Research Brief

Otolith microchemistry of koi carp in the Waikato region, New Zealand: a tool for identifying recruitment locations?

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Abstract

We assessed differences in the otolith microchemistry of koi carp, a colour variant of the invasive common carp *Cyprinus carpio*, at various locations in the Waikato region of New Zealand. Although koi carp are abundant here, little is known about where and in what habitats they breed. We investigated the feasibility of determining the natal habitats of adult koi carp (in the Waikato River, selected tributaries, and riverine lakes in the catchment) using otolith elemental signatures and employing laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). Differences in elemental concentrations in water among the sites indicated that variation in otolith microchemistry was likely. Ratios of manganese (Mn), rubidium (Rb), strontium (Sr), and barium (Ba) to calcium (Ca) in otolith edges differed significantly among the sites, and Sr:Ca in the water and otoliths was positively correlated. A discriminant function analysis using Rb, Sr, and Ba accurately classified the otolith edge signatures of koi carp from some locations, but the otolith signatures of koi carp caught from adjacent locations were often indistinguishable. This suggests that our results could have been confounded by either (1) recent movement of koi carp or (2) a lack of differences in water chemistry among sites. Taken together, these results demonstrate that otolith microchemistry can be used to test retrospectively for koi carp migration between sites on a broad scale in the Waikato region, but fine-scale movements may not be detectable.

Key words: *Cyprinus carpio*, habitat utilization, invasive species, LA-ICP-MS, migration, Waikato River

Introduction

Common carp (*Cyprinus carpio*) have been introduced to or have invaded dozens of countries, are now distributed widely around the world (FAO 2011), and are apt to spread further due to their broad ecological tolerances (Koehn 2004, Zambrano et al. 2006). This is cause for concern because common carp act as ecosystem engineers, affecting nutrient concentrations, turbidity, phytoplankton, zooplankton, benthic macro-invertebrates, waterfowl, and submerged macrophytes (Bajer et al. 2009, Matsuzaki et al. 2009, Weber and Brown 2009). Common carp may also cause shallow lakes to change from clear and macrophyte-dominated to turbid and phytoplankton-dominated (Matsuzaki et al. 2009, Weber and Brown 2009). These negative effects are most often attributed to the suspension of fine sediments that occurs during carp foraging (Sibbing et al. 1986).

Common carp were introduced to New Zealand waters in the 1960s (McDowall 1990) and have been classified as an unwanted organism (Biosecurity Act 1993). The strain present in New Zealand is the koi carp, a highly coloured variety that originated from ornamental stocks (McDowall 1990). Koi carp account for up to 95% of the fish biomass at some locations in the Waikato region and can reach densities of 2000 kg ha^{-1} (Osborne 2006). The potential impacts of their introduction were reviewed by Hanchet (1990).

Adult common and koi carp in Australia and New Zealand show variable movement patterns; tagging studies showed that some individuals remained within limited ranges (<5 km), but others moved over 100 km within weeks and often returned to their original locations (Stuart and Jones 2006a, Osborne et al. 2009, Daniel et al. 2011). Migrations are most common during the spawning season and following reductions in water levels that affect habitat

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availability (Daniel et al. 2011). Floodplains and riverine lakes provide spawning habitat for common carp in Australia (King et al. 2003, Crook and Gillanders 2006, Stuart and Jones 2006b). This is also likely to be true in the Waikato region of New Zealand, where adult koi carp have been observed moving repeatedly between rivers and riverine lakes (Boubée et al. 2004, Daniel et al. 2011); however, the spawning locations of New Zealand koi carp have yet to be identified.

Large-scale habitat changes in fishes can be detected by testing for differences in otolith elemental concentrations. The applications include stock determination (e.g., Campana et al. 2000), determining natal habitats (e.g., Thorrold et al. 2001), and determining the timing and source of new species introductions (e.g., Munro et al. 2005). Otolith concentrations of such elements as strontium and barium are related to water concentrations (Bath et al. 2000, Elsdon and Gillanders 2005, Collingsworth et al. 2010). Otoliths reflect the chemical environment experienced by the fish throughout its lifetime (Campana 1999), making it possible to infer the natal environment of adult fish using elemental concentrations in the otolith nucleus (Wells et al. 2003, Brazner et al. 2004, Clarke et al. 2007). Of the 3 types of otolith (lapillus, sagitta, and asteriscus), the asterisci are largest in ostariophysan fishes such as carp (Secor et al. 1991) and were used in this study.

