Transactions of the American Fisheries Society 148:417–425, 2019

ISSN: 0002-8487 print / 1548-8659 online
DOI: 10.1002/tafs.10142

ARTICLE

Sources of Bighead Carp and Silver Carp Found in Chicago Urban Fishing Program Ponds

Seth A. Love*
Illinois Department of Natural Resources, Division of Fisheries, 13608 Fox Road, Yorkville, Illinois 60560, USA; and Illinois Natural History Survey, Illinois River Biological Station, 704 North Shrader Avenue, Havana, Illinois 62644, USA

Nathan J. Lederman
Illinois Department of Natural Resources, Division of Fisheries, 13608 Fox Road, Yorkville, Illinois 60560, USA

Tristan Widloe
Illinois Department of Natural Resources, Division of Fisheries, 5931 Fox River Drive, Plano, Illinois 60545, USA

Gregory W. Whitledge
Center for Fisheries, Aquaculture and Aquatic Sciences, Southern Illinois University, Carbondale, Illinois 62901, USA

Abstract
Planktivorous Bighead Carp *Hypophthalmichthys nobilis* and Silver Carp *H. molitrix* are two invasive species that pose a severe threat to native aquatic biota. Efforts have been made to inhibit Bighead Carp and Silver Carp expansion into the Great Lakes through hydrologically connected systems, but understanding their expansion to and from hydrologically disconnected systems could further reduce this risk. We assessed the origin of 23 Bighead Carp and 1 Silver Carp captured from Chicago Urban Fishing Program ponds using otolith chemistry. Otolith core $\delta^{18}O$ and $\delta^{13}C$ of captured Bighead Carp did not overlap with ranges of otolith $\delta^{18}O$ and $\delta^{13}C$ from Bighead Carp and Silver Carp from the Illinois River but was consistent with otolith $\delta^{18}O$ and $\delta^{13}C$ of Bighead Carp obtained from aquaculture facilities. Likewise, otolith core Sr:Ca of 19 captured Bighead Carp was higher than the range of otolith Sr:Ca from Illinois River Bighead Carp and Silver Carp. Due to inferred timing of introduction (likely age-0 or age-1 fish), these Bighead Carp may have been released incidentally via stocking sport fish shipments contaminated with the carp. Contrastingly, otolith chemistry results suggest that the captured Silver Carp originated from the Illinois River, although timing of introduction of this fish could not be inferred. Overall, our results indicate that nearly all fish analyzed did not originate from rivers within the Mississippi River basin and were instead likely introduced through stocking contaminated shipments of fish. Even though Chicago Urban Fishing Program ponds now pose a minimal threat for Bighead Carp and Silver Carp expansion into Lake Michigan, sustained urban pond monitoring and nonnative fish removal may limit or eliminate this alternative invasion pathway. Additionally, continued vigilance in understanding the origin of stocked fish and culture environment (e.g., polyculture) could decrease the likelihood of future invasive species introductions through contaminated sport fish stockings.

While nonnative species have been invading native ecosystems for millennia, globalization has increased the number of biological invasions (Hulme 2009). Approximately 50,000 invasive species have been introduced within the United States alone, costing US$120 billion annually in environmental damages and control efforts (Pimentel et al.

*Corresponding author: seth.love@illinois.gov
Received June 18, 2018; accepted November 30, 2018

2005). Biological invasions also represent the second greatest threat to imperiled species (Wilcove et al. 1998) because invasive species can outcompete native species for resources (Schrank et al. 2003; Irons et al. 2007), reduce native populations through predation (Albins and Hixon 2008), or alter native community structure (Solomon et al. 2016). Thus, understanding invasive species expansion and preventing new introductions are necessary to conserve native ecosystems and curtail economic losses (Leung et al. 2002).

Two invasive species that pose a severe threat to native aquatic biota within the United States are planktivorous Bighead Carp *Hypophthalmichthys nobilis* and Silver Carp *H. molitrix*. Following introduction into the United States in the 1970s (Henderson 1976), Bighead Carp and Silver Carp escaped confinement and began spreading throughout the Mississippi River basin (Sampson et al. 2009). Range expansion of Bighead Carp and Silver Carp has caused great concern amongst Mississippi River basin fisheries managers because they are highly fecund (Schrank and Guy 2002; Williamson and Garvey 2005), exhibit rapid growth rates (Williamson and Garvey 2005), and can rapidly disperse (DeGrandchamp et al. 2008). Furthermore, Bighead Carp and Silver Carp are voracious planktivores capable of consuming 20% of their body weight per day (Kolar et al. 2007) allowing them to outcompete native adult and juvenile planktivores for food (Pendleton et al. 2017; Love et al. 2018). Consequently, established populations of Bighead Carp and Silver Carp have negatively impacted native aquatic ecosystems within the Mississippi River basin (Solomon et al. 2016; DeBoer et al. 2018).

Bighead Carp and Silver Carp were first reported within the Illinois River, a tributary of the Mississippi River, in 1986 (river kilometer [rkm] from the confluence of the Mississippi River 160.9) and 1998 (rkm 204.4), respectively (USGS 2018). Following initial detection, Bighead Carp and Silver Carp exhibited upstream migration within the Illinois River, and the current population front is 71.8 rkm downstream from Lake Michigan (ACRCC 2016). A direct hydrological connection between Lake Michigan and the Illinois River through the Chicago Area Waterway System (Figure 1) has made the prevention of Bighead Carp and Silver Carp expansion into the Great Lakes a management priority (Cooke and Hill 2010).

