Environ Monit Assess (2016) 188: 243
DOI 10.1007/s10661-016-5248-9

Bioaccumulation of metals in common carp (*Cyprinus carpio* L.) from water bodies of Anatolia (Turkey): a review with implications for fisheries and human food consumption

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Received: 1 January 2016 / Accepted: 14 March 2016 / Published online: 23 March 2016

Abstract Although fish is widely consumed by humans for its nutritional properties, accumulation of heavy metals can pose serious health hazards. Widespread common carp *Cyprinus carpio* is cultured worldwide and represents an economically important species for fisheries in several countries. These include Turkey, where *C. carpio* often makes for a large part of the sales of the locally marketed fish and also for a traditional dish. This study provides a review of bioaccumulation of metals in tissues of *C. carpio* from water bodies of Anatolia and also includes reference to worldwide studies. From 42 water bodies across the region, 27 metals in total were studied, of which Cd, Cr, Cu, Fe, Mn, Ni, Pb and Zn were the most widely analysed, mainly in the muscle, liver and gill tissues. Amongst the potentially toxic metals, Cd, Cr and Pb occurred in several water bodies at concentrations not only above maximum allowed limits but also higher relative to other water bodies worldwide, even though As, Hg and Ni were also sometimes present at potentially hazardous concentrations. The essential metals Cu, Fe, Mn, Se and Zn were detected at various concentrations, with the latter two occasionally above limit. All water bodies flagged as having especially critical (i.e. above limit) concentrations of toxic metals supported *C. carpio* fisheries from highly populated regions, raising concern about food safety and calling for preventative measures. Given the significantly lower bioaccumulation levels in the muscle relative to the liver and gill tissues, it is suggested that consumption of *C. carpio* as fillets may be safer than after processing into e.g. meat balls and sausages. The limits of 1.0 μg/g for Cr and 1.15 μg/g for Se, currently lacking from the Turkish food safety legislation, are proposed, and it is suggested that a similar meta-analytical approach as adopted in this study may benefit other countries where *C. carpio* represents an important fisheries resource.

Keywords Muscle · Liver · Gill · Quartile analysis · PERMANOVA

Introduction

Fish is widely consumed by humans for its high content in protein and omega-3 polyunsaturated fatty acids, which help abate cholesterol levels and consequently the risk of certain types of cancer and cardiovascular diseases (Storelli 2008). However, teleost fishes are known to accumulate heavy metals (hereafter, 'metals' including metalloids: Duffus 2002) in their body by direct uptake from water (via gills) and through diet. Although there can be considerable variability in

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Electronic supplementary material The online version of this article (doi:10.1007/s10661-016-5248-9) contains supplementary material, which is available to authorized users.

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bioaccumulation amongst fish species depending on life history (Short et al. 2008), the levels of certain metals in fish tissues generally reflect those found in their biotic and abiotic environments (Birge et al. 2000; Wang and Rainbow 2008). Not surprisingly, a high content of heavy metals (mainly, potentially toxic ones such as As, Cd, Cr, Hg, Ni, Pb, but also essential ones such as Cu, Fe, Mn, Se, Zn, if present at elevated concentrations) may lead to severe threat to fish. This, in turn, can represent a serious health hazard for human consumption (Sorensen 1991; Tüzen 2003; Blanco-Penedo et al. 2006).

The common carp *Cyprinus carpio* is the most widely distributed freshwater fish worldwide (Vilizzi 2012). It represents a major resource for aquaculture production in several countries (http://www.fao.org/fishery/culturedspecies/Cyprinus_carpio/en), makes for valuable and productive fisheries (e.g. Shumka et al. 2008; Harlioğlu 2011) and is sometimes appreciated as a traditional ethnic dish (Balon 1974). In Turkey, *C. carpio* is native to the ecoregions (sensu Abell et al. 2008) of Thrace, northern Anatolia, western Transcaucasia and upper Tigris and Euphrates (Memiş and Kohlmann 2006; Vilizzi 2012). However, following translocations since the 1960s (Innal and Erk'akan 2006; Çetinkaya 2010; Tarkan et al. 2015), *C. carpio* is now widespread throughout the rest of the region, where it represents the most important species for inland fisheries (Turkish Statistical Institute 2014). Indeed, stocking of *C. carpio* by local government agencies especially into newly established (artificial) reservoirs (e.g. Özuluğ et al. 2005; Balık and Ustaoğlu 2006; Önsoy et al. 2011) is common practice, and also provides for an alternative source of revenue for local communities to compensate for the economic losses resulting from private land encroachment following reservoir construction (Gaygusuz et al. 2015; Tarkan et al. 2015).

Traditionally, in Turkey *C. carpio* has represented a favourite dish especially in the regions of central and eastern Anatolia, where it makes for a large part of the sales of the locally marketed fish (e.g. Orsay and Duman 2008a). To improve the quality of the product for human consumption, studies have therefore investigated the physicochemical and microbiological characteristics of smoked (mirror) *C. carpio* fillets (Patir and Duman 2006; Duman and Dartay 2007; Duman and Patir 2007; Can et al. 2011), as well as the processing of its flesh into meat balls and sausages (Yanar and Fenercioğlu 1999; Arslan et al. 2001; Can and Coban 2012).

Clearly, given the importance of *C. carpio* as a food resource in Turkey, it is imperative that a deeper understanding should be gained on the safety of this fish as a consumer's product, including knowledge of those water bodies sustaining profitable fisheries but more prone to pollution-induced hazards. The objective of the present study was to provide a synthesis on bioaccumulation of metals in *C. carpio* from water bodies of the region. Based on an extensive review of the literature: (i) a quantitative evaluation was made of the concentration of various metals in body tissues of *C. carpio* and relative, whenever possible, to established maximum allowed limits for human consumption; (ii) water bodies of the region with above-limit concentration of metals in *C. carpio* tissues were identified and flagged according to their level of contamination; and (iii) a comparison was made with bioaccumulation of metals in *C. carpio* tissues from water bodies worldwide with the aim to cast the outcomes of the present study within a global perspective. It is recommended that measures be implemented for enhancing the safety of *C. carpio* fisheries of the region for human food consumption.

Material and methods

Data collation

Bioaccumulation data for *C. carpio* in Anatolia were obtained from peer-reviewed papers, thesis dissertations and, occasionally, conference proceedings. A necessary criterion for inclusion of a study into the review was that it should deal with *C. carpio* sampled under natural conditions. For this reason, laboratory-based (bioassay) studies carried out in situ (Kargın and Erdem 1991; Canlı and Kargın 1995; Barlas 1999b; Cicik 2003; Karaytug et al. 2007; Çoban et al. 2013; Cogun and Kargın 2013; Yeşilbudak and Erdem 2013, 2014) or on fish sampled from one or more water bodies under monitoring (Ozkurt 2000; Sahan et al. 2010; Uysal et al. 2010; Güngördü et al. 2012) were not included. Notably, the dataset provided by Küçükbay and Örün (2003) for Karakaya Reservoir was excluded because of the unrealistic concentration values provided; whereas the study by Çiçek and Koparal

(2001) did not present data in a format suitable for analysis and that by Yaman et al. (2013), albeit reporting average concentration values for some metals, relied on samples of *C. carpio* pooled across several water bodies.

The same criterion used for selection of the Turkish-based studies was applied to bioaccumulation data for *C. carpio* worldwide. In this case, the studies by Yousafzai et al. (2012) for Kabul River, Pakistan, and by Gummadavelli et al. (2013) for Edulabad Reservoir, India, were excluded from analysis due to unrealistically high values reported. Similarly, the study by Zubcov et al. (2012) from Dubasari Reservoir in Moldova was excluded because of metal concentration values provided only for gonads (i.e. not muscle, liver and/or gill).

Data preparation

For each study from Anatolia, information was retrieved about the water body under investigation, which was classified into artificial reservoir, natural lake or water course. For both the Anatolian and worldwide studies, the concentration of metals analysed for bioaccumulation and the type of tissue examined were then recorded, even though metals present at levels below detection (with limits determined depending on the individual study) were excluded from the dataset. This was because the aim of the present study was to provide a ‘quantitative’ rather than a ‘methodological’ review, but also for reasons of parsimony in the presentation of results (e.g. Patiño et al. 2013) and considering that ‘blank’ values would have not affected the outcomes of the meta-analysis. Overall, this ensured equality control and quality assurance of the methods utilised in the reviewed studies. Further, despite early attempts, no grouping of metals into ‘classes’ was made because of inconsistencies in their classification (see Nieboer and Richardson 1980; Duffus 2002; Mahboob 2013). In case of studies with replicated spatial (i.e. site level) and/or temporal (i.e. seasonal, monthly) sampling or dealing with *C. carpio* scale variants (i.e. scale, mirror) or different sexes, the mean concentration value of a metal was taken for the comparative analyses. The same criterion was applied to studies carried out in the same water body by different authors.

Owing to concentration measurements being reported in different forms (i.e. mg/g, mg/kg, μg/g, μg/kg, ppm) and to μg/g being taken as the reference measure in the present study due to its wider employment throughout the reviewed literature, the following relationship was used for conversion:

$$\mathrm{ppm} = \mathrm{mg/kg} = \mu\mathrm{g/g} = \mathrm{mg/g} \times 0.001 = \mu\mathrm{g/g}$$
$$= \mathrm{ng/g} \times 1000$$

Similarly, being wet weight most commonly reported across studies than dry weight, the following relationship was used (after Sorensen 1991):

$$\text{Wet weight} = \text{Dry weight} \times 0.33$$

Finally, whenever possible, the maximum allowed limit for concentration of a metal was obtained from the Turkish Food Codex (TFC 2002, 2011) and, if not provided therein, from FAO guidelines (Nauen 1983), with values averaged over all countries for which it was reported. Notably, except for As, Cu and Zn, for which the limits provided in the reviewed studies reporting such values were in agreement with those specified in the TFC, those for other metals were defined based on a combination of the latter whereby the selected value was set following a ‘precautionary approach’.