The objective of this study was to examine the feasibility of using otolith elemental signatures to identify koi carp spawning locations in the lower Waikato River and surrounding areas by examining between-site differences in (1) elemental concentrations in water and (2) otolith elemental signatures.

Study site

The koi carp we studied were residents of the Waikato River in New Zealand's North Island (450 km long; catchment 11 395 km^2; Fig. 1). The river's watershed has been modified by agriculture, forestry, and urban development, and hydroelectric dams regulate its flows. Lakes Whangape, Waikare, and Waahi are eutrophic shallow riverine lakes that drain to the Waikato River via controlled outlets. The Whangamarino Wetland is a complex of peat bogs, swamp, open water, and river systems that drains to the Waikato River and is connected

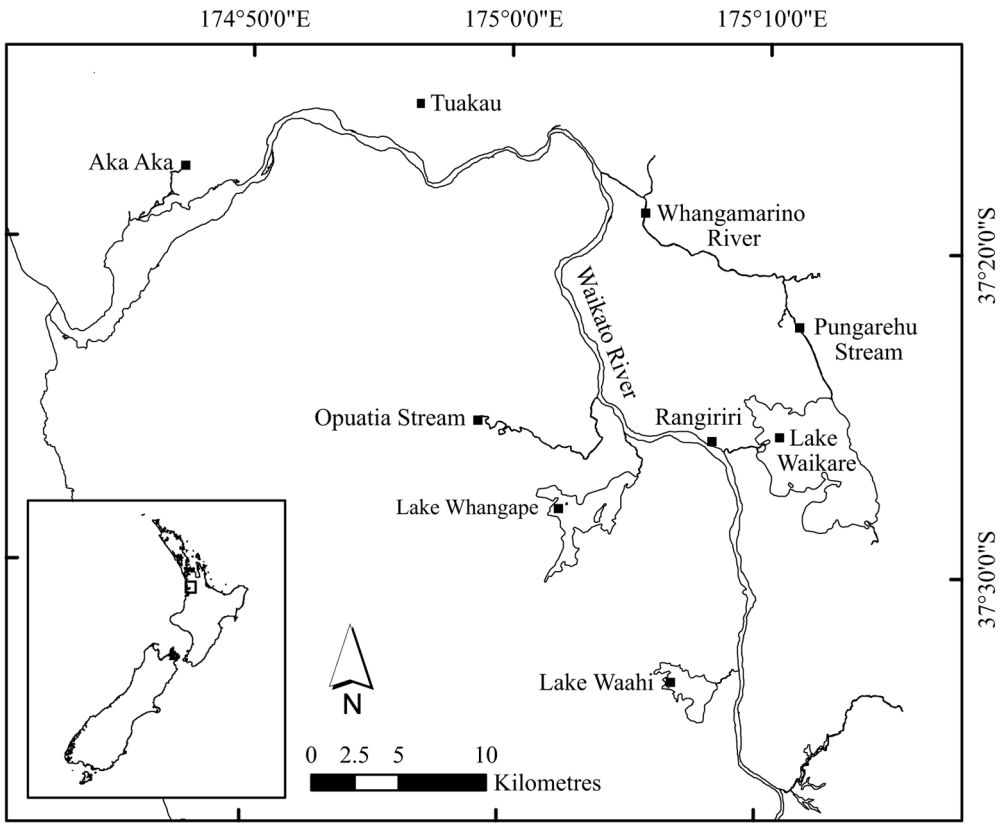

Fig. 1. Study area in the lower Waikato region, North Island, New Zealand, showing locations where koi carp were collected.

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to Lake Waikare via Pungarehu Stream (Fig. 1). Opuatia Stream drains the Opuatia Wetland, a peat bog entering the Waikato River downstream of Rangiriri.

Methods

We characterised otolith microchemistry in adult and juvenile koi carp collected from the lower Waikato River and surrounding areas using boat electric fishing, backpack electric fishing, fyke nets, trammel nets, and bow hunting. We caught 77 adult koi carp between November 2007 and March 2008 from Lakes Whangape, Waikare, and Waahi, from the Whangamarino River, Opuatia Stream, and Pungarehu Stream, and from 2 locations in the Waikato River (Fig. 1, Table 1). We caught 14 juvenile koi carp between November 2007 and March 2008 from Lake Waikare, Pungarehu Stream, and the Whangamarino River, and 14 adult koi carp between November 2002 and November 2003, including 2 carp from Opuatia Stream, 5 from Lake Whangape, 4 from the Whangamarino River, and 3 from Lake Waikare. Sample locations were close to major centres of carp abundance in the Waikato River basin (Osborne 2006) and included the largest lakes and wetlands in the lower Waikato River catchment.