Various management strategies have been implemented to deter Bighead Carp and Silver Carp expansion into Lake Michigan (ACRCC 2016). Deterrents include the activation of an electric fish barrier 60 rkm downstream from Lake Michigan (in the Chicago Sanitary and Ship Canal) in 2002 (Dettmers et al. 2005; Figure 1) and the implementation of a contracted harvest program upstream from the Starved Rock Lock and Dam on the Illinois River (rkm 371.8) in 2010 (ACRCC 2016). Furthermore, routine electrofishing, gill-netting, and seining surveys above and below the electric fish barrier have been conducted to monitor the current population front and determine whether upstream expansion has occurred (ACRCC 2016). Although these efforts seek to prevent and monitor their upstream expansion through the Illinois and Des Plaines rivers, Bighead Carp and Silver Carp could enter Lake Michigan through alternative invasion pathways such as transplantation from urban ponds in the Chicago metropolitan area.

In 1985 the Illinois Department of Natural Resources (IDNR) initiated the Chicago Urban Fishing Program and routinely stocks selected ponds in the Chicago, Illinois, metropolitan area with catchable-sized sport fish (e.g., Channel Catfish *Ictalurus punctatus*, Bullheads *Ameiurus* spp., and hybrid sunfish *Lepomis* spp.; IDNR 1996). Following a report of large koi carp, a variant of Common Carp *Cyprinus carpio*, in one of those urban fishing ponds (Flatfoot Lake) the IDNR response assessment removed 14 large (>21.8 kg) Bighead Carp in 2011. As a result of capturing Bighead Carp in Flatfoot Lake, the IDNR expanded Bighead Carp and Silver Carp sampling to all other Chicago Urban Fishing Program ponds and has cumulatively removed 34 Bighead Carp from these ponds since 2011 (Figure 1; Table 1). Additionally, nine other Bighead Carp and one Silver Carp have been removed through nonconventional means (e.g., fish kills, snagging, and rotenone rehabilitation). While managers are unaware of how these Bighead Carp and Silver Carp were introduced, they speculate that these fish were introduced either (1) accidentally by bait bucket transfers from nearby rivers with established populations (e.g., Illinois River), (2) incidentally during sport fish stockings by means of contaminated shipments, (3) intentionally by humans, or (4) through a combination of these means. Understanding the origin of urban pond Bighead Carp and Silver Carp could help prevent further urban pond introductions and reduce the risk of urban pond Bighead Carp and Silver Carp being transferred into Lake Michigan.

Fish origin has traditionally been determined through the application of physical markers (e.g., fin clips; Guy et al. 1996) or the insertion of identifiable tags (e.g., PIT and coded wire tags; Jenkins and Smith 1990; Johnson 1990). Physical markers and identifiable tags are useful for identifying hatchery individuals from wild individuals but do not provide geographical information pertaining to wild fish origin. Fish otoliths, on the other hand, incorporate the chemical elements from the surrounding environment during their formation and remain metabolically inert during a fish's life (Campana and Thorrold 2001). Thus, trace element concentrations and stable isotope ratios of some chemical elements present in fish otoliths are strongly correlated with the elemental concentrations