Statistical analysis

Differences in mean concentration amongst waterbody types (i.e. artificial reservoirs, natural lakes and water courses) and the most widely analysed tissues (i.e. muscle, liver and gill) for the eight most studied metals (i.e. Cd, Cr, Cu, Fe, Mn, Ni, Pb and Zn) on *C. carpio* in Anatolia were tested by permutational univariate analysis of variance (PERANOVA). This was based on a three-way (fully-crossed) design, which included the fixed factors waterbody type, tissue and metal. Analysis was carried out in PERMANOVA + v1.0.1 for PRIMER v6.1.11 (Anderson et al. 2008) following normalisation of the data, using a Euclidean distance and 9999 permutations of the raw data (Anderson and Robinson 2001), and with statistical effects (including a posteriori pairwise comparisons, in case of significance) evaluated at $\alpha = 0.05$. Briefly, the advantage of PERANOVA compared to traditional parametric analysis of variance is that the stringent assumptions of normality and homoscedasticity, which proved very often unrealistic when dealing with ecological datasets, are ‘relaxed’ considerably.

For the worldwide comparison, the mean values of the eight most studied metals (as above) were

Table 1 Metals and metalloids (collectively, 'metals') analysed for concentration in various tissues of *C. carpio* from water bodies of Anatolia (Turkey). For each water body, the corresponding code, type (N = natural lake; R = artificial reservoir; W = water course), latitude and longitude are given

Waterbody	Code	Type	Lat	Lon	Metal																										
					Al	As	B	Ba	Bi	Ca	Cd	Co	Cr	Cu	Fe	Ga	Hg	K	Li	Mg	Mn	Mo	Na	Ni	Pb	Se	Si	Sr	Te	V	Zn
Akın Pond[§, 28]	Akı	R	40° 19′ N	36° 27′ E									√	√	√						√			√	√						√
Almus Reservoir[§, 23, 29]	Alm	R	40° 25′ N	36° 54′ E	√						√		√	√	√						√			√	√					√	√
Altınkaya Reservoir[§, 36]	Alt	R	41° 21′ N	35° 43′ E							√			√	√						√			√	√						√
Ataköy Reservoir[§, 28]	At2	R	40° 42′ N	36° 88′ E									√	√	√						√			√	√						√
Atatürk Reservoir[¶, 20, 32]	At1	R	37° 28′ N	28° 19′ E		√								√	√						√				√						√
Avara Reservoir[§, 28]	Ava	R	40° 07′ N	36° 16′ E									√	√	√						√			√	√						√
Avşar Reservoir[38]	Avş	R	38° 25′ N	28° 60′ E							√		√	√	√									√	√						
Bafra Balık Lakes[18]	Baf	L	41°34′N	35°54′E		√					√	√	√	√	√						√			√		√					√
Bedirkale Reservoir[§, 21, 28]	Bed	R	40° 02′ N	36° 27′ E	√						√		√	√	√						√			√	√					√	√
Belpınar Reservoir[§, 28]	Bel	R	40° 10′ N	35° 56′ E									√	√	√						√			√	√						√
Beyşehir Lake[§, 1, 35, 41]	Bey	L	37° 47′ N	31° 33′ E					√	√	√	√	√	√	√		√	√	√	√	√		√	√	√			√			√
Boztepe Reservoir[§, 28]	Boz	R	40° 10′ N	35° 51′ E									√	√	√						√			√	√						√
Buldan Reservoir[39]	Bul	R	38° 16′ N	28° 84′ E										√			√														√
Çamlıgöze Reservoir[10]	Çam	R	40° 13′ N	38° 04′ E									√											√							√
Damsa Reservoir[§, 31]	Dam	R	38° 32′ N	34° 55′ E	√						√	√	√	√	√	√					√			√	√	√			√		√
Demirköprü Reservoir[37]	Dem	R	38° 61′ N	28° 31′ E							√		√	√	√									√	√						
Dutluca Reservoir[§, 29]	Dut	R	37°85′N	29°63′E							√		√	√	√						√			√	√						√
Eğirdir Lake[19]	Eği	W	38° 03′ N	30° 51′ E							√		√	√	√						√	√		√	√	√					√
Enne Reservoir[25]	Enn	R	39° 47′ N	29° 86′ E						√	√				√					√											√
Geyik Reservoir[33]	Gey	L	37° 28′ N	27° 89′ E							√	√		√	√						√			√	√						√
Goksü Delta[2]	Gok	R	36° 17′ N	34° 02′ E													√								√						
Gölcük Lake[42]	Gö1	R	38° 49′ N	39° 40′ E							√			√	√		√								√						√
Gölmarmara Lake[15, 42]	Gö2	W	38° 43′ N	27° 55′ E							√	√	√	√	√		√							√	√						√
Hampınar Pond[§, 29]	Ham	L	40° 15′ N	36° 39′ E							√		√	√	√						√			√	√						√
Işıklı Reservoir[§,17,40]	Işı	L	38° 17′ N	29° 35′ E		√		√	√	√	√	√	√	√	√			√	√	√	√		√	√	√			√			√
Karacaören I Reservoir[17]	Ka1	R	37° 37′ N	30° 83′ E					√	√	√	√	√	√	√			√	√	√	√		√	√	√			√			√
Karacaören II Reservoir[§, 24]	Ka2	R	37° 30′ N	30° 81′ E	√									√	√						√				√			√			√
Karakaya Reservoir* ,[§, 34]	Kar	R	38° 13′ N	39° 08′ E							√			√											√						√
Kaz Lake[22]	Kaz	R	40°15′N	40°22′E	√						√		√	√	√									√	√						√
Keban Reservoir[16, 43]	Keb	R	38° 48′ N	38° 45′ E							√		√	√	√									√	√						√

Table 1 (continued)

Waterbody	Code	Type	Lat	Lon	Metal																										
					Al	As	B	Ba	Bi	Ca	Cd	Co	Cr	Cu	Fe	Ga	Hg	K	Li	Mg	Mn	Mo	Na	Ni	Pb	Se	Si	Sr	Te	V	Zn
Kuş (Manyas) Lake*, [3, 9]	Kuş	L	39° 38′ N	27° 53′ E	√						√			√	√						√			√	√						√
Menzelet Reservoir[12]	Men	R	37°68′N	36°85′E							√			√																	
Mogan Lake[6]	Mog	L	39° 46′ N	32°47′E	√								√	√	√						√				√		√			√	√
Porsuk River*, [26]	Por	R	39° 42′ N	31° 59′ E			√																								
Sakarya River*, §, [5, 27]	Sak	L	41° 12′ N	30°64′E	√		√	√			√	√	√	√	√						√			√	√			√			√
Sapanca Lake[27]	Sap	L	40° 43′ N	30 °15′ E	√		√						√	√	√						√			√				√			√
Seyhan Reservoir[14]	Se1	W	37° 02′ N	35° 19′ E							√				√																√
Seyhan River*, [8]	Se2	W	36° 59′ N	35° 20′ E							√		√	√										√	√						
Sır Reservoir[11, 13]	Sır	L	37° 30′ N	36° 35′ E								√			√		√				√			√	√						
Suğla Lake§, [7]	Suğ	R	37° 34′ N	32° 03′ E									√	√	√						√			√	√						√
Yeşilırmak River§, [30]	Yeş	W	41° 22′ N	36° 39′ E							√			√	√						√			√	√						√
Zamantı River[4]	Zam	W	37° 36′ N	35° 35′ E							√		√								√										

*Spatial sampling at the site level

§ Temporal sampling at the seasonal or monthly level

¶ Scale and mirror variants

[1] Altındağ and Yiğit (2005); [2] Ayaş and Kolankaya (1996); [3] Ayas et al. (2007); [4] Aydın and Coskun (2013); [5] Barlas (1999a); [6] Benzer et al. (2013); [7] Çağlar (2010); [8] Canlı et al. (1998); [9] Çiçek et al. (2009); [10] Dirican et al. (2013); [11] Erdoğrul (2007); [12] Erdoğrul and Ateş (2006); [13] Erdoğrul and Erbilir (2007); [14] Göksu et al. (2003); [15] Gurcu et al. (2010); [16] İlhak et al. (2012); [17] Kalyoncu et al. (2012); [18] Kandemir et al. (2010); [19] Kaptan and Tekin-Özan (2014); [20] Karadede and Ünlü (2000); [21] Karatas (2008); [22] Karatas and Seker (2008); [23] Karatas et al. (2007); [24] Kır and Tumantozlu (2012); [25] Köse and Uysal (2008); [26] Köse et al. (2012); [27] Küpeli et al. (2014); [28] Mendil and Uluözlü (2007); [29] Mendil et al. (2005), [30] (2010); [31] Mert et al. (2014); [32] Mol et al. (2010); [33] Özdemir et al. (2010); [34] Özmen et al. (2006); [35] Özparlak et al. (2012); [36] Oztürk et al. (1995), [37] (2008), [38] (2009); [39] Sanlı et al. (1990); [40] Tekin-Özan and Aktan (2012); [41] Tekin-Özan and Kir (2008); [42] Uysal et al. (1987); [43] Yaman et al. (2013)