We measured elemental concentrations in otoliths using laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). Asteriscus otoliths were used because they are the largest otoliths in koi carp (Vilizzi and Walker 1995). Otoliths were removed, rinsed in Milli-Q ultrapure water, dried in a laminar flow cabinet, mounted in PELCO Epoxy Resin and Fast Cure Hardener (Redding, CA), and cut into 0.5 mm sections using a Buehler IsoMet low-speed saw (model 11-1280-160, Lake Bluff, IL). Sections were polished until the nucleus was reached using a sequence of 400–2000 grit waterproof silicon carbide papers wetted with Milli-Q water. The polished sections were then mounted on microscope slides using Crystalbond 509 adhesive (12 per slide), rinsed in Milli-Q water, and dried overnight in a laminar flow cabinet.

Table 1. Fork lengths (mean ± 1 standard error) and sample sizes (*N*) of sampled juvenile and adult koi carp reported by site.

Adult/ juvenile	Capture site	Fork length (mm)	*N*
Juvenile	Lake Waikare	68.6 ± 3.8	5
	Pungarehu Stream	50.8 ± 5.4	7
	Whangamarino River	134.0 ± 2.4	2
	Juveniles - all sites	69.8 ± 8.3	14
Adult	Lake Waahi	490.1 ± 15.8	11
	Lake Waikare	432.7 ± 12.4	14
	Lake Whangape	424.2 ± 13.5	14
	Opuatia Stream	334.5 ± 38.5	8
	Pungarehu Stream	247.4 ± 13.1	7
	Aka Aka	459.7 ± 15.2	11
	Rangiriri	478.4 ± 11.1	16
	Whangamarino River	378.9 ± 14.2	10
	Adults - all sites	419.2 ± 9.1	91

Otoliths were ablated in a sealed chamber using a New Wave Research UP-213 Laser Ablation System (Fremont, CA) with a 213 nm Nd-YAG laser. The ablated material was carried in a helium (He) and argon (Ar) gas mixture to a Perkin Elmer DRCII ELAN 6000 ICP-MS (Waltham, MA), which determined the elemental compositions of magnesium (^{25}Mg), aluminium (^{27}Al), calcium (^{42}Ca and ^{43}Ca), manganese (^{55}Mn), copper (^{65}Cu), zinc (^{66}Zn), nickel (^{62}Ni), rubidium (^{85}Rb), strontium (88Sr), and barium (^{137}Ba). National Institute of Standards and Technology Standard Reference Material 612 (NIST SRM 612) was used as a standard for all our analyses using the elemental concentrations reported by Pearce et al. (1997). For our NIST 612 analyses, our laser settings were 60% laser power, 60 µm spot size, 10 Hz repetition rate, and a 60 s laser dwell time. For the otoliths, the settings were 50% laser power, 50 µm spot size, 5 Hz repetition rate, and a 40 s laser dwell time. These settings, respectively, produced stable signals. Background elemental concentrations were measured for 60 s prior to each ablation by analysing a gas blank (firing the laser with the shutter closed). Two spots on the NIST 612 reference material were ablated before otolith analysis began, and then after every 10–12 otolith spots to account for instrument drift during the session. The sample chamber was purged with Ar and He for at least 10 min after each introduction of new samples. Two circular spots were ablated on each otolith: one at the centre of the primordium (referred to hereafter as the nucleus), representing early growth, and one as close as possible to the dorsal or ventral otolith edge, representing recent growth.

The GLITTER software package (GEMOC Laser ICP-MS Total Trace Element Reduction) version 4.4.1 (Van Achterbergh et al. 2001) was used to select the relevant background and sample signals and calculate elemental concentrations in otoliths relative to background levels. The first 5 s of ablation were excluded from analysis to avoid results from otolith surface contamination. Minimum detection limits (99% confidence interval) were calculated by GLITTER using background readings and Poisson counting statistics (Table 2). Readings below detection limits were not used in analyses. Elemental

Table 2. Minimum detection limits (MDL) and the percentage of otolith readings measuring above the MDL for Ca, Mn, Rb, Sr, and Ba.