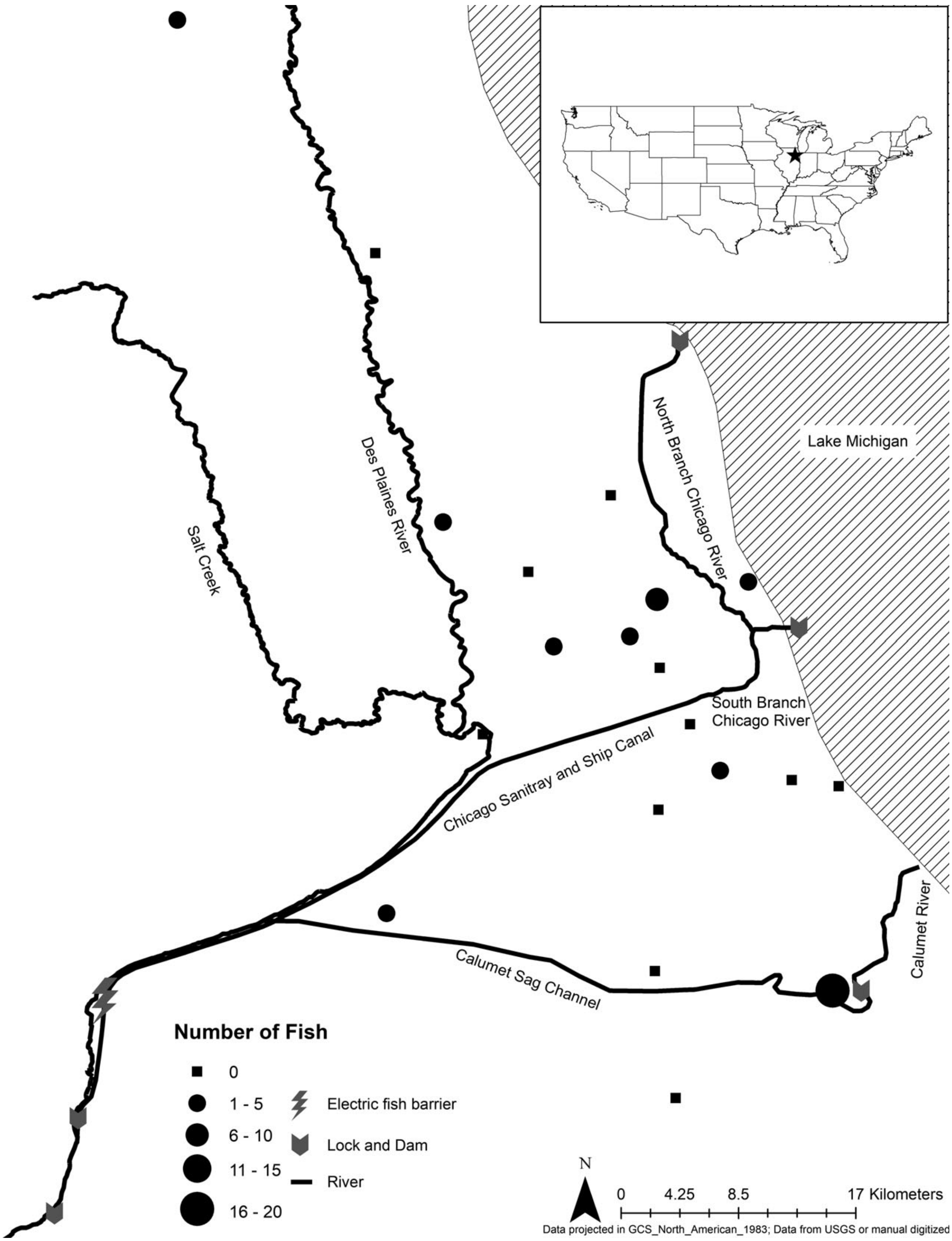

FIGURE 1. Location of IDNR Chicago Urban Fishing Program ponds sampled for Bighead Carp and Silver Carp. Graduated symbol size indicates the number of Bighead Carp and Silver Carp captured with the largest circle indicating 20 individuals and squares indicating none were captured. Fish passage barriers are displayed as a gray lightning bolt (electric fish barrier) or gray arrow (lock and dam).

TABLE 1. Locations and number (n) of Bighead Carp and Silver Carp captured in Chicago Urban Fishing Program ponds. Conventional IDNR sampling (electrofishing and netting) and nonconventional collection methods are listed, along with the amount of sampling effort where appropriate. The number in parentheses behind collection method indicates the number of Bighead Carp and Silver Carp captured.

Location	Minutes of electrofishing	Meters of net	Bighead Carp (n)	Silver Carp (n)	Collection method
Cermak Quarry	60	0			
Columbus Park	48	160	3		Winterkill
Commissioners Park	30	160			
Community Park	30	160	1		Citizen snagging
Douglas Park	48	322			
Flatfoot Lake	780	4,345	20		IDNR sampling
Garfield Park	216	160	3		IDNR sampling (2), summerkilll (1)
Gompers Park	18	0			
Humboldt Park	138	805	9		IDNR sampling (8), winterkill (1)
Jackson Park	258	2,897			
Joe's Pond	30	483	1		IDNR sampling
Lake Owens	60	483			
Lake Shermerville	60	483			
Lincoln Park South	0	0	3		Rotenone rehabilitation
Marquette Park	78	644			
McKinley Park	60	483			
Riis Park	12	0			
Schiller Pond	120	0	3		IDNR sampling
Sherman Park	60	483		1	Winterkill
Washington Park	90	483			
Totals	2,196	12,553	43	1	

of water the fish inhabits (Pracheil et al. 2014). This allows otolith chemistry to provide insight into the environmental life history of an individual fish (Pracheil et al. 2014). Otolith chemistry has been used to identify sources and natal habitats of introduced fish species including Lake Trout *Salvelinus namaycush*, Largemouth Bass *Micropterus salmoides*, Bluegill *Lepomis macrochirus*, and Common Carp (Munro et al. 2005; Whitledge et al. 2007; Crook et al. 2013). More specifically, Norman and Whitledge (2015) characterized relationships between water and otolith chemistry for Bighead Carp and Silver Carp and used otolith stable oxygen and carbon isotope ($\delta^{18}O$, $\delta^{13}C$) and strontium : calcium (Sr:Ca) ratios to assess natal environments of these species in the Illinois River. We assessed the probable origin of Bighead Carp and Silver Carp removed from urban ponds by comparing their otolith chemistry ($\delta^{18}O$, $\delta^{13}C$, and Sr:Ca ratios) with otolith chemistry data from Bighead Carp previously collected from an aquaculture facility and Bighead Carp and Silver Carp from the Illinois River.

METHODS

A electrofishing boat using pulsed DC and/or trammel and gill nets ranging from 89 to 108 mm bar mesh were used to monitor urban ponds for Bighead Carp and Silver Carp. Both electrofishing and netting were conducted so that most, if not all, of the waterbody was sampled. Some fish were also collected via summerkill and winterkill assessment, rotenone application, or snagging by citizens. Lapilli otoliths were removed from Bighead Carp and Silver Carp using nonmetallic forceps, rinsed with distilled water to remove adhering tissue, and stored dry in polyethylene microcentrifuge tubes until their preparation for stable isotope and elemental analysis. One lapillus from each fish was used for stable oxygen and carbon isotope analysis. Otoliths were embedded in Epo-fix epoxy, sectioned in the transverse plane using an ISOMET low-speed saw, sanded using silicon carbide sandpaper (800 and 1,000 grit) to achieve a 0.7-mm section centered on the otolith primordium, and polished with lapping film. Sectioned otoliths were affixed to glass microscope slides using double-sided tape. A 250-μg subsample of $CaCO_3$ powder was drilled from the core of each otolith (centered on the primordium) using a New Wave Research micromill and placed in a Labco Exetainer vial. A stable oxygen and carbon isotope analysis of otolith subsamples was conducted using a ThermoFinnigan Delta V isotope ratio mass spectrometer interfaced with a Gas Bench II carbonate analyzer at the Southern Illinois University Mass Spectrometry Facility. All measurements are reported in standard delta notation relative to the Vienna Pee Dee Belemnite standard: $\delta^{18}O$ or $\delta^{13}C$ (‰) = $[(R_{sample}/R_{standard}) - 1] \times 1{,}000$; where R represents $^{18}O{:}^{16}O$ or $^{13}C{:}^{12}C$. Analytical precision estimated from the analysis of laboratory standards was 0.09‰ for $\delta^{18}O$ and 0.07‰ for $\delta^{13}C$.