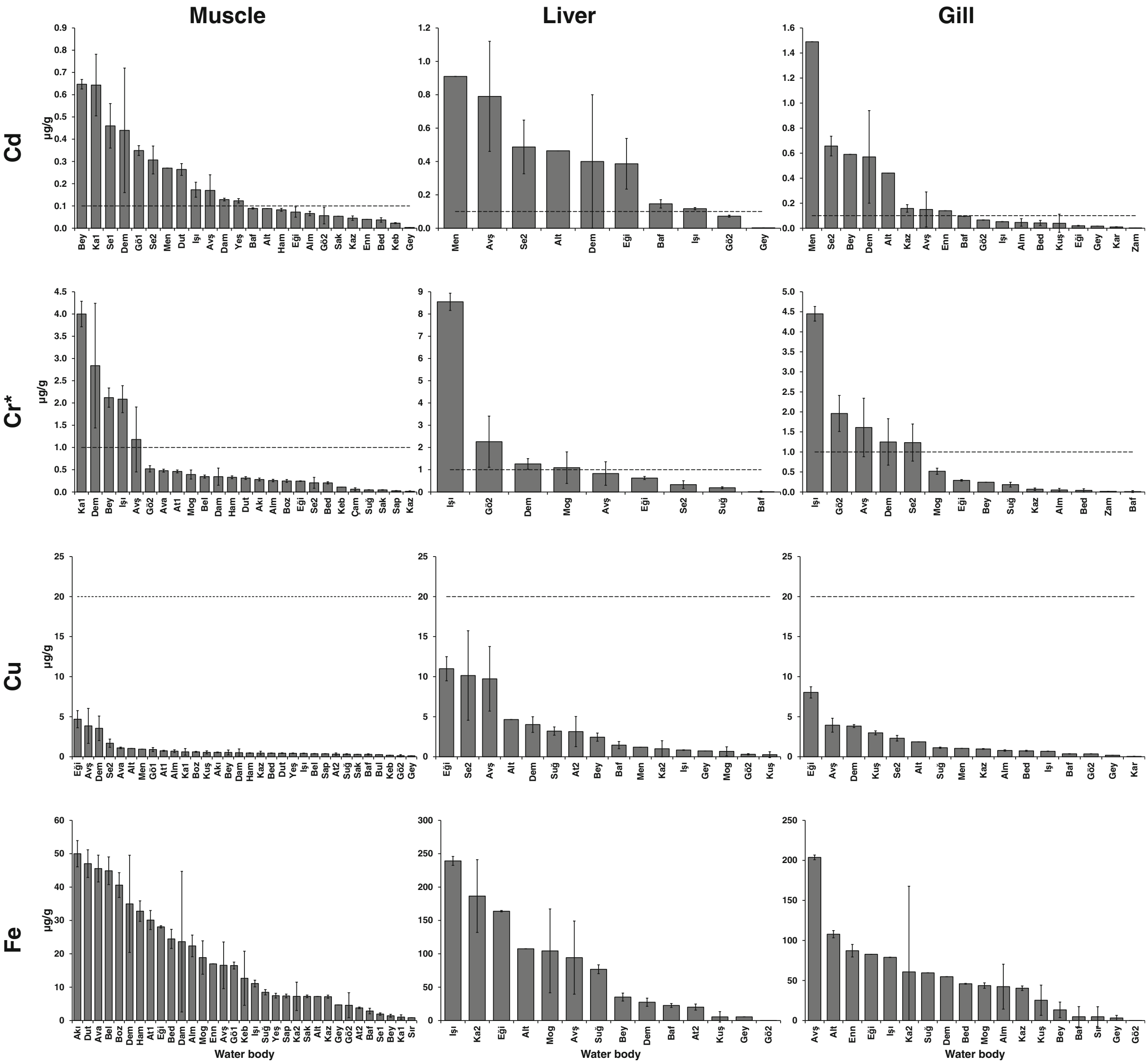

Fig. 1 Mean (± SD) concentration of the eight most abundant metals in the muscle, liver and gill tissues of *C. carpio* from water bodies of Anatolia (codes in Table 1). Whenever provided, the maximum allowed limit for concentration is indicated by a *dashed line* after Turkish Food Codex (TFC 2002, 2011), if available, or as a mean value after FAO (Nauen 1983) (corresponding metal marked by an *asterisk*; see also Appendix Table A2)

assessed against those for *C. carpio* from water bodies worldwide by means of quartile analysis (computed under Excel® 2013 as: Q0 = minimum; Q1 = lower quartile or 25th percentile; Q2 = second quartile or 50th percentile; Q3 = third quartile or 75th percentile; Q4 = maximum). Notably, quartiles were computed based on the mean concentration values of each metal from the water bodies worldwide. The waterbody-specific concentration values for *C. carpio* in Anatolia were then ranked from 0 to 4 according to the quartile into which they fell.

Results

Based on the 43 studies in total selected for review, bioaccumulation data were retrieved for *C. carpio* sampled from 42 water bodies across Anatolia (Table 1). In

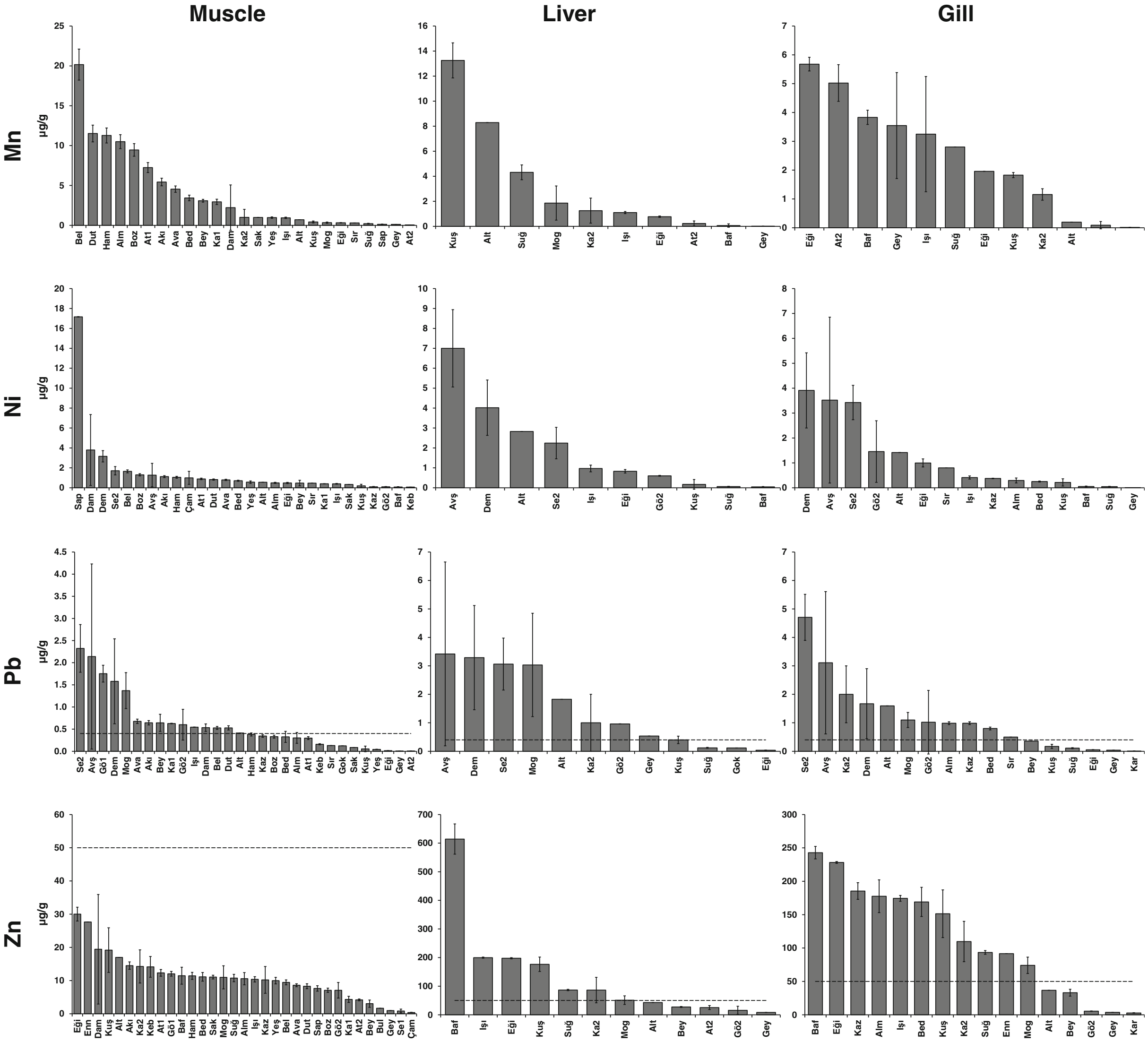

Fig. 1 continued.

total, 27 metals (Table 1) were analysed for concentration from twelve tissues of carp (Appendix Table A1). Amongst metals, Cd, Cr, Cu, Fe, Mn, Ni, Pb and Zn were the most widely analysed; amongst tissues, the muscle, liver and gill were the most commonly used (Appendix Table A2). Maximum allowed limits were provided by the TFC for As, Cd, Cu, Hg, Pb and Zn, and worldwide by FAO for Cr and Se (Appendix Table A2). Of the eight most studied metals, Cd, Cr and Pb occurred in the muscle, liver and gill in concentrations above or well above the maximum allowed limit in several water bodies, and the same was true for Zn except for the muscle tissue (Fig. 1). On the contrary, Cu was always present in concentrations below limit, whereas no limits were available for Fe, Mn and Ni, whose concentrations varied from (comparatively) high to (comparatively) low across the water bodies in which they were studied. Of the lesser-studied metals for which a limit was available, As occurred above threshold in two of the three water bodies where it was investigated, similar to Se, whereas Hg occurred at concentrations above limit in only one waterbody, and its detection was limited to the muscle tissue (Fig. 2).