Attribute	Ca	Mn	Rb	Sr	Ba
MDL (μg g^{-1})	3792	0.82	0.42	3.8	0.85
Readings > MDL (%)	100	52.0	47.6	100	100

concentrations were analysed as molar ratios to Ca, and outliers that fell outside 2 standard deviations from the mean value were excluded from further analyses.

Water samples were taken from lakes Waikare, Waahi, and Whangape and the Whangamarino and Waikato rivers at Aka Aka and Rangiriri (Fig. 1) in January 2008. Three samples were taken from each site using 15 mL syringes, filtered using Millipore 0.45 μm glass fibre filter units, and preserved with nitric acid (2% of sample volume). Elemental concentrations in the filtered water samples were determined using the same ICP-MS as the otoliths. Water samples were introduced to the ICP-MS using a Perkin-Elmer S10 autosampler (Waltham, MA).

Between-site differences in element ratios to Ca in water, otolith edges, and otolith nuclei were assessed using a one-way ANOVA, or a nonparametric Kruskal-Wallis ANOVA by ranks for elements where the data were not normally distributed. Normality of data was tested using the Kolmogorov-Smirnov test ($\alpha < 0.05$). Tukey's HSD was used to evaluate which locations showed differences in water elemental concentrations. Because Mn is often elevated at the otolith nucleus in other fish species, we tested if this was the case in koi carp by comparing Mn between otolith nuclei and edges using a Wilcoxon matched pairs test, with the edge and nucleus measurements on each otolith treated as a matched pair. Correlations between element ratios in water and otolith edges were assessed using the Pearson product-moment correlation coefficient.

We used a linear discriminant function analysis (DFA) to evaluate the possibility of distinguishing koi carp caught at different sites on the basis of otolith elemental concentrations. The DFA used Wilks' Lambda and the *F*-statistic to test mean differences between more than 2 groups. A linear stepwise DFA was carried out using the otolith edge concentrations of Rb, Sr, and Ba. These elements were used because they met the assumptions of this method (normality and homogeneity of variances) and have been used successfully in previous studies of otolith microchemistry (Friedrich and Halden 2008, Collingsworth et al. 2010). Rb, Sr, and Ba all had sufficient discriminatory power (i.e., the *F*-statistic was >1) and were included in the final model. We did not use the DFA to classify elemental concentrations in the otolith nuclei because juveniles were not caught from all locations, meaning that we could not adequately characterise natal signatures from all possible source habitats. All data analyses were carried out using STATISTICA (Statsoft Inc., Tulsa, OK).

Results

Elemental concentrations in water

Ca concentrations in our water samples varied significantly among sites (Kruskal-Wallis test; $N = 18$, $p = 0.005$; Table 3). Ratios of elements to Ca in water differed among sites, although no particular site showed consistently high ratios of all the elements. Median Mn:Ca, Rb:Ca, Sr:Ca, and Ba:Ca values in our water samples differed significantly among sites, although no significant differences were found in element ratios to Ca between the 2 river sites (Fig. 2).

Elemental concentrations in koi carp otoliths

Elemental ratios in koi carp otoliths were also highly variable. The median Mn:Ca and mean Rb:Ca, Sr:Ca, and Ba:Ca values from the koi carp otolith edges (representing recent growth) and otolith nuclei (early growth) differed significantly across our sites (Fig. 3; Table 4). The Mn:Ca values were consistently higher in the otolith nuclei than at their edges (Wilcoxon matched pairs test; $N = 34$, $Z = 3.68$, $p < 0.001$; Fig. 3). Ratios of Mn, Rb, Sr, and Ba to Ca seemed to vary between adults and juveniles caught at the same locations, although this difference was not statistically significant for Sr or Ba ratios (Mann-Whitney U-test, $p > 0.05$). We did not obtain sufficient readings of Mn and Rb above detection limits in the otolith edges of juvenile koi carp, preventing comparison of these elements between adults and juveniles caught at the same site. Sr:Ca in the otolith edges was positively correlated to values in the respective fish source waters (Table 5).

Table 3. Mean ± 1 standard error (SE) of Ca concentrations (μg kg^{-1}) in water samples from locations in the Waikato region.

