months to years for slower-growing species (Kidd et al. 2001; Tittlemier et al. 2002). In general, $\delta^{15}N$ in consumers increases 3.4‰ on average relative to prey eaten, and thus can be used to determine the trophic position of each organism in a food web. While for the $\delta^{13}C$, it is enriched slightly by about 1 ‰ per trophic level and is used mostly to identify primary carbon sources in a food web (Vander Zanden and Rasmussen 2001; Post 2002). In the present study, mean stable isotopes

including both $\delta^{13}C$ and $\delta^{15}N$ in muscles of bighead carp and silver carp are shown in Fig. 4. The $\delta^{13}C$ and $\delta^{15}N$ stable isotopes in muscles of bighead carp ranged from 25.0 to 25.3 and from 8.3 to 10.2‰, respectively. While for silver carp, the $\delta^{13}C$ and $\delta^{15}N$ stable isotopes ranged from 27.0 to 29.5 and from 7.3 to 8.1‰, respectively. Although no obvious trophic level difference was observed between bighead carp and silver carp based on the $\delta^{15}N$ isotopes, the relative higher values of $\delta^{13}C$ in bighead carp indicated the main carbon sources were from benthos, while the silver carp mainly take pelagic biotas as food, which demonstrated that the feeding habit difference of both fishes might be the determined factor responsible for the species-specific bioaccumulation of OCPs.

Tissue-specific bioaccumulation of OCPs in fish

The response of an organism to a toxic substance is determined by the quantity of the substance which reaches the target organ or tissue. For both fish, bile, liver, kidney, and heart were the predominant tissues for OCP bioaccumulation, while gill, skin, muscle, squama, and gall bladder were found at lower concentrations, which demonstrated higher bioaccumulation potency in hepatobiliary system than the extrahepatic tissues. Studies conducted by Guo et al. (2008a) also suggested liver had the highest OCP levels and contained higher p,p′-DDD abundances than other tissues. As for the higher residual levels detected in kidney, this might simply be a result of the high perfusion of blood suggested by Martin et al. (2003). Lee et al. (1972) suggested the path of polycyclic aromatic hydrocarbons (PAHs) uptake by fish would appear to be through gill, followed by accumulation of hydrocarbon and its metabolites by the liver, gut, and flesh, and then the gall bladder was the final storage site, which was consistent with the present study showing that the highest concentrations of OCPs were detected in bile for both fishes. The relative lower residual levels found in muscle for both fish demonstrated that muscle is not a target organ for the accumulation of lipophilic substances during exposures (Ballesteros et al. 2011). Furthermore, significant positive correlations of compositions
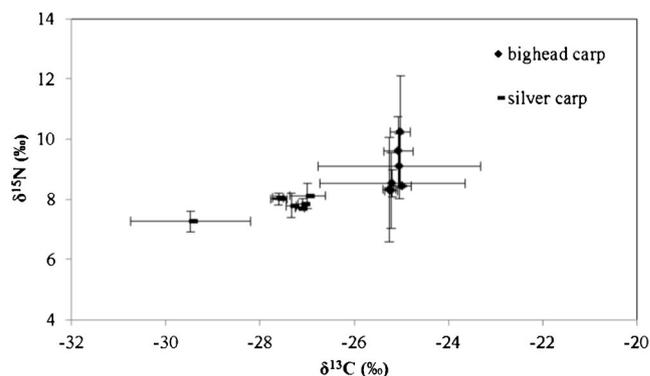

Fig. 4 Mean stable nitrogen $\delta^{15}N$ and carbon $\delta^{13}C$ isotopes (‰, ±SD) in muscles of studied silver carp and bighead carp

between tissues were detected for both bighead carp (R^2= 0.228–0.990, P=0–0.033<0.05, n=20) and silver carp (R^2= 0.264–0.990, P=0–0.017<0.05, n=20) except for the weak positive correlations between bile and extrahepatic tissues (R^2=0.011–0.125, P=0.127–0.667>0.05, n=20) for silver carp. Therefore, the OCP profiles in the environment could be well reflected in any studied fish tissue as suggested by Guo et al. (2008a), and then it could also be expected using viscera to monitor such pollutants in aquatic organisms.

Since the bioaccumulation of toxic chemicals in fishes occurred mainly through both the direct absorption by external membrane and by dietary uptake, gill was generally found to be the primary tissue of filter-feeding fishes for pollutant accumulation through gill–water transfer (Yang et al. 2007), while the other tissues concerning internal gastrointestinal tracts showed higher concentrations of target pollutants due to the food uptake (Ballesteros et al. 2011; Murakami et al. 2011). However, rather higher values of OCPs were found in other tissues than gill for both species, indicating that food uptake would be the main exposure route for both fishes accumulating OCPs from environment.