Across Anatolia, amongst the metals for which maximum allowed limits were available, only Cu

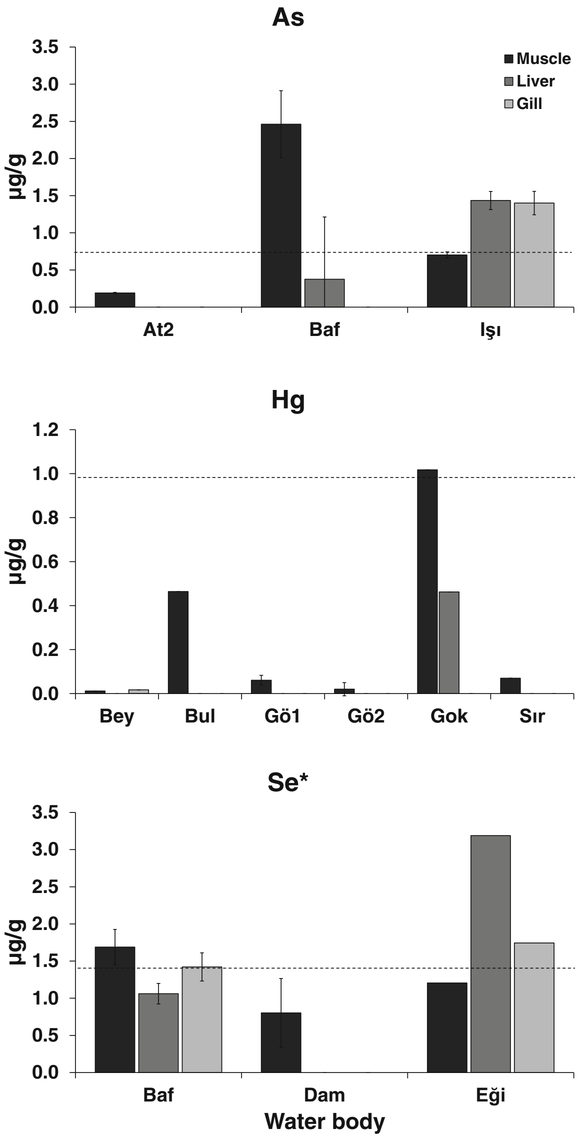

Fig. 2 Mean (± SD) concentration of three metals in the muscle, liver and gill tissues of *C. carpio* from water bodies of Anatolia (codes in Table 1). Limits as in Fig. 1

and Hg always occurred below threshold at overall mean concentrations (i.e. averaged over muscle, liver and gill tissues). Conversely, concentrations of Cd and Pb were above limit in 18 and 20 water bodies, respectively (out of the 42 in total investigated), that of Cr and Zn in six and ten water bodies, respectively, and that of As and Se in one water body (namely, Bafra Balık Lakes) in each case (Fig. 3). Overall, in 27 of the water bodies examined (equal to 67.5 % of the total) *C. carpio* was found to have one or more metals in overall mean concentrations above limit. Specifically, Bafra Bal k Lakes and Işıklı Reservoir were the water bodies with the largest number ($n = 4$) of such metals at critical concentrations, namely As, Cd, Se and Zn for the former and Cd, Cr, Pb and Zn and for the latter. Of the other water bodies, six (22 % of total) had three metals, ten (37 %) two metals and the other nine (33 %) one metal above limit (Fig. 4).

For the eight most investigated metals, there were no significant differences in their mean concentration amongst waterbody types, but there were differences amongst tissues depending on the metal (Table 2). Specifically, the mean concentrations of Cu, Fe, Pb and Zn (with the latter two metals above limit) were always significantly higher in the liver relative to muscle tissue and, except for Cu, the same was true for the gill relative to muscle tissue (Fig. 5). Conversely, there were no significant differences in the concentration amongst tissues for Cd, Cr, Mn and Ni.

Worldwide, based on 56 studies in total (Table 3), bioaccumulation data for *C. carpio* were retrieved for 102 water bodies across 23 countries. Upon comparison with the worldwide dataset (Table 3): for Cd, eight out of 18 Anatolian water bodies had concentration values (muscle, liver and/or gill tissues combined) above Q2, of which three within Q3 and the other five within Q4; for Cr, five out of six Anatolian waterbodies had concentration values above Q2, of which one within Q3 and the other four within Q4; for Pb, nine out of 20 Anatolian water bodies had concentration values above Q2, of which four within Q3 and the other five within Q4; for Se, only one water body (namely, Bafra Bal k Lakes) had a critical value within Q0; and for Zn, four out of ten Anatolian water bodies had concentration values above Q2, of which three within Q3 and the other one within Q4 (Fig. 6).

In total, in 16 out of the 42 water bodies examined (equal to 38 %) *C. carpio* was found to have one or more metals in a concentration (muscle, liver and/or gill tissues combined) within or above Q3 (Fig. 7). Specifically, Beyşehir Lake together with Demirköprü and Işıklı reservoirs were the water bodies with the largest number ($n = 3$) of metals at critical concentrations, and specifically Cd, Cr and Pb. Of the other water bodies, six (31 % of total) had two metals and the remaining eight (50 %) one metal within or above Q3.

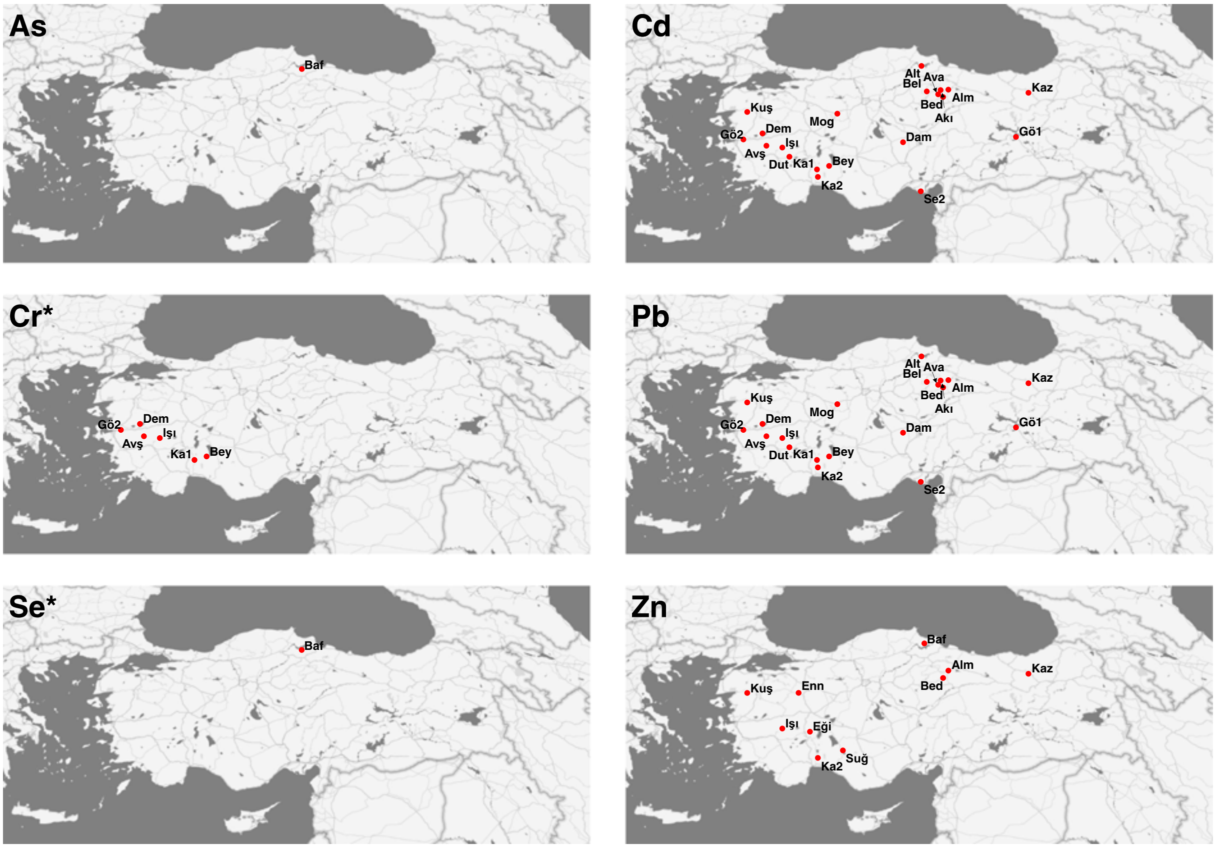

Fig. 3 Water bodies of Anatolia with above-limit mean concentrations of metals in tissues (muscle, liver and gill combined) of *C. carpio*. Limits as in Fig. 1

Discussion

Similar to other biological aspects of *C. carpio* investigated for Turkey (Vilizzi et al. 2013, 2014a, b, 2015a, b), the dense matrix of studies available at the country level has provided an extensive dataset from which to draw general conclusions about the extent of bioaccumulation of metals in *C. carpio* tissues. Cd, Cr and Pb were the toxic metals that occurred in several cases at concentrations not only above maximum allowed limits but also comparatively higher relative to other water bodies worldwide. Other toxic metals such as As, Hg and, possibly, Ni also were present in some cases at