The second lapillus from each fish was used for Sr:Ca analysis. Otolith embedding, sectioning, and polishing were as described for stable oxygen isotope analysis, except that the target thickness of the sectioned otolith for Sr:Ca analysis was 0.5 mm. Polished sections were mounted on acid-washed glass microscope slides using double-sided tape, ultrasonically cleaned for 5 min in ultrapure water, dried for 24 h under a class 100 laminar flow hood, and stored in acid-washed polypropylene petri dishes within a sealed container until analysis. Otoliths were analyzed for strontium and calcium concentrations using a Perkin-Elmer DRC II inductively coupled plasma mass spectrometer paired with a CETAC Technologies LSX-213 laser ablation system. The laser ablated a transect extending from one side of the otolith primordium to the edge of the opposite side of the otolith (beam diameter = 25 μm, scan rate = 5 μm/s, laser pulse rate = 20 Hz, laser energy level = 75%). Isotopes assayed included ^{43}Ca and ^{86}Sr. Each sample analysis was preceded by a 30-s gas blank measurement. A calcium carbonate standard (MACS-3; U.S. Geological Survey) was analyzed every 12–15 samples to enable quantification and correction of possible instrumental drift. Correction for gas blank and drift effects and conversion of raw isotopic counts to elemental concentrations (μg/g) were performed using a Microsoft Excel macro (GeoPro) developed by CETAC Technologies. Strontium concentrations were converted to molar Sr:Ca ratios (μmol/mol) using calcium as an internal standard and the stoichiometric concentration of calcium in aragonite.

Potential sources of individual Bighead Carp and Silver Carp from urban ponds were inferred by comparing otolith core $\delta^{18}O$, $\delta^{13}C$, and Sr:Ca of urban pond fish with otolith $\delta^{18}O$, $\delta^{13}C$, and Sr:Ca of previously captured Bighead Carp and Silver Carp from the Illinois River (Norman and Whitledge 2015). The Illinois River is the nearest waterbody that has established, self-sustaining populations of Bighead Carp and Silver Carp and thus represented a plausible source of urban pond fish. Other rivers within the established U.S. ranges of Bighead Carp and Silver Carp (including the Mississippi, Missouri, Ohio, and Wabash rivers) were also assessed as potential sources of urban pond fish by comparing published water chemistry data (and, by extension, expected otolith chemistry values for Bighead Carp and Silver Carp) for these rivers with Illinois River water chemistry data (Coplen and Kendall 2000; Zeigler and Whitledge 2011; Norman and Whitledge 2015; Laughlin et al. 2016). Otolith core $\delta^{18}O$ and $\delta^{13}C$ were also compared with otolith $\delta^{18}O$ and $\delta^{13}C$ of juvenile and adult Bighead Carp (197–953 mm TL) obtained from aquaculture ponds in the south-central USA (G. W. Whitledge, unpublished data). The probable timing of introduction of individual fish was assessed by associating locations of abrupt shifts in otolith Sr:Ca along laser ablation transects (indicative of fish movement between waters with different Sr:Ca ratios) with distance from the otolith primordium. Individual fish were inferred to have potentially been introduced into the pond in which they were collected at age 0 or age 1 if their otolith Sr:Ca declined to values expected for Chicago urban ponds within approximately 300–350 μm of the otolith primordium. This distance threshold was used because the reported otolith radius of age-0 Bighead Carp collected during late fall was 325 ± 29 μm (mean ± SE) (Norman and Whitledge 2015). Probable fish introduction into ponds at larger sizes and/or older ages would have been inferred from shifts in otolith Sr:Ca to values expected for Chicago urban ponds at locations along laser ablation transects that were closer to the otolith edge; however, this was never observed among the 24 fish analyzed.

RESULTS

Overall, 2,196 min of electrofishing and 12,553 m of gill net were used to monitor 19 urban ponds, and one pond was assessed by rotenone rehabilitation (Table 1). Twenty-four lapilli otoliths were used for Sr:Ca analysis, and 16 were used for stable isotope analysis due to difficulties locating both otoliths during extraction. Otolith $\delta^{18}O$ values of Bighead Carp captured from Chicago urban fishing ponds did not overlap with those of Bighead Carp and Silver Carp from the Illinois River but were consistent with aquaculture-reared Bighead Carp (Figure 2). Similarly, otolith core Sr:Ca of 19 out of 23 Bighead Carp from urban ponds were higher than the otolith Sr:Ca range for Bighead Carp and Silver Carp from the Illinois River (Figure 3). However, otolith core $\delta^{18}O$, $\delta^{13}C$, and Sr:Ca of the Silver Carp removed from Sherman Park Pond fell within the ranges of otolith $\delta^{18}O$, $\delta^{13}C$, and Sr:Ca for Bighead Carp and Silver Carp from the Illinois River (Figures 2, 3).