Once the pollutants were absorbed through dietary uptake, they may be transported via the lymphatic system or blood stream and distributed to various body tissues, including those of storage depots and sites for metabolism or biotransformation. Therefore, the physiological characteristics of target tissues such as the lipid content and potential metabolic potency resulting in different uptake and elimination rates of contaminants might be the key factors accounting for the observed OCP difference among tissues. Lipid contents of different tissues in both bighead carp and silver carp are shown in Table 2. Correlation analysis performed between lipid contents and concentrations of both total OCPs and individual compounds in different tissues showed weak positive or negative correlations (bighead carp, R^2=0.002–0.378, P=0.078–0.905>0.05, n=9; silver carp, R^2=0–0.158, P=0.289–0.950>0.05, n=9), and thus, further indicating lipid might not be the

key factor accounting for both the species-specific and tissue-specific accumulation of OCPs.

The metabolism of toxicants may be carried out at entry points (gill and intestine) or at other organs such as liver and kidney. The liver is located in a strategic position within the organisms, receiving a large quantity of blood, which contributed to the distribution of toxics and their metabolites to other organs. Stapleton et al. (2004) pointed out that absolute concentrations of polychlorinated biphenyls (PCBs) in liver tissues of *Cyprinus carp* were 1.1 to 7.7 times higher than those in whole-body tissues on both a wet-weight and a lipid-weight basis. Additionally, they also suggested that the relative assimilation rates for each congener were also greater in liver tissue compared to whole-body tissues. This phenomenon implied that liver in carp is not a contact organ anterior to the intestinal mass. The liver extends longitudinally and wraps around the intestinal mass throughout the entire length of the gastrointestinal tract. This physical contact acts to increase the surface area contact with the intestine and could increase the capacity for metabolism of contaminants absorbed through dietary intake, which therefore made the liver perform as the target organ for OCP bioaccumulation. In addition, the metabolic potency of particular tissues could also be demonstrated by the stable isotopes in tissues. Generally, as shown for seals and mice, tissues with lower metabolic rates (blood, muscle) have lower diet-tissue discrimination than tissues exhibiting higher metabolic rates, such as liver and brain, which thus induced greater ^{15}N enrichment and higher values of $\delta^{15}N$ in tissues with higher metabolic rate (Arneson and MacAvoy 2005). $\delta^{15}N$ in tissues of bighead carp ranged from 6.89 to 9.33‰, while for silver carp, the values were in the range of 6.00–8.34‰ (Table 2). Typically, $\delta^{15}N$ in the internal organs such as liver, kidney, heart, and bile were higher than other external tissues like muscle, gall bladder, skin, squama, and gill, which might therefore further demonstrate higher metabolic activities of the internal organs than the external ones. Furthermore, correlation analysis between $\delta^{15}N$ and log-

Table 2 Mean stable nitrogen $\delta^{15}N$ (‰) and standard deviation (SD) in different tissues of both bighead carp and silver carp

Tissues	Bighead carp				Silver carp			
	$\delta^{15}N$ (‰)	SD	Lipids (%)	SD	$\delta^{15}N$ (‰)	SD	Lipids (%)	SD
Bile	8.84	0.06	0.08	0.04	7.59	0.00	0.14	0.04
Scale	8.67	0.03	0.03	0.02	6.00	0.11	0.15	0.10
Heart	8.96	0.01	0.16	0.05	7.70	0.15	0.21	0.04
Muscle	8.16	0.15	0.10	0.04	7.38	0.04	0.13	0.07
Gill	6.89	0.08	0.05	0.02	6.97	0.14	0.23	0.10
Skin	7.96	0.02	0.23	0.10	6.78	0.17	0.37	0.12
Bladder	7.62	0.03	0.10	0.00	7.28	0.19	0.30	0.01
Liver	9.06	0.29	0.26	0.11	8.34	0.04	0.40	0.12
Kidney	9.33	0.38	0.29	0.12	8.05	0.06	0.61	0.14

transformed concentration of OCPs in tissues of both species showed significant positive correlation between $\delta^{15}N$ and total OCPs ($P=0.033<0.05$, $n=9$) in bighead carp, and the positive correlation was also found in silver carp ($P=0.188>0.05$, $n=9$), which indicated the metabolic activity difference might be the potential factor accounting for the tissue distribution of OCPs.

Conclusion

The study could be performed as a preliminary investigation focused on OCPs in edible fishes from such an important freshwater ecosystem receiving little attention before. OCPs were detected in all samples with aldrins, chlordanes, HCHs being the predominant compounds in bighead and silver carp. Both fish were living in the same contaminated environment, and the higher concentrations of OCPs detected in bighead carp than silver carp might be mainly attributed to the age difference as well as the different feeding habits. Tissue distribution indicated the dietary intake was the major exposure route with the hepatobiliary-related tissues such as liver, kidney, heart, and bile being the predominant tissues, while muscle was not an active tissue for both fish. The metabolic activity difference might be the potential factor accounting for the tissue-specific accumulation of OCPs, which should be further studied to well understand the tissue distribution of such pollutants in fish. Obtained results could be performed as the basis for future ecological risk assessment of organochlorines around Poyang Lake.

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