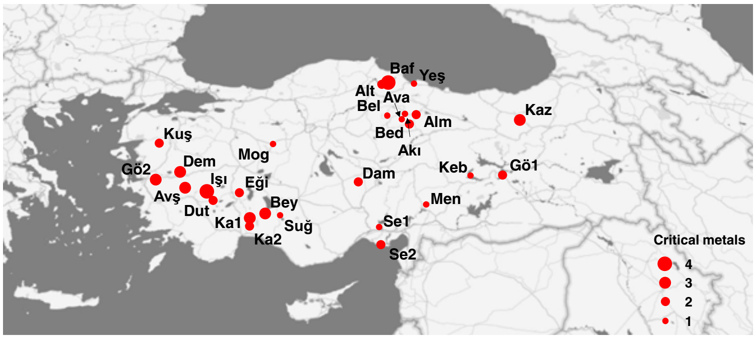

Fig. 4 Water bodies of Anatolia with one to four metals in *C. carpio* tissues (muscle, liver and gill combined) above maximum allowed limit for concentration

Table 2 PERANOVA results showing differences in the concentration of the eight most abundant metals in the muscle, liver and gill tissues of *C. carpio* from water bodies of Anatolia. Statistically significant effects ($\alpha = 0.05$) are highlighted in italic, including those for a posteriori pair-wise comparisons (# = permutational value based on 9999 permutations). See also Fig. 4

Source	df	MS	$F^{\#}$	$t^{\#}$	$P^{\#}$
Waterbody type	2	0.034	0.058		0.949
Metal	7	5.966	10.066		0.015
Tissue	2	4.249	7.169		0.020
Waterbody type × metal	14	1.086	1.833		0.082
Waterbody type × tissue	4	0.102	0.172		0.921
Metal × tissue	14	4.368	7.370		*0.017*
Cd					
Muscle vs liver				1.704	0.103
Muscle vs gill				0.648	0.509
Liver vs gill				0.622	0.518
Cr					
Muscle vs liver				1.445	0.128
Muscle vs gill				0.823	0.406
Liver vs gill				0.756	0.411
Cu					
Muscle vs liver				4.786	*0.001*
Muscle vs gill				1.717	0.079
Liver vs gill				2.184	0.066
Fe					
Muscle vs liver				4.367	*<0.001*
Muscle vs gill				3.755	*<0.001*
Liver vs gill				1.210	0.236
Mn					
Muscle vs liver				0.021	0.983
Muscle vs gill				0.290	0.740
Liver vs gill				0.291	0.790
Ni					
Muscle vs liver				0.396	0.645
Muscle vs gill				0.171	0.859
Liver vs gill				0.434	0.629
Pb					
Muscle vs liver				2.572	*0.013*
Muscle vs gill				4.951	*0.003*
Liver vs gill				1.213	0.242
Zn					
Muscle vs liver				3.654	*<0.001*
Muscle vs gill				6.809	*<0.001*
Liver vs gill				0.176	0.890
Waterbody type × metal × tissue	23	0.372	0.628		0.731
Residual	382	0.655			

potentially hazardous concentrations. Whereas, the essential metals Cu, Fe, Mn, Se and Zn were detected at various concentrations, with the latter two in some cases above limit. Overall, the present findings warrant careful evaluation given that *C. carpio* is caught throughout the country (Harlioğlu 2011) and represents in most areas an important food resource (Turkish Statistical Institute 2014).

Amongst the metals regarded as toxic (and studied more extensively in Turkey): cadmium (Cd) injures the kidney and causes symptoms of chronic toxicity, including impaired kidney function, poor reproductive capacity, hypertension, tumours and hepatic dysfunction (Waalkes 2000); chromium (Cr + 6), despite being in some cases a nutrient essential to glucose metabolism, at higher doses may cause severe environmental and public health problems and is considered a carcinogenic and mutagenic substance for humans (Rowbotham et al. 2000); lead (Pb) is known to be toxic for the brain, kidney and reproductive system and can also cause impairment in intellectual functioning, fertility, miscarriage and hypertension (Flora 2002; Yaman 2006); arsenic (As) can cause acute and chronic toxicity and turn minor disorders into cancer and even death (Bhattacharya et al. 2007); mercury (Hg) is highly toxic in metabolically active tissues causing high ecotoxicological risks (Pelletier 1995); finally, nickel (Ni), despite its being a moderately toxic element, when present in high concentrations in food may be responsible for a number of diseases (Schiavino et al. 2006).

Amongst the metals regarded as essential (and studied more extensively in Turkey): copper (Cu) is known to play a role in the activation of some important enzymes, so that changes in concentration may cause various metabolic alterations (Ozen et al. 2002); iron (Fe) plays an important role in fighting anaemia, which is not uncommon in children and women across Turkey (Walter et al. 1998); manganese (Mn) is a vital trace metal for the functioning of many organic systems where it plays a major role in the regulation of blood sugar and reproduction, digestion, and bone growth and also acts as a cellular antioxidant (Aschner and Aschner 2005); selenium (Se) has attracted attention because of its antioxidant properties, thereby protecting cells from damage (Sorensen 1991); finally, zinc (Zn) is an important trace element in human metabolism and

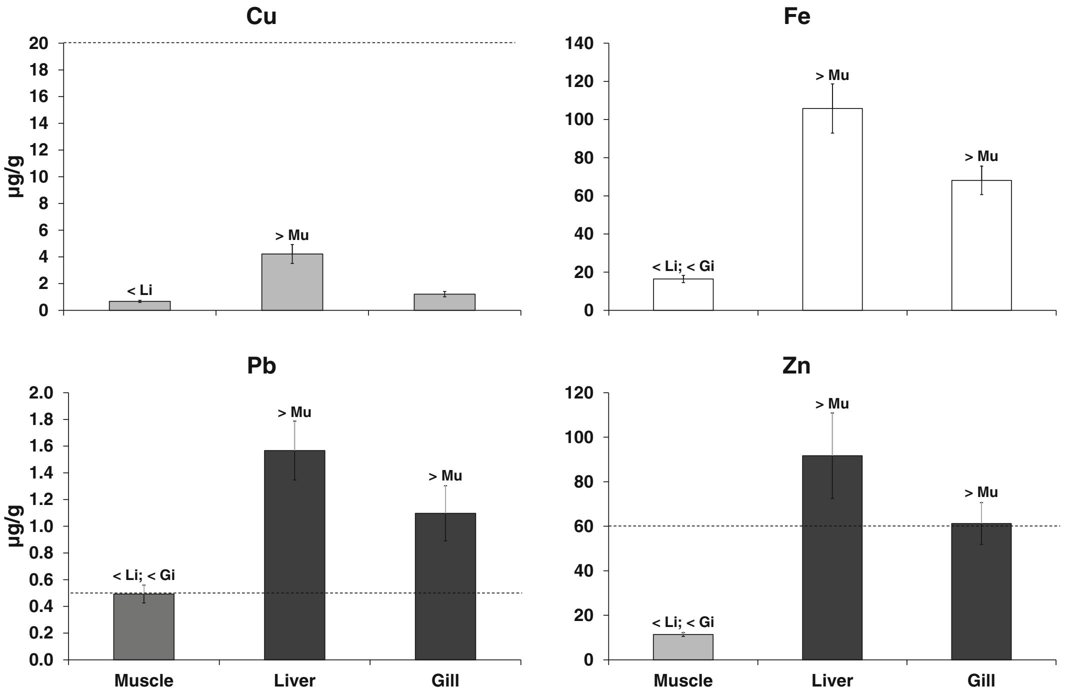

Fig. 5 Differences in mean (± SD) concentration for four of the eight most studied metals in the muscle, liver and gill tissues of *C. carpio* from water bodies of Anatolia. Limits as in Fig. 1. *Black bars*: mean concentration above limit; Pair-wise statistically significant differences are indicated (see Table 2)

nutrition and plays a major role in the functioning of many biochemical processes (Scherz and Kirchhoff 2006).

Contrary to ponds and water courses, which are generally subjected only to limited angling activities and exploitation mainly related to sport fishing, reservoirs and large natural lakes in Turkey are usually targeted by professional fishing cooperatives (but also amateur fishermen), with the rate of exploitation becoming more intense in the vicinity of highly populated areas. This is the case of e.g. Almus Reservoir (Zengin and Buhan 2007), Keban Reservoir (Celayir et al. 2006; Orsay and Duman 2005, 2008b; Yüngül et al. 2012), Menzelet Reservoir (Alp et al. 2003), Seyhan Reservoir (Ozyurt et al. 2004; Çiçek et al. 2006; Mete and Yüksel 2014) and Lake Eğirdir (Balık et al. 2007). All these water bodies support productive *C. carpio* fisheries and were flagged in the present study as having critical levels of certain toxic metals in *C. carpio* tissues.

Based on the current review, an even more critical situation was identified for Bafra Balık Lakes and Işıklı Reservoir (relative to Turkish water bodies) and for Beyşehir Lake (relative to water bodies worldwide), and this was due to elevated concentrations of both toxic and essential metals. Notably, Işıklı Reservoir is located in populated Denizli Province and supports cooperative-based fishing exploitation of *C. carpio* (Eren and Tenekecioğlu 2006), whereas Beyşehir lake (which is located in the city of Konya) is known to support very large catches of *C. carpio* (Balık and Çubuk 2004).