Location	Ca (μg kg^{-1}) ± SE
Lake Waahi	11930 ± 218
Lake Waikare	2091 ± 25
Lake Whangape	8167 ± 49
Waikato River at Aka Aka	2900 ± 24
Waikato River at Rangiriri	2618 ± 32
Whangamarino River	3000 ± 10

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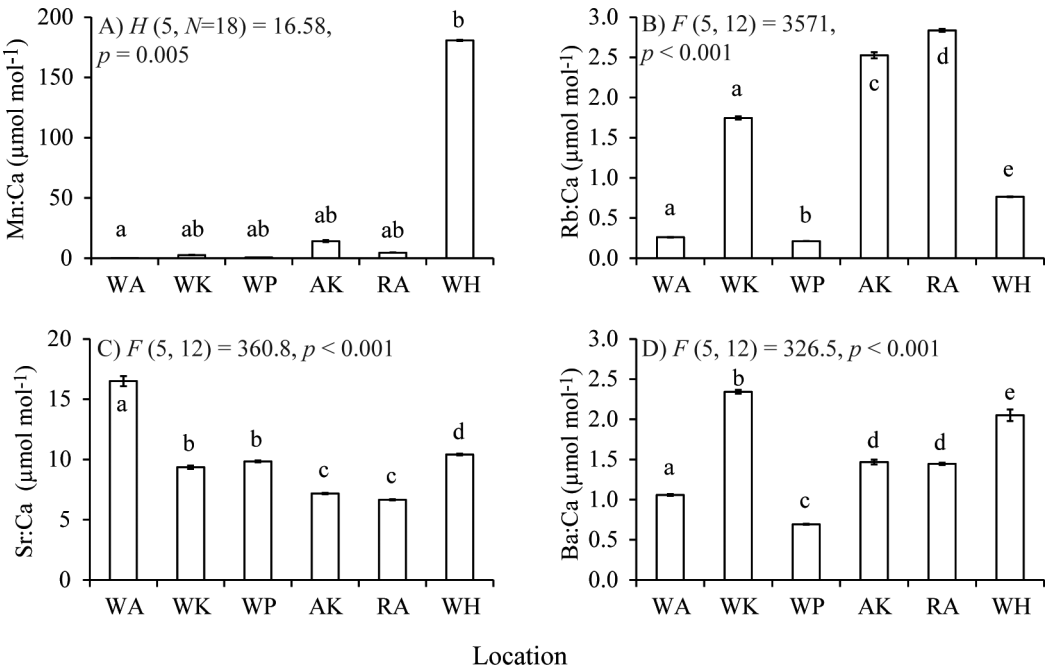

Fig. 2. Mean molar ratios of elements to Ca in water from various locations in the Waikato River catchment. Median Mn ratios between sites tested with a Kruskal-Wallis ANOVA by ranks; mean Rb, Sr, and Ba ratios between sites tested with a one-way ANOVA. Error bars show ± 1 standard error. WA = Lake Waahi, WK = Lake Waikare, WP = Lake Whangape, AK = Aka Aka, RA = Rangiriri, WH = Whangamarino River (refer to Fig. 1 for site locations). For all elements, df = 5 and $N = 18$. Letters *a–e* denote groups that did not differ (Kruskal-Wallis test using multiple comparisons for Mn; Tukey's HSD for Rb, Sr, and Ba).