Otoliths from 19 of 23 Bighead Carp analyzed (83%) exhibited a decline in Sr:Ca from high values in the otolith

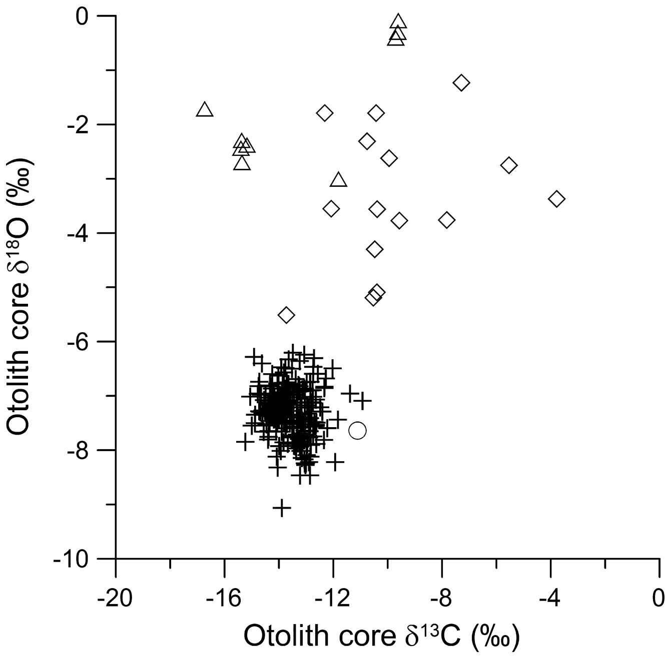

FIGURE 2. Otolith core $\delta^{18}O$ and $\delta^{13}C$ for Bighead Carp (n = 15, open diamonds) and Silver Carp (n = 1, open circle) captured in Chicago Urban Fishing Program ponds, otolith $\delta^{18}O$ and $\delta^{13}C$ of Bighead Carp reared in aquaculture ponds (n = 9, open triangles), and otolith core $\delta^{18}O$ and $\delta^{13}C$ of Bighead Carp and Silver Carp from the Illinois River (n = 237, plus symbols).

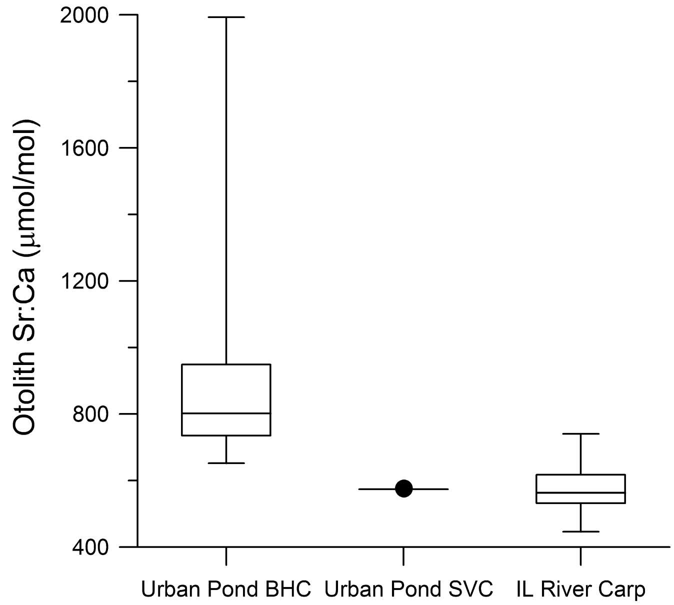

FIGURE 3. Boxplot showing range, interquartile range, and median otolith core Sr:Ca for Bighead Carp (BHC) and Silver Carp (SVC) captured from Chicago Urban Fishing Program ponds (n = 24) and for resident Bighead Carp and Silver Carp from the Illinois River (IL River Carp) (n = 82: Norman and Whitledge 2015).

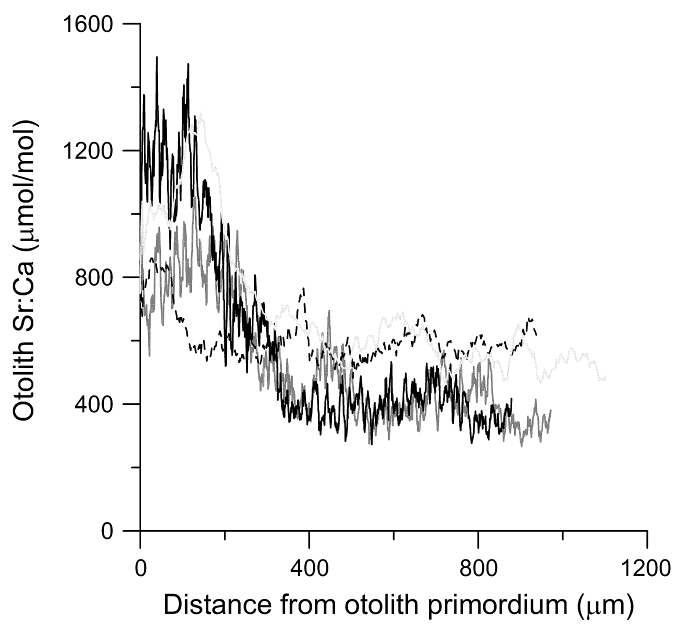

FIGURE 4. Otolith Sr:Ca along laser ablation transects from the otolith primordium to the otolith edge for four Bighead Carp (each represented by a different line) captured in Chicago Urban Fishing Program ponds.

core (750–1,900 μmol/mol; within 50–150 μm of the otolith primordium) to lower values (range, 400–650 μmol/mol) toward the otolith edge (mean, 618 μmol/mol; within 50 μm of the otolith edge) (Figure 4). Mean otolith edge Sr:Ca of 618 μmol/mol was consistent with expected otolith Sr:Ca for resident fish in Chicago urban ponds based on Sr:Ca of water samples taken from these sites during 2010–2012 (range, 1.5–1.8 mmol/mol) and a regression relating water Sr:Ca and Bighead Carp and Silver Carp otolith Sr:Ca (Norman and Whitledge 2015). Otolith Sr:Ca for the Silver Carp collected in Sherman Park Pond remained between 550 and 650 μmol/mol throughout the laser ablation transect.