Bafra Balık Lakes also were flagged in the present study as yielding high concentrations of toxic As (but also essential Se and Zn) in *C. carpio* tissues. This lake system consists of 33 small water bodies located in Samsun Province, where *C. carpio* also represents a favourite local dish. Contrary to artificial reservoirs, with their typical V-shaped profile and high depth resulting in a restricted littoral zone area, this type of water bodies provides for extensive shallow and vegetated areas ideal for successful spawning of *C. carpio* (Balon 1995). In this respect, it has been argued that, if successful stocking of *C. carpio* and related productive fisheries are to be achieved, shallow (natural) lakes in general should be targeted as potential alternative waterbodies to

Table 3 Comparative table for the concentration (μg/g) of metals in carp from water bodies of Anatolia (Turkey) relative to waterbodies worldwide. For each of the most widely studied metals, the mean concentration is provided only if above the maximum allowed limit, otherwise indicated by a '<' value (see Appendix Table A2). For water bodies of Anatolia, the quartile range (0 = minimum; 1 = lower quartile or 25th percentile; 2 = second quartile or 50th percentile; 3 = third quartile or 75th percentile; 4 = maximum) is given based on the mean concentration values for the water bodies worldwide

Country	Waterbody	As	Cd	Cr	Cu	Hg	Pb	Se	Zn	Source
Turkey	Akın Pond	–	–	<1	<20	–	0.64 (2)	–	<50	Mendil and Uluözlü (2007)
	Almus Reservoir	–	<0.1	<1	<20	–	<0.4	–	<50	Mendil et al. (2005)
		–	<0.1	<1	<20	–	0.67 (2)	–	92.98 (2)	Karatas et al. (2007)
	Altınkaya Reservoir	–	0.33 (2)	–	<20	–	1.28 (3)	–	<50	Oztürk et al. (1995)
	Ataköy Reservoir	–	–	<1	<20	–	<0.4	–	<50	Mendil and Uluözlü (2007)
	Atatürk Reservoir	–	–	–	<20	–	–	–	<50	Karadede and Ünlü (2000)
		<1	–	–	<20	–	<0.4	–	<50	Mol et al. (2010)
	Avara Reservoir	–	–	<1	<20	–	0.68 (2)	–	<50	Mendil and Uluözlü (2007)
	Avşar Reservoir	–	0.37 (3)	1.21 (1)	<20	–	2.89 (4)	–	–	Öztürk et al. (2009)
	Bafra Balık Lakes	1.42*	0.11 (1)	<1	<20	–	–	1.39 (0)	289.53 (4)	Kandemir et al. (2010)
	Bedirkale Reservoir	–	–	<1	<20	–	<0.4	–	<50	Mendil and Uluözlü (2007)
		–	<0.1	<1	<20	–	0.53 (2)	–	88.50 (2)	Karatas (2008)
	Belpınar Reservoir	–	–	<1	<20	–	0.53 (2)	–	<50	Mendil and Uluözlü (2007)
	Beyşehir Lake	–	0.58 (4)	<1	–	<1	<0.4	–	–	Altındağ and Yiğit (2005)
		–	–	–	<20	–	–	–	<50	Tekin-Özan and Kir (2008)
		–	0.72 (4)	4.00 (4)	<20	–	0.94 (3)	–	<50	Özparlak et al. (2012)
	Boztepe Reservoir	–	–	<1	<20	–	<0.4	–	<50	Mendil and Uluözlü (2007)
	Buldan Reservoir	–	–	–	<20	<1	–	–	<50	Sanlı et al. (1990)
	Çamlıgöze Reservoir	–	–	<1	–	–	–	–	<50	Dirican et al. (2013)
	Damsa Reservoir	–	0.13 (1)	<1	<20	-	0.53 (2)	<1.15	<50	Mert et al. (2014)
	Demirköprü Reservoir	–	0.47 (3)	1.78 (4)	<20	–	2.18 (4)	–	–	Öztürk et al. (2008)
	Dutluca Reservoir	–	0.26 (2)	<1	<20	–	0.53 (2)	–	<50	Mendil et al. (2005)
	Eğirdir Lake	–	0.16 (1)	<1	<20	–	<0.4	<1.15	151.96 (3)	Kaptan and Tekin-Özan (2014)
	Enne Reservoir	–	<0.1	–	–	–	–	–	59.60 (0)	Köse and Uysal (2008)
	Geyik Reservoir	–	<0.1	–	<20	–	<0.4	–	<50	Özdemir et al. (2010)
	Goksü Delta	–	–	–	–	<1	<0.4	–	–	Ayaş and Kolankaya (1996)
	Gölcük Lake	–	0.35 (2)	–	<20	<1	1.75 (4)	–	<50	Uysal et al. (1987)
	Gölmarmara Lake	–	0.11 (0)	–	<20	<1	0.89 (3)	–	<50	Uysal et al. (1987)
		–	<0.1	1.58 (3)	<20	–	0.76 (3)	–	<50	Gurcu et al. (2010)
	Hampınar Pond	–	<0.1	<1	<20	–	<0.4	–	<50	Mendil et al. (2005)
	Işıklı Reservoir	–	0.66 (4)	4.06 (4)	<20	–	0.54 (2)	–	<50	Kalyoncu et al. (2012)
		<1	<0.1		<20	–	–	–		Tekin-Özan and Aktan (2012)

Table 3 (continued)

Country	Waterbody	As	Cd	Cr	Cu	Hg	Pb	Se	Zn	Source
				4.86 (4)					128.90 (3)	
	Karacaören I Reservoir	–	0.64 (4)	4.00 (4)	<20	–	0.63 (2)	–	<50	Kalyoncu et al. (2012)
	Karacaören II Reservoir	–	–	–	<20	–	1.50 (3)	–	70.08 (1)	Kır and Tumantozlu (2012)
	Karakaya Reservoir	–	<0.1	–	<20	–	<0.4	–	<50	Özmen et al. (2006)
	Kaz Lake	–	0.10 (0)	<1	<20	–	0.67 (2)	–	97.80 (2)	Karatas and Seker (2008)
	Keban Reservoir	–	0.16 (1)	–	<20	–	<0.4	–	<50	İlhak et al. (2012)
		–	<0.1	<1	<20	–	<0.4	–	–	Yaman et al. (2013)
	Kuş (Manyas) Lake	–	–	–	–	–	<0.4	–	–	Ayas et al. (2007)
		–	<0.1	–	<20	–	0.48 (1)	–	115.69 (3)	Çiçek et al. (2009)
	Menzelet Reservoir	–	0.89 (4)	–	<20	–	–	–	–	Erdoğrul and Ateş (2006)
	Mogan Lake	–	–	<1	<20	–	1.83 (4)	–	<50	Benzer et al. (2013)
	Sakarya River	–	<0.1	–	<20	–	<0.4	–	–	Barlas (1999a)
		–	–	<1	<20	–	–	–	<50	Küpeli et al. (2014)
	Sapanca Lake	–	–	<1	<20	–	–	–	<50	Küpeli et al. (2014)
	Seyhan Reservoir	–	0.46 (3)	–	–	–	–	–	<50	Göksu et al. (2003)
	Seyhan River	–	0.48 (4)	<1	<20	–	3.36 (4)	–	–	Canlı et al. (1998)
	Sır Reservoir	–	–	–	–	<1	–	–	–	Erdoğrul (2007)
		–	–	–	–	–	<0.4	–	–	Erdoğrul and Erbilir (2007)
	Suğla Lake	–	–	<1	<20	–	<0.4	–	63.60 (1)	Çağlar (2010)
	Yeşilırmak River	–	0.12 (1)	–	<20	–	<0.4	–	<50	Mendil et al. (2010)
	Zamantı River	–	<0.1	<1	–	–	–	–	–	Aydın and Coskun (2013)
Rest of the world		–	2.86	–	<20	–	8.97	–	65.40	
Algeria	El Izdihar Reservoir	–	0.86	–	<20	–	2.83	–	<50	Zineb and Nacéra (2013)
		<1	0.38	–	–	<1	0.87	–	–	Derrag and Youcef (2014)
Bosnia and Herzegovina	Buško Blato Reservoir	–	–	–	–	–	–	–	62.22	Has-Schön et al. (2015)
Bulgaria	Kardjali Reservoir	–	–	–	–	–	–	–	99.62	Velcheva (2006)
	Studen Kladenetz Reservoir	<1	1.81	–	<20	–	1.36	–	93.67	Velcheva (2006)
	Topolnitsa Reservoir	<1	0.35	–	<20	–	0.42	–	<50	Yancheva et al. (2014)
China	Nansi Lake	–	<0.1	–	–	–	<0.4	–	<50	Zhu et al. (2015)
	Taihu Lake	–	<0.1	–	–	<1	<0.4	–	–	Chi et al. (2007)
Czech Republic	Berounka River	–	<0.1	–	–	<1	<0.4	–	–	Cerveny et al. (2014)
	Dalesice Reservoir	–	–	–	–	<1	–	–	–	Cerveny et al. (2014)
	Domani Reservoir	–	<0.1	–	–	<1	<0.4	–	–	Cerveny et al. (2014)
	Elbe River, Obristvi	–	–	–	–	<1	<0.4	–	–	Cerveny et al. (2014)
	Elbe River, Pardubice	–	–	–	–	<1	<0.4	–	–	Cerveny et al. (2014)
	Elbe River, Svadov	–	–	–	–	<1	<0.4	–	–	Cerveny et al. (2014)
	Hnevkovice Reservoir	–	<0.1	–	–	<1	<0.4	–	–	Cerveny et al. (2014)
	Jesenice Reservoir	–	–	–	–	<1	<0.4	–	–	Cerveny et al. (2014)

Table 3 (continued)