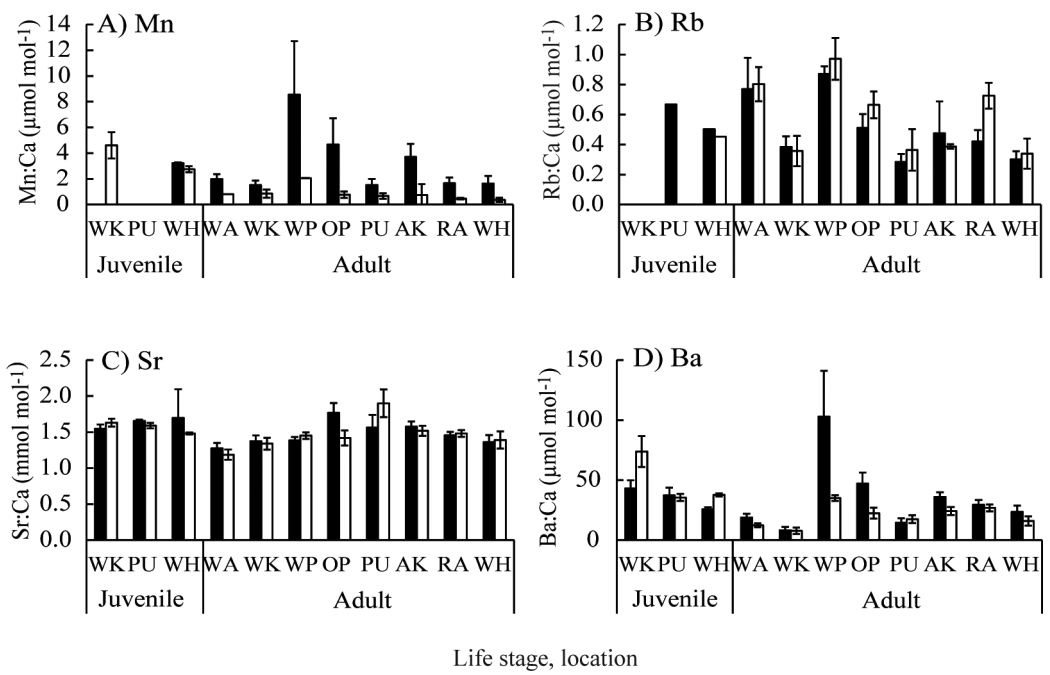

Fig. 3. Mean molar ratios of elements to Ca in the nucleus (solid bars) and edge (open bars) of juvenile (<140 mm fork length) and adult (>140 mm fork length) koi carp otoliths. Error bars show ± 1 standard error. WA = Lake Waahi, WK = Lake Waikare, WP = Lake Whangape, OP = Opuatia Stream, PU = Pungarehu Stream, AK = Aka Aka, RA = Rangiriri, WH = Whangamarino River (refer to Fig. 1 for site locations). Missing bars indicate where an element was not measured at a level exceeding detection limits (Table 2).

Table 4. Results of tests comparing element ratios to Ca in koi carp otolith edges and nuclei across all sites (for site locations see Fig. 1). Mn:Ca ratios between sites tested with a Kruskal-Wallis ANOVA by ranks; Rb:Ca, Sr:Ca, and Ba:Ca tested with a one-way ANOVA. Bold italics indicate *p*-values significant at $\alpha < 0.05$.

Element ratio	Otolith edge		Otolith nucleus	
	Test statistic	*p*	Test statistic	*p*
Mn:Ca	H (7, N = 96) = 17.4	***0.015***	H (7, N = 96) = 18.4	***0.010***
Rb:Ca	F (7, 42) = 5.202	***<0.001***	F (7, 38) = 2.525	***0.031***
Sr:Ca	F (7, 74) = 4.447	***<0.001***	F (7, 81) = 3.326	***0.004***
Ba:Ca	F (7,74) = 5.874	***<0.001***	F (7, 81) = 3.857	***0.001***

Table 5. Pearson product-moment correlation coefficients (r) between the mean ratios of elements to Ca in otolith edges and the mean ratios of elements to Ca in water. Bold italics indicate *p*-values significant at $\alpha < 0.05$. N = 6 for all elements.

Element	*r*	*p*
Mn	−0.423	0.403
Rb	0.621	0.188
Sr	0.909	***0.012***
Ba	0.706	0.117

A forward stepwise discriminant function analysis of ratios of Ba, Sr, and Rb to Ca in koi carp otolith edges was able to correctly classify otoliths to some capture sites (Wilks' Lambda = 0.239, F (15, 119) = 5.387, $p < 0.001$; Table 6). The 2 Waikato River sites and Lake Waikare and Pungarehu Stream sites were combined because initial analyses were unable to distinguish between them. Otolith edge elemental concentrations were classified to their capture site with an overall accuracy of 59%. The majority of otoliths from fish caught at Lake Waahi, Lake Waikare/Pungarehu Stream, and the Waikato River were classified accurately to their site of capture, whereas none of the otoliths of fish caught from the Whangamarino River and Opuatia Stream were classified accurately. Several otoliths were assigned to the Waikato River in error, and several otoliths from the Whangamarino River and Opuatia Stream were mistakenly assigned to adjacent habitats (i.e. Pungarehu Stream/Lake Waikare, and Lake Whangape, respectively).