DISCUSSION

Otolith chemistry helped determine the potential origins of invasive Bighead Carp and Silver Carp in hydrologically disconnected urban ponds in the Chicago metropolitan area. Otolith $\delta^{18}O$ is strongly correlated to $\delta^{18}O$ of ambient water (Dufour et al. 2005; Ashford and Jones 2007; Norman and Whitledge 2015). Thus, large-scale geographic differences in precipitation $\delta^{18}O$ and corresponding differences in surface water $\delta^{18}O$ between the south-central USA (where aquaculture facilities with Bighead Carp existed) and the north-central USA (Kendall and Coplen 2001) were likely responsible for the observed differences in otolith $\delta^{18}O$ of Illinois River Bighead Carp and Silver Carp compared with aquaculture-reared

Bighead Carp. The substantial difference between otolith $\delta^{18}O$ of aquaculture-reared Bighead Carp and Illinois River Bighead Carp and Silver Carp, coupled with differences between otolith core $\delta^{18}O$ of urban pond Bighead Carp and Illinois River fish, suggests that urban pond Bighead Carp likely did not originate from the Illinois River. Mismatch between otolith core Sr:Ca of most of the urban pond Bighead Carp and otolith Sr:Ca of Illinois River Bighead Carp and Silver Carp provided further evidence that the Illinois River was probably not the source of these fish. In contrast to otolith $\delta^{18}O$, otolith $\delta^{13}C$ is influenced by $\delta^{13}C$ of both dissolved inorganic carbon in ambient water and metabolically derived carbon (Solomon et al. 2006). This may explain why $\delta^{13}C$ was more variable among urban pond and aquaculture-reared Bighead Carp sampled in this study (Figure 2). Thus, otolith $\delta^{13}C$ does not appear to be useful for distinguishing between aquaculture-origin and wild Bighead Carp in our study area. Overall, these results raise questions on how and when these Bighead Carp were introduced to these urban ponds, especially if they did not originate from the nearby Illinois River.

Other rivers within the Mississippi River basin or aquaculture facilities where Bighead Carp were present may have served as a source for urban pond fish in Chicago. However, available water $\delta^{18}O$ data from the Mississippi (maximum $\delta^{18}O$, −4.75‰; mean, −7.5‰), Missouri (maximum $\delta^{18}O$, −6.2‰; mean, −9.4‰), Ohio (maximum $\delta^{18}O$, −5.82‰; mean, −6.85‰), and Wabash (maximum $\delta^{18}O$, −5.56‰; mean, −6.0‰) rivers indicate that none of these rivers have water $\delta^{18}O$ values that are higher (i.e., less negative) than that of the Illinois River (maximum $\delta^{18}O$, −4.22‰; mean, −5.52‰) (Coplen and Kendall 2000; Zeigler and Whitledge 2011; Norman and Whitledge 2015; Laughlin et al. 2016; Whitledge, unpublished data). Thus, none of these rivers would be expected to yield otolith core $\delta^{18}O$ values consistent with those of urban pond Bighead Carp and are therefore not likely the source. However, otolith core $\delta^{18}O$ of urban pond Bighead Carp was consistent with otolith core $\delta^{18}O$ of Bighead Carp raised in aquaculture pond facilities. Thus, aquaculture facilitates appear to have been the source of evaluated urban pond Bighead Carp. In contrast, the Sherman Park Pond Silver Carp had otolith core $\delta^{18}O$, $\delta^{13}C$ and Sr:Ca values consistent with those of resident fish in the Illinois River. These results, coupled with the fact that the Illinois River is the nearest river to the Chicago metropolitan area having an established Silver Carp population, suggest that this fish may have been transported from the Illinois River and introduced into Sherman Park Pond.

Inferred timing of urban pond Bighead Carp introduction lends additional support to the aquaculture origin hypothesis. Based on previously published data relating lapillus radius to TL of Bighead Carp <150 mm (Norman and Whitledge 2015), abrupt drops in Sr:Ca within 150 μm of the otolith primordium for most of the urban pond Bighead Carp suggests these fish may have been transferred into ponds at a relatively small size (≤100 mm TL) likely during age 0 or age 1 rather than at older ages. These results indicate that captured Bighead Carp spent their early life in water(s) with higher Sr:Ca and the remainder of their lives as residents of water(s) with Sr:Ca consistent with that of the urban ponds. Relatively consistent Sr:Ca values across the sectioned otolith of the Sherman Park Pond Silver Carp indicated similarity of water Sr:Ca among locations occupied during its lifetime. Thus, no inferences regarding the timing of introduction into Sherman Park Pond or its potential mode of introduction could be established (e.g., accidental bait bucket release at a young age or intentional introduction at a larger size and older age).

Because of their likely aquaculture origin and introduction at a relatively small size and young age, we hypothesize that the Bighead Carp analyzed in this study were incidentally introduced into Chicago Urban Fishing Program ponds during sport fish stocking. Chicago Urban Fishing Program ponds have been stocked with catchable-sized Channel Catfish (IDNR 2010), in some cases from out-of-state production facilities (Vic Santucci, Illinois Department of Natural Resources, personal communication). Some of these stockings took place during a time when Channel Catfish and Bighead Carp polyculture was common in the United States (i.e., during the early years of the urban pond fishing program) (Kolar et al. 2007). Contemporary game fish stocking shipments are probably less likely to be contaminated with Bighead Carp and Silver Carp because both are now a federally listed injurious species (Lacey Act 2004; Spacapan et al. 2016), and the state of Illinois has banned their live transport (Fish and Aquatic Life Code 2003). While contaminated sport fish stocking shipments appear to be the source of Bighead Carp in Chicago Urban Fishing Program Ponds, we acknowledge that these fish could have been transported via bait buckets (e.g., from a contaminated bait pond) because bait ponds and aquaculture ponds may share similar chemical signatures. Nevertheless, continued monitoring of and removal from past and present Chicago Urban Fishing Program Ponds may limit or eliminate this alternative invasion pathway for these and other invasive species.