Country	Waterbody	As	Cd	Cr	Cu	Hg	Pb	Se	Zn	Source
	Jordan Reservoir	–	<0.1	–	–	<1	<0.4	–	–	Cerveny et al. (2014)
	Korensko Reservoir	–	–	–	–	<1	<0.4	–	–	Cerveny et al. (2014)
	Lipno Reservoir	–	<0.1	–	–	<1	<0.4	–	–	Cerveny et al. (2014)
	Luznice River, Majdalena	–	<0.1	–	–	<1	<0.4	–	–	Cerveny et al. (2014)
	Luznice River, Sobeslav	–	<0.1	–	–	<1	<0.4	–	–	Cerveny et al. (2014)
	Musov Reservoir	–	–	–	–	<1	<0.4	–	–	Cerveny et al. (2014)
	Nechranice Reservoir	–	<0.1	–	–	<1	<0.4	–	–	Cerveny et al. (2014)
	Odra River, Ostrava	–	<0.1	–	–	<1	<0.4	–	–	Cerveny et al. (2014)
	Odra River, Strakonice	–	<0.1	–	–	<1	<0.4	–	–	Cerveny et al. (2014)
	Olesna Reservoir	–	<0.1	–	–	<1	<0.4	–	–	Cerveny et al. (2014)
	Orlik Reservoir	–	–	–	–	<1	–	–	–	Cerveny et al. (2014)
	Pliska Reservoir	–	–	–	–	<1	<0.4	–	–	Vicarova et al. (2014)
	Rozkos Reservoir	<1	<0.1	–	<20	–	<0.4	–	<50	Cerveny et al. (2014)
	Skalka Reservoir	–	<0.1	–	–	<1	<0.4	–	–	Sevcikova et al. (2013)
		–	–	–	–	<1	–	–	–	Cerveny et al. (2014)
	Slapy Reservoir	–	<0.1	–	–	<1	<0.4	–	–	Cerveny et al. (2014)
	Slezska Harta Reservoir	–	<0.1	–	–	<1	<0.4	–	–	Cerveny et al. (2014)
	Terlicko Reservoir	–	–	–	–	<1	<0.4	–	–	Cerveny et al. (2014)
	Trnavka Reservoir	–	<0.1	–	–	<1	<0.4	–	–	Cerveny et al. (2014)
	Vetrov Reservoir	–	<0.1	–	–	<1	<0.4	–	–	Cerveny et al. (2014)
	Vranov Reservoir	–	<0.1	–	–	<1	<0.4	–	–	Cerveny et al. (2014)
	Zermanice Reservoir	–	0.17	<1	<20	–	0.41	–	<50	Cerveny et al. (2014)
Ethiopia	Hashenge Lake	–	–	1.45	<20	–	1.60	–	<50	Asgedom et al. (2012)
India	Gomti River	–	0.38	<1	<20	–	<0.4	–	<50	Tiwari and Dwivedi (2014)
	Mudasalodai coastal waters	–	0.17	<1	<20	–	<0.4	–	<50	Santhi and Prabhahar (2014)
	Muzhukuthurai coastal waters	–	<0.1	<1	<20	–	<0.4	–	<50	Santhi and Prabhahar (2014)
	Tumkur Tank	–	<0.1	<1	<20	–	<0.4	–	<50	Sreedhara Nayaka et al. (2009)
	Vellar Estuary	–	–	–	–	<1	–	–	–	Santhi and Prabhahar (2014)
Iran	Anzali Wetland	–	0.11	–	<20	–	0.45	–	<50	Tabatabaie et al. (2011)
		–	<0.1	<1	<20	–	0.51	–	<50	Babaei and Khodaprast (2013)
		–	<0.1	–	<20	<1	–	–	<50	Panahandeh et al. (2014)
	Caspian Sea	–	<0.1	<1	–	–	<0.4	–	–	Saravi et al. (2013)
	Eastern beach	–	–	–	–	<1	–	–	–	Saeedi Saravi and Shokrzadeh (2013)
	Gomishan Wetland	–	<0.1	<1	–	–	<0.4	–	–	Tabatabaie et al. (2011)
		–	<0.1	–	<20	–	<0.4	–	<50	Saeedi Saravi and Shokrzadeh (2013)
	Gorgan Bay (Caspian Sea)	–	<0.1	<1	–	–	<0.4	–	–	Raeisi et al. (2014)
	Gorgan coast	–	–	–	–	<1	–	–	–	Saeedi Saravi and Shokrzadeh (2013)
	Karoun River	<1	<0.1	–	–	<1	0.73	–	–	Maktabi et al. (2015)
	Kor River	–	–	–	–	67.16	–	–	–	Ebrahimi and Taherianfard (2011)

Table 3 (continued)

Country	Waterbody	As	Cd	Cr	Cu	Hg	Pb	Se	Zn	Source
	Sanandaj Gheshlagh Reservoir	–	–	–	–	<1	–	–	–	Khoshnamvand et al. (2013)
		–	0.38	<1	<20	–	0.63	–	<50	Mansouri et al. (2014)
		–	0.48	1.73	<20	–	6.09	–	407.22	Maleki et al. (2015)
	Shadegan Wetland	–	–	–	<20	–	<0.4	–	<50	Alhashemi et al. (2012)
	Shirinsu Wetland	1.01	<0.1	–	–	<1	–	–	–	Ardakani and Jafari (2014)
		<1	<0.1	–	<20	<1	<0.4	–	<50	Ardakani and Jafari (2015)
	Taham Reservoir	–	<0.1	<1	–	–	<0.4	–	–	Sobhanardakani et al. (2014a)
	Western beach	–	<0.1	<1	<20	–	0.64	–	<50	Saeedi Saravi and Shokrzadeh (2013)
	Zabol Chahnimeh Reservoirs	–	<0.1	–	<20	<1	0.50	–	–	Ariyaee et al. (2015)
	Zarivar Wetland	–	–	–	<20	–	<0.4	–	<50	Majnoni et al. (2013)
		<1	<0.1	–	–	<1	–	–	–	Jafari and Sobhanardakani (2014)
		<1	<0.1	<1	<20	–	<0.4	<1.15	103.22	Sobhanardakani and Jafari (2014b)
Japan	Lake Kasumigaura	–	0.14	–	<20	–	–	–	<50	Alam et al. (2002)
Jordan	Wadi El-Arab River	–	<0.1	–	<20	–	<0.4	–	–	Al-Weher (2008)
Kenya	Lake Naivasha	–	–	<1	<20	–	<0.4	–	<50	Ogendi et al. (2014)
	Masinga Reservoir	<1	–	–	<20	<1	<0.4	–	<50	Nzeve (2015)
Mexico	Luis L. Leon Reservoir	–	<0.1	–	–	–	<0.4	–	–	Luna-Porres et al. (2014)
	River Palisade	<1	–	–	–	–	–	7.68	–	Jarquín-Raymundo et al. (2014)
Nigeria	Alaro Stream	–	–	1.89	–	1.53	0.70	–	175.05	Tyokumbur and Okorie (2014)
Pakistan	Indus River	–	–	–	<20	–	–	–	–	Jabeen and Chaudhry (2010)
	Kalpani stream	–	0.20	1.36	<20	–	1.62	–	63.38	Yousafzai et al. (2014)
	Rawal Lake	–	<0.1	–	–	–	–	–	–	Iqbal and Shah (2014)
Philippines	Bulacan River	–	–	–	<20	–	<0.4	–	<50	De Regla et al. (2015)
Romania	Danube River	<1	<0.1	<1	<20	<1	–	<1.15	172.78	Ioniță et al. (2014)
Serbia	Danube River	–	0.18	–	–	<1	–	–	–	Subotić et al. (2013)
Slovakia	Kolíňany Pond	–	–	1.40	<20	–	<0.4	–	<50	Tóth et al. (2014)
South Africa	Medunsa Lake	–	<0.1	–	–	<1	–	–	–	Olowoyo et al. (2014)
Sri Lanka	Bomuruella Reservoir	–	0.50	–	<20	–	–	–	260.28	Hettige et al. (2015)
Ukraine	Seret River	–	–	–	–	<1	–	–	–	Falfushynska and Stoliar (2009)
USA	Arkansas River	–	0.13	–	–	–	3.18	–	<50	Chalmers et al. (2011)
	Bir River	–	–	–	–	<1	–	–	–	Schmitt et al. (2006)
	Colorado River, Imperial Reservoir	–	–	–	–	<1	–	–	–	Chalmers et al. (2011)
	Columbia River	–	–	–	–	<1	–	–	–	Chalmers et al. (2011)
	Cumberland River	–	–	–	–	<1	–	–	–	Chalmers et al. (2011)
	Des Moines River	–	–	–	–	<1	–	–	–	Chalmers et al. (2011)
	Green River	–	–	–	–	<1	–	–	–	Chalmers et al. (2011)
	Illinois River	–	–	–	–	<1	–	–	–	Chalmers et al. (2011)
	James River	–	–	–	–	<1	–	–	–	Chalmers et al. (2011)
	Lake Huron	<1	<0.1	<1	<20	<1	<0.4	1.93	83.90	Chalmers et al. (2011)
	Lake Mead	–	–	–	–	<1	–	–	–	Patiño et al. (2013)
	Lake Powell, Colorado River	–	–	–	–	<1	–	–	–	Chalmers et al. (2011)

Table 3 (continued)

