Review

Catching carp: a review of bigheaded carp capture strategies

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Abstract

We conducted a review to summarize the settings, configurations, and capture data for an array of fisheries gear types used to capture invasive bigheaded carps (*Hypophthalmichthys* spp.) in North America. The goal of this paper was to synthesize patterns of bigheaded carp catch data across various gear types and capture methods. Data consisted of bigheaded carps captured among a variety of riverine habitats where their populations are well-established (e.g., lower pools of the Illinois River), as well as near the leading edge of their invasion front (e.g., Upper Mississippi, Upper Illinois, Upper Missouri, Red River). Our synthesis provides a summary of (1) capture gears and their settings/configurations, (2) catches (fish size, number captured, precision of estimates), and (3) assessment of gears that were robust (i.e., high precision, low cost, high catch, sample many habitat types) in riverine environments and impoundments. Across the 26 gear types used to target bigheaded carps, catch rates of silver carp were consistently higher than bighead carp, which may result from a combination of sampling inefficiencies, sampling biases, and spatial dynamics of their invasions. Gear performance matrices combining catch rate, precision, and labor cost indicated that DC electrofishing and herding fish into gill nets and/or trammel nets were the top-ranked capture methods. This review provides guidance for the development of detection, monitoring, and control programs that target bigheaded carp species, as well as identifies future research to fill critical data gaps.

Key words: catch rate, fisheries science, gear precision, invasive species

Introduction

Bigheaded carps (silver carp *Hypophthalmichthys molitrix* Valenciennes, 1844; bighead carp *H. nobilis* Richardson, 1845) have inhabited the Mississippi River basin for nearly a half-century (Chick and Pegg 2001; Kolar et al. 2007). These invasive planktivores are thought to have persisted at relatively low numbers for the first 30 years after introduction, as evidenced by sporadic detections by commercial fishers and agency scientists (Freeze and Henderson 1982). However, their numbers increased rapidly in the Illinois and Mississippi Rivers in the early 2000's, causing reductions in zooplankton and body conditions of native fishes (Chick and Pegg 2001; Irons et al. 2007, 2011).

Since then, there has been a concerted and widespread effort to study and control bigheaded carp populations, with the goal of preventing their spread through the Mississippi River basin and connected waterways (Conover et al. 2007; Herborg et al. 2007; ACRCC 2021).

Efforts to detect, monitor, or remove bigheaded carp in the Mississippi River basin have generated considerable catch data across a relatively large geographic area. Sampling for these carps has included traditional (e.g., gill nets, hoop nets, electrofishing, mini-fyke nets; Wanner and Klumb 2009; Irons et al. 2011; Hayer et al. 2014; Collins et al. 2015, 2017; Stuck et al. 2015) and novel fishing gears and techniques (e.g., pound nets, dozer trawl, Paupier trawl; Collins et al. 2015; Hammen et al. 2019; Ridgway et al. 2020). It is generally assumed that these diverse gears target and capture bighead carp and silver carp similarly. Information pertaining to individual gear performance metrics (e.g., gear selectivity, catch rates, precision) and associated costs (e.g., time, labor) have been disseminated across numerous manuscripts, agency reports, and online repositories. Understanding relative capture performance among various gears and methods can be of assistance as agencies develop management plans for controlling or detecting bigheaded carp (ACRCC 2021). Across the Mississippi River basin, management objectives vary among the subbasins due to variation in carp abundance, the likelihood of invading new waterbodies, and impacts on ecological systems (Rodgers et al. 2019; ACRCC 2021; Chapman et al. 2023). Consequently, the control, detection, or monitoring of bigheaded carp may benefit from differing sampling approaches that yield data appropriate for the analysis of each objective (ACRCC 2021; Chapman et al. 2023).

The goal of this paper was to synthesize patterns of bigheaded carp catch data across various gear types and capture methods. Data consisted of bigheaded carps captured among a variety of riverine habitats where their populations are well-established (e.g., lower pools of the Illinois River), as well as near the leading edge of their invasion front (e.g., Upper Mississippi, Upper Illinois, Upper Missouri, Red River; Figure 1). Our synthesis provides a summary of (1) capture gears and their settings/configurations, (2) catches (fish size, number captured, precision of estimates), and (3) assessment of gears that were robust (i.e., high precision, low cost, high catch, sample many habitat types) in riverine environments and impoundments. This summary should benefit the decision-making process while developing strategic management plans for bigheaded carp populations across North America (e.g., Rodgers et al. 2019; ACRCC 2021; Chapman et al. 2023).

Materials and methods

Study methodology

Data were included from peer-reviewed studies, grey literature, digital repositories, and solicitations from natural resource professionals. A review of primary and secondary literature was conducted using Google Scholar