Although identifying sources of introduced fishes is often difficult or impossible, our results further demonstrate the utility of otolith chemistry for determining potential sources of nonnative fish species. Our results also provided insight regarding the probable sources of Bighead Carp and Silver Carp in Chicago Urban Fishing Program Ponds and suggest that both previous stocking events that used contaminated shipments (Bighead Carp) and transport from the nearby Illinois River (Silver Carp) were introduction pathways for these species. Removal of Bighead Carp and Silver Carp from urban ponds in Chicago likely aided in reducing the probability of their range expansion into Lake Michigan either through potential overflow events during extreme high water (which, to our knowledge, has never occurred) or by human transfer. Monitoring these ponds in response to public sightings and removal of captured individuals should continue, and managers should be vigilant over other alternative invasion pathways (e.g., illegal fish importation and sales: ACRCC 2016). Furthermore, fisheries managers from other Great Lakes basin states should monitor ponds that may have been stocked with populations of game fish contaminated with the carps and, if found, remove the nonnative fish. Such efforts should help reduce the probability of urban ponds serving as alternative invasion pathways for Bighead Carp and Silver Carp.

ACKNOWLEDGMENTS

We thank Illinois Department of Natural Resources and Forest Preserve District of Cook County biologists for their assistance in collecting data used in these analyses. Funding for this project was provided by the U.S. Environmental Protection Agency's Great Lakes Restoration Initiative and administered by the Illinois Department of Natural Resources. There is no conflict of interest declared in this article.

REFERENCES

ACRCC (Asian Carp Regional Coordinating Committee). 2016. Asian carp action plan for fiscal year 2017. Council on Environmental Quality, Washington, D.C.

Albins, M. A., and M. A. Hixon. 2008. Invasive Indo-Pacific Lionfish *Pterois volitans* reduce recruitment of Atlantic coral-reef fishes. Marine Ecology Progress Series 367:233–238.

Ashford, J., and C. Jones. 2007. Oxygen and carbon stable isotopes in otoliths record spatial isolation of Patagonian Toothfish (*Dissostichus eleginoides*). Geochimica et Cosmochimica Acta 71:87–94.

Campana, S. E., and S. R. Thorrold. 2001. Otoliths, increments, and elements: keys to a comprehensive understanding of fish populations? Canadian Journal of Fisheries and Aquatic Sciences 58:30–38.

Cooke, S. L., and W. R. Hill. 2010. Can filter-feeding Asian carp invade the Laurentian Great Lakes? A bioenergetic modelling exercise. Freshwater Biology 55:2138–2152.

Coplen, T. B., and C. Kendall. 2000. Stable hydrogen and oxygen isotope ratios for selected sites of the U.S. Geological Survey's NASQAN and BENCHMARK surface water networks. U.S. Geological Survey, Open-File Report 00-160, Reston, Virginia.

Crook, D. A., J. I. Macdonald, D. G. McNeil, D. M. Gilligan, M. Asmus, R. Maas, and J. Woodhead. 2013. Recruitment sources and dispersal of an invasive fish in a large river system as revealed by otolith chemistry analysis. Canadian Journal of Fisheries and Aquatic Sciences 70:953–963.

DeBoer, J. A., A. M. Anderson, and A. F. Casper. 2018. Multi-trophic response to invasive Silver Carp (*Hypophthalmichthys molitrix*) in a large floodplain river. Freshwater Biology 63:597–611.

DeGrandchamp, K. L., J. E. Garvey, and R. E. Colombo. 2008. Movement and habitat selection by invasive Asian carps in a large river. Transactions of the American Fisheries Society 137:45–56.

Dettmers, J. M., B. A. Boisvert, T. Barkley, and R. E Sparks. 2005. Potential impact of steel-hulled barges on movement of fish across an electric barrier to prevent the entry of invasive carp into Lake Michigan. Illinois State Natural History Survey, Aquatic Ecology Technical Report 2005/19, Zion.

Dufour, E., W. P. Patterson, T. O. Hook, and E. S. Rutherford. 2005. Early life history of Lake Michigan Alewives (*Alosa pseudoharengus*) inferred from intra-otolith stable isotope ratios. Canadian Journal of Fisheries and Aquatic Sciences 62:2362–2370.

Fish Aquatic Life Code. 2003. Code of Illinois, section 805.30.

Guy, C. S., H. L. Blankenship, and L. A. Nielsen. 1996. Tagging and marking. Pages 353–383 *in* B. R. Murphy and D. W. Willis, editors. Fisheries techniques, 2nd edition. American Fisheries Society, Bethesda, Maryland.

Henderson, S. 1976. Observations on the Bighead and Silver carp and their possible application in pond fish culture. Arkansas Game and Fish Commission, Little Rock.

Hulme, P. E. 2009. Trade, transport and trouble: managing invasive species pathways in an era of globalization. Journal of Applied Ecology 46:10–18.

IDNR (Illinois Department of Natural Resources). 1996. Illinois urban fishing program. IDNR, Springfield.

IDNR (Illinois Department of Natural Resources). 2010. Illinois urban fishing program: Division of Fisheries Fiscal Year 2010 Annual Report. IDNR, Springfield.

Irons, K. S., G. G. Sass, M. A. McClelland, and J. D. Stafford. 2007. Reduced condition factor of two native fish species coincident with invasion of non-native Asian carps in the Illinois River, U.S.A. Is this evidence for competition and reduced fitness? Journal of Fish Biology 71:258–273.

Jenkins, W. E., and T. I. J. Smith. 1990. Use of PIT tags to individually identify Striped Bass and Red Drum brood stocks. Pages 341– 345 *in* N. C. Parker, A. E. Giorgi, R. C. Heidinger, D. B. Jester Jr., E. D. Prince, and G. A. Winans, editors. Fish-marking techniques. American Fisheries Society, Symposium 7, Bethesda, Maryland.