Country	Waterbody	As	Cd	Cr	Cu	Hg	Pb	Se	Zn	Source
	Mississippi River	–	–	–	–	<1	–	–	–	Chalmers et al. (2011)
	Missouri River	–	<0.1	–	–	–	<0.4	–	<50	Chalmers et al. (2011)
	Neosho River	–	<0.1	–	–	–	<0.4	–	<50	Schmitt et al. (2006)
	Neosho River-Tar Creek	–	–	–	–	<1	–	–	–	Schmitt et al. (2006)
	North Platte River, Lake McConaughy	–	–	–	–	<1	–	–	–	Chalmers et al. (2011)
	Ohio River (IL/KY)	–	–	–	–	<1	–	–	–	Chalmers et al. (2011)
	Ohio River (OH/KY)	–	–	–	–	<1	–	–	–	Chalmers et al. (2011)
	Red River, Lake Texoma	–	–	–	–	<1	–	–	–	Chalmers et al. (2011)
	Sacramento River	–	<0.1	–	–	–	0.49	–	<50	Chalmers et al. (2011)
	Spring River	–	–	–	–	<1	–	–	–	Schmitt et al. (2006)
	Susquehanna River, Conowingo Dam	<1	<0.1	<1	<20	<1	<0.4	<1.15	–	Chalmers et al. (2011)
	US Rivers	–	–	–	–	<1	–	–	–	Hinck et al. (2008)
	Utah Lake	–	–	–	–	<1	–	–	–	Chalmers et al. (2011)
	Verdigris River, Bartlesville Reservoir	–	–	–	–	<1	–	–	–	Chalmers et al. (2011)
	Wabash River	–	–	–	–	<1	–	–	–	Chalmers et al. (2011)
	Wisconsin River	–	0.11	1.02	<20	–	1.02	–	<50	Chalmers et al. (2011)
Vietnam	West Lake	–	–	<1	<20	–	0.64 (2)	–	<50	Pham et al. (2007)

* No quartile category indicated because of lack of reference values for the worldwide data

reservoirs (Gaygusuz et al. 2015). As Bafra Balık Lakes does represent one such potential area in a country with overall limited availability of shallow water bodies, the finding of elevated metal concentrations in the feral population of *C. carpio* in these lakes raises concerns not only about the feasibility of suggested potential stocking alternatives but also about the safety of *C. carpio* consumed locally as food.

The significantly higher concentrations of some metals (namely, Cu, Fe, Pb and Zn) in the liver (but also gill) relative to the muscle tissue are in line with findings from other studies, which indicate that the liver and gill are metabolically active and accumulate metals in higher levels relative to the muscle, not only in *C. carpio* (e.g. Velcheva 2006; Alhashemi et al. 2012; Ardakani and Jafari 2014) but more generally in fish (Allen 1994, 1995; Spehar et al. 1998). This is because, unlike other tissues, the muscle does not come into direct contact with metals as it is covered externally by the skin and also does not function as an active site for detoxification (hence transport of trace metals to other tissues). Further, as regards food processing, this finding is noteworthy as it may have important implications for health and food safety should the preparation of meat balls and sausages from *C. carpio* involve the utilisation of body parts other than the muscle (fillet).

Unlike the many studies (both Turkey-based and worldwide, and reviewed herein) on *C. carpio* bioaccumulation that have focused on individual water bodies, to the author's knowledge, the present review has been the first one to provide a country-level synthesis and evaluation of the topic. This is important if guidelines are to be provided for the management of sustainable and healthy fisheries and related legislation is to be amended/implemented. To this end, a similar meta-analytical approach as the one used in the current study is suggested for other countries where *C. carpio* represents an important resource for fisheries. This could be the case for e.g. Iran, where in the last two decades the per capita consumption of fish (including *C. carpio*) has increased sharply (Ebrahimi and Taherianfard 2011),

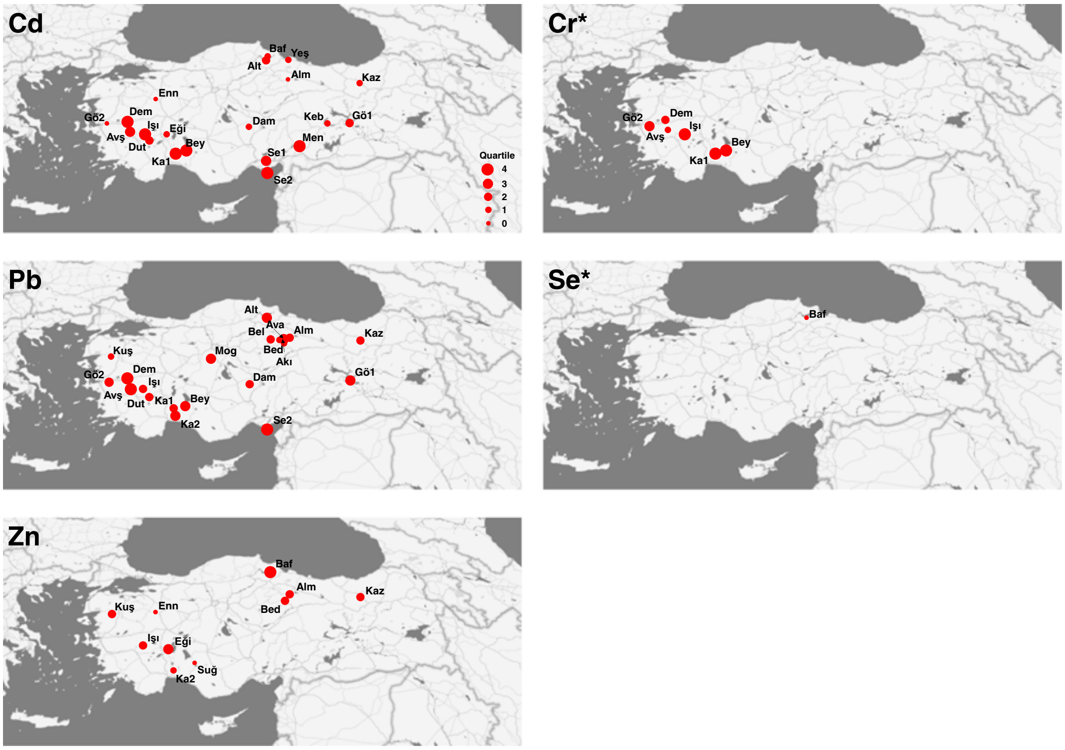

Fig. 6 Water bodies of Anatolia with concentration of metals in *C. carpio* tissues (muscle, liver and gill combined) above maximum allowed limit relative to critical values worldwide. Quartiles as defined in Table 3

and for which the second largest number of bioaccumulation studies (after Turkey) was retrieved in this review (Table 3).

At the country level, the present findings indicate that there is a pressing need to re-evaluate the status of *C. carpio* fisheries in most water bodies, and especially those located in the proximity of highly populated areas due to potentially excessive levels of bioaccumulated metals that may ultimately pose a risk to human health. As the current TFC does not include limits for toxic Cr, the value of 1.0 μg/g suggested in the present study may be included in future legislation and the same could

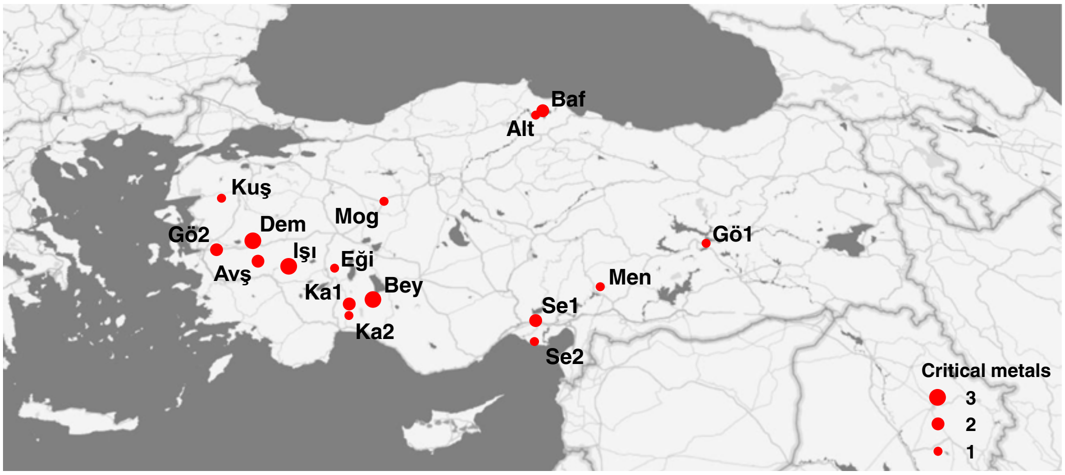

Fig. 7 Water bodies of Anatolia with one to four metals above maximum allowed limit for concentration in *C. carpio* tissues (muscle, liver and gill combined) relative to critical values worldwide. Quartiles as defined in Table 3

apply to the value of 1.15 μg/g for (essential) Se. Finally, within a broader international context, the current synthesis and evaluation study on bioaccumulation of metals in (edible) *C. carpio* in Turkey will help contribute to the improvement of the country's food safety policy, so as to align with e.g. expected European Commission standards (European Commission 2013).

Acknowledgments The authors are grateful to to Güler Ekmekçi, Baran Yoğurtçuoğlu, Fatma Kübra Erbay, Cüneyt Solak, Ünal Erdem, Naime Arslan, Ruşen Ustaoğlu, Oğuz Öztürk and İbrahim Cengizler for assistance with literature retrieval and organisation. Contribution to this study by LV was through a 2221 Fellowship Programme granted by The Scientific & Technological Research Council of Turkey (TÜBİTAK) and The Department of Science Fellowships & Grant Programs (BİDEB).

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