Discussion

Among-site variation in koi carp otolith microchemistry

Our initial detection of differences in water chemistry across locations in the Waikato River indicated that finding differences in the otolith chemistry of the fish captured therein was a possibility. Our subsequent results showed that that koi carp otolith chemistry did indeed differ between capture locations and could potentially be

Table 6. Stepwise discriminant function analysis (DFA) of Ba, Sr, and Rb concentrations in otolith edges of 71 adult and young-of-the-year koi carp from 6 capture locations in the Waikato River and surrounding areas, showing predicted classification compared to capture site. Expected classifications (based on capture site) are given in parentheses. AK = Aka Aka, RA = Rangiriri, OP = Opuatia Stream, PU = Pungarehu Stream, WK = Lake Waikare, WA = Lake Waahi, WH = Whangamarino River, WP = Lake Whangape.

Capture site (observed classification)	Predicted classification using otolith edge						Total	% correct
	AK/RA	OP	PU/WK	WA	WH	WP		
AK/RA	21 (27)	0 (0)	4 (0)	1 (0)	0 (0)	1 (0)	27	77.8
OP	3 (0)	0 (8)	1 (0)	0 (0)	0 (0)	4 (0)	8	0.0
PU/WK	5 (0)	0 (0)	23 (29)	0 (0)	0 (0)	1 (0)	29	79.3
WA	2 (0)	0 (0)	0 (0)	7 (9)	0 (0)	0 (0)	9	77.8
WH	4 (0)	0 (0)	7 (0)	0 (0)	0 (11)	0 (0)	11	0.0
WP	6 (0)	0 (0)	1 (0)	1 (0)	0 (0)	4 (12)	12	33.3

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used to detect differences in carp habitat use over time. The consideration of Rb:Ca, Sr:Ca, and Ba:Ca ratios is recommended for future studies of koi carp movement in the Waikato River system because otolith concentrations of these elements (1) varied across sites and (2) are influenced by ambient water concentrations. Various combinations of Mg, K, Mn, Sr, and Ba have been used elsewhere to trace the movements of various fish species (Thorrold et al. 1998, Wells et al. 2003, Brazner et al. 2004). From other work, we know that Mn concentrations in otoliths are influenced by temperature, and that Mg is metabolically regulated in freshwater fish such that a significant relationship between water and otolith concentrations may not be apparent (Collingsworth et al. 2010); therefore, ratios of Mg and Mn to Ca are unlikely to be useful for future studies of koi carp movement in the Waikato River catchment. Although Rb is analysed less commonly in studies of fish movement, concentrations of Rb in fish otoliths have been found to vary between capture sites where Rb is present in the surrounding environment (Friedrich and Halden 2008).

The linear discriminant function analysis of Rb, Sr, and Ba classified the otoliths of koi carp to their site of capture with an overall accuracy of 59%. The low classification accuracy of the otolith elemental concentrations of fish from some sites may be due to recent migration of fish between sites or similarity of elemental concentrations in water between sites. Carp in Australia and New Zealand typically migrate between river main stems and off-channel habitats, including shallow lakes (Jones and Stuart 2009, Daniel et al. 2011). Proportions of koi carp otoliths from all our sites were mistakenly assigned to the Waikato River, possibly indicating recent movement between these habitats. Also, otoliths of koi carp from Opuatia Stream were often misclassified to Lake Whangape, and otoliths from the Whangamarino River were erroneously classified to adjacent and connecting habitats, such as the Waikato River, Pungarehu Stream, and Lake Waikare; however, we were unable to determine the cause of these misclassifications in this study.

Assumptions of otolith microchemical methods

Conclusions regarding fish movement derived from otolith chemistry assessments assume that fish have been residents at their capture locations long enough for their otoliths to deposit an analysable increment that incorporates the trace elements present at that site (Elsdon et al. 2008). For common carp in the Murray River, Australia, growth in otolith length can be described by a log-linear function, where otolith length (mm) = 3.556 + 2.508 × ln (age in years) (Vilizzi and Walker 1999). Although variation between fish is likely, if we assume that otolith growth rates are similar in New Zealand and Australian carp, the laser spot size used in this study (50 μm) would represent approximately 9 d of growth for a 2-year-old fish, or approximately 13 d of growth for a 5-year-old fish. Because otolith growth slows as the fish grows older, older koi carp would need to have been resident at their capture location for longer to incorporate the local elemental signature.