Johnson, J. K. 1990. Regional overview of coded wire tagging of anadromous salmon and steelhead in northwest America. Pages 782–816 *in* N. C. Parker, A. E. Giorgi, R. C. Heidinger, B. D. Jester Jr., E. D. Prince, and G. A. Winans, editors. Fish-marking techniques. American Fisheries Society, Symposium 7, Bethesda, Maryland.

Kendall, C., and T. B. Coplen. 2001. Distribution of oxygen-18 and deuterium in river waters across the United States. Hydrological Processes 15:1363–1393.

Kolar, C. S., D. C. Chapman, W. R. Courtenay Jr., C. M. Housel, J. D. Williams, and D. P. Jennings. 2007. Bigheaded carps: a biological synopsis and environmental risk assessment. American Fisheries Society, Special Publication 33, Bethesda, Maryland.

Lacey Act. 2004. U.S. Code, volume 18, sections 42 and 3372.

Laughlin, T. W., G. W. Whitledge, D. C. Oliver, and N. P. Rude. 2016. Recruitment sources of Channel and Blue catfishes inhabiting the middle Mississippi River. River Research and Applications 32: 1808–1818.

Leung, B., D. M. Lodge, D. Finnoff, J. F. Shogren, M. A. Lewis, and G. Lamberti. 2002. An ounce of prevention or a pound of cure: bioeconomic risk analysis of invasive species. Proceedings of the Royal Society of London B: Biological Sciences 269:2407–2413.

Love, S. A., N. J. Lederman, R. L. Anderson, J. A. DeBoer, and A. F. Casper. 2018. Does aquatic invasive species removal benefit native fish? The response of Gizzard Shad (*Dorosoma cepedianum*) to commercial harvest of Bighead Carp (*Hypophthalmichthys nobilis*) and Silver Carp (*H. molitrix*). Hydrobiologia 817:403–412.

Munro, A. R., T. E. McMahon, and J. R. Ruzycki. 2005. Natural chemical markers identify source and date of introduction of an exotic species: Lake Trout (*Salvelinus namaycush*) in Yellowstone Lake. Canadian Journal of Fisheries and Aquatic Sciences 62: 79–87.

Norman, J. D., and G. W. Whitledge. 2015. Recruitment sources of invasive Bighead Carp (*Hypophthalmichthys nobilis*) and Silver Carp (*H. molitrix*) inhabiting the Illinois River. Biological Invasions 17:2999–3014.

Pendleton, R. M., C. Schwinghamer, L. E. Solomon, and A. F. Casper. 2017. Competition among river planktivores: are native planktivores still fewer and skinnier in response to the Silver Carp invasion? Environmental Biology of Fishes 100:1213–1222.

Pimentel, D., R. Zuniga, and D. Morrison. 2005. Update on the environmental and economic costs associated with alien-invasive species in the United States. Ecological Economics 52:273–288.

Pracheil, B. M., J. D. Hogan, J. Lyons, and P. B. McIntyre. 2014. Using hard-part microchemistry to advance conservation and management of North American freshwater fishes. Fisheries 39:451–465.

Sampson, S. J., J. H. Chick, and M. A. Pegg. 2009. Diet overlap among two Asian carp and three native fishes in backwater lakes on the Illinois and Mississippi rivers. Biological Invasions 11: 483–496.

Schrank, S. J., and C. S. Guy. 2002. Age, growth, and gonadal characteristics of adult Bighead Carp, *Hypophthalmichthys nobilis,* in the lower Missouri River. Environmental Biology of Fishes 64: 443–450.

Schrank, S. J., C. S. Guy, and J. F. Fairchild. 2003. Competitive interactions between age-0 Bighead Carp and Paddlefish. Transactions of the American Fisheries Society 132:1222–1228.

Solomon, C. T., P. K. Weber, J. J. Cech Jr., B. L. Ingram, M. E. Conrad, M. V. Machavaram, A. R. Pogodina, and R. L. Franklin. 2006. Experimental determination of the sources of otolith carbon and associated isotopic fractionation. Canadian Journal of Fisheries and Aquatic Sciences 63:79–89.

Solomon, L. E., R. M. Pendleton, J. H. Chick, and A. F. Casper. 2016. Long-term changes in fish community structure in relation to the establishment of Asian carps in a large floodplain river. Biological Invasions 18:2883–2895.

Spacapan, M. M., J. F. Besek, and G. G. Sass. 2016. Perceived influence and response of river users to invasive Bighead and Silver carp in the Illinois River. Illinois Natural History Survey, Technical Report 2016 (20), Champaign.

USGS (U.S. Geological Survey). 2018. Nonindigenous aquatic species database. USGS, Gainesville, Florida. Available: http://nas.er.usgs.gov. (May 2018).

Whitledge, G. W., B. M. Johnson, P. J. Martinez, and A. M. Martinez. 2007. Sources of nonnative centrarchids in the upper Colorado River revealed by stable isotope and microchemical analyses of otoliths. Transactions of the American Fisheries Society 136:1263–1275.

Wilcove, D. S., D. Rothstein, J. Dubow, A. Phillips, and E. Losos. 1998. Quantifying threats to imperiled species in the United States. BioScience 48:607–615.

Williamson, C. J., and J. E. Garvey. 2005. Growth, fecundity, and diets of newly established Silver Carp in the middle Mississippi River. Transactions of the American Fisheries Society 134:1423–1430.

Zeigler, J. M., and G. W. Whitledge. 2011. Otolith trace element and stable isotopic compositions differentiate fishes from the middle Mississippi River, its tributaries, and floodplain lakes. Hydrobiologia 66:289–302.