Philopatry seems to be common in New Zealand and Australian carp, although intervening movements may be substantial (Jones and Stuart 2009, Osborne et al. 2009, Daniel et al. 2011): correspondingly, 82% of radio-tracked carp in the Waikato region returned to a site after absences of more than 6 months (Daniel et al. 2011), whereas 74% of radio-tracked carp moved between the Waikato River and its riverine lakes and wetlands over a period of 250 days. Given these movement tendencies, recent movements by the koi carp we sampled may have possibly resulted in otolith elemental signatures that did not yet match those of their capture sites, resulting in high variability in otolith elemental signatures within sites and misclassification of otoliths to sites. To reduce this variability, the elemental signature of source habitats should be characterised using otoliths from juvenile koi carp, which are less likely to have moved between locations.

Temporal variability in elemental concentrations in the surrounding water may also increase the variability of otolith elemental concentrations. Our measured Ca concentrations in the Waikato River at Rangiriri and Aka Aka were lower than previously measured yearly means (Lam 1981), indicating that elemental concentrations likely changed over time, and may change seasonally. In our study, however, this variation was not measured because water samples were taken on one occasion, and koi carp were collected over a longer time period. This probably contributed to the lack of correlation between concentrations of most elements in water and concentrations in otoliths collected from the same sites. Because temporal variation in elemental concentrations in water is common and may cause variation in otolith elemental signatures of resident fish, otolith signatures may not be stable over time (Elsdon et al. 2008). A series of water samples taken over time would be needed to fully characterize the elemental concentrations in water at a particular site. Equally, fish should be collected on several occasions to take into account temporal variability of elemental concentrations in the water. Otolith chemical signatures from one year may differ significantly from those in fish collected at the same site the next year (Gillanders 2002, Schaffler and Winkleman 2008, Pangle et al. 2010);

therefore, the otoliths collected in 2003–2004 possibly increased the variability of our data. We recommend compiling a "library" of juvenile otoliths from multiple years so that fish movement patterns can be evaluated with precision (Elsdon et al. 2008), especially because within-site temporal variability in koi carp otolith signatures has yet to be assessed.

Common carp usually spawn in floodplain wetlands, isolated anabranches, and billabongs (King et al. 2003), and floodplain lakes are important sources of carp recruits to the Murray River (Crook and Gillanders 2006). To enable biologists to identify the previously-occupied natal sources of the older carp they capture, knowledge of the otolith microchemistry of fish from all potential source locations must be obtained (Elsdon et al. 2008). Thus, for the Waikato system, future studies must consider juveniles from all possible spawning locations (i.e., all significant wetlands and lakes in the catchment). We collected adult koi carp from the largest lakes and wetlands in the lower Waikato catchment (below Karapiro dam), and our sample sites probably provided adequate coverage of possible habitat. The sampled lakes (Waahi, Whangape, and Waikare) measure 5414 ha, comprising 90% of the total area of lakes in the catchment (5986 ha). We also sampled outlets of the 2 largest wetlands in the catchment (Beard 2010). Smaller lakes and wetlands not sampled in this study may also provide spawning habitat, but the contribution of these lakes and wetlands to overall habitat is likely to be comparatively small.

Mn concentrations in otoliths

Elevated Mn:Ca values in the nuclei of otoliths have been observed in several species and from across a range of habitats and locations worldwide (Brophy et al. 2004, Ruttenberg et al. 2005). These studies analysed sagittal otoliths, which are composed of aragonite, whereas koi carp asteriscus otoliths are made of vaterite (Lenaz et al. 2006); consequently, Mn seems to be elevated at the cores of both otolith types. The deposition of elements in otoliths is affected by differences in the structures of the 2 minerals (Lenaz et al. 2006), and the uptake of Mn has been shown to be higher in vateritic sections of the otolith than in aragonitic sections (Melancon et al. 2005). Differences in the mineral structure of koi carp otoliths may possibly account for the elevated Mn levels in the nuclei; also, differences in otolith structure may have caused variation in elemental concentrations among otoliths. To resolve this issue, verification of the mineral structure of koi carp otoliths in the Waikato region is required.

Conclusion

Compared to mark–recapture methods, otolith microchemical signatures provide a straightforward and cost-effective method for identifying natal habitats in fishes and can be used to detect the occurrence of broad-scale, long-term movements without the need to tag and monitor individuals. Because the otoliths of koi carp from some locations in the Waikato River could be correctly classified to their capture site based on elemental concentrations, this technique shows promise for identifying movements on a broad spatial scale, providing that the appropriate technical improvements are incorporated; however, lack of differences in water chemistry between adjacent locations may mean that fine-scale movements cannot be detected with this method.

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