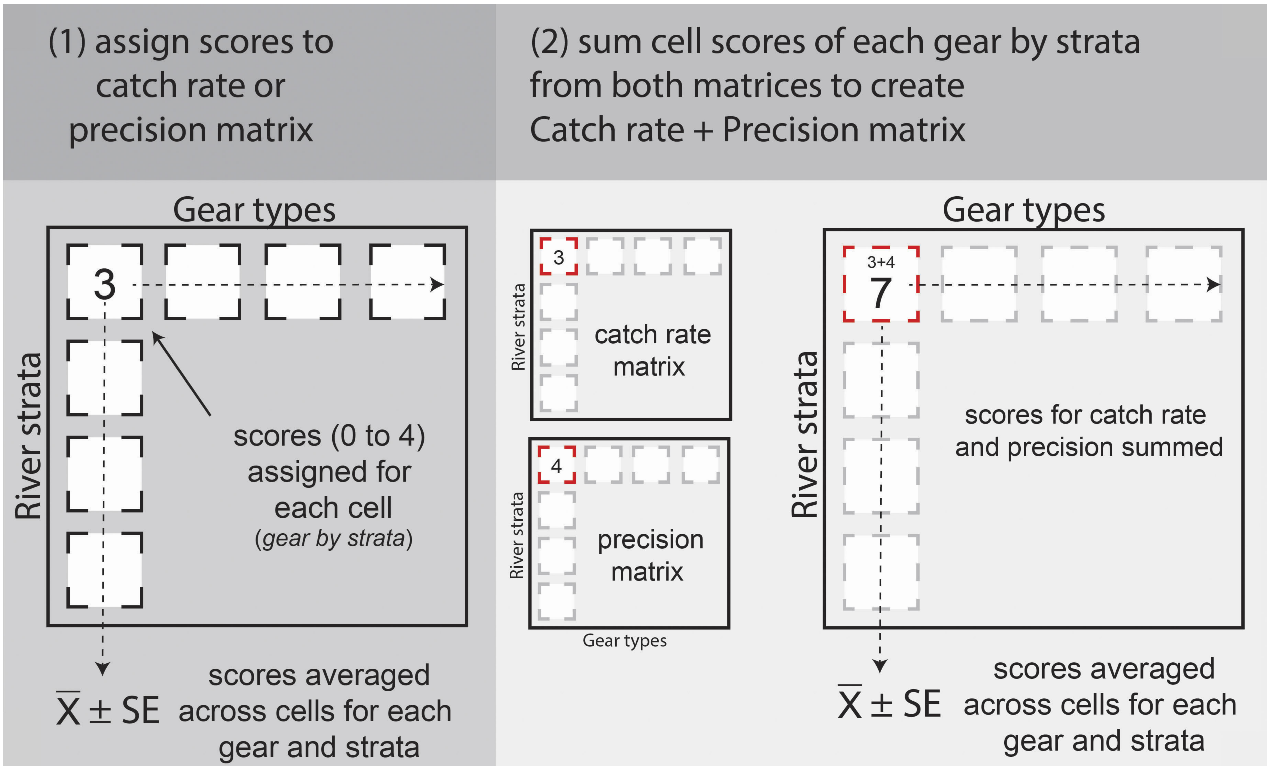

Figure 1. Conceptual representation of the gear performance matrices used to evaluate gear catch rates or gear precision in differing river strata. (Step 1) Each cell (representing gear by strata) was assigned a score (see methods). Averages (± SE) across river strata and gear types (see dashed arrows) were used to compare gear performance. (Step 2) Scores from each matrix were summed to create a third matrix representing the combined Catch rates and Precision attributes.

and Web of Science using combinations of the search terms "bighead carp", "silver carp", "bigheaded carp", "Asian carp", and "*Hypophthalmichthys*". Literature referenced within relevant papers/reports were also included when appropriate. Data were also solicited via email or online repositories (e.g., USGS Long Term Resource Monitoring; Long Term Survey and Assessment of Large River Fishes in Illinois) from federal and state conservation agencies and universities throughout the United States known to sample for bigheaded carp species. When available, we extracted catch rate means, standard errors, life stages targeted (e.g., eggs, larvae, juveniles, or adults), and gear specifications (e.g., mesh size, net diameter, etc.) from text, tables, and figures within the source. In some cases, we directly contacted authors of papers to solicit additional information such as individual length measurements (total length) of captured bigheaded carps. Data from open-source repositories were analyzed by the authors to quantify catch rate means, standard errors, life stages targeted, and individual total length data by source. Individual length data was pooled from author solicitations and data repositories to construct box-whisker plots to directly compare the distribution of lengths captured by gears. When catch rate data from a published study was also available in a digital repository, only the repository data was used in subsequent summaries and analyses.

Following data collection, gears were classified into two categories: active (i.e., techniques that physically move to collect fish; Hayes et al. 2012) or passive (i.e., techniques that remain stationary during sampling; Lagler

1978; Hubert et al. 2012). In a few cases, hybrid approaches involving driving bigheaded carp into gill/trammel nets were encountered and were reported as active sampling. Due to difficulty differentiating bighead carp from silver carp at the egg and larval life stages, and in hydroacoustic signals, some studies reported aggregate “bigheaded carp” catches. In such cases, catch metrics in this study were reported for bigheaded carp. Finally, sampling environments were classified following major river strata types as described by Wilcox (1993): backwaters (BW), main channel borders (MCB), side channel border (SC), tributary (TRI), tailwater (TW), and impoundments (IMP).

Analyses

Length distributions of captured bigheaded carps (total length, mm) were evaluated to identify potential size biases among gears. Length data were examined by constructing whisker plots to depict the range of individuals sampled and to identify any length-based sampling biases among capture gear types. Relative abundance estimates among gears were evaluated to assess variation in catch rates among gears. In many cases, such units are not directly comparable because effort can be a function of time (e.g., electrofishing time) or action (e.g., a seine haul). We standardized catches within similar scales and measures of effort for comparability whenever possible: gill and trammel sets were represented as the number of fish captured per 182 meters; overnight sets were adjusted to the number of fish captured in 24 hours; volumetric samples were adjusted to the number of fish captured per 100 m^3 of water; timed samples were adjusted to the number of fish captured in 1-hour of sampling; and gears using a sample action (e.g., fish per seine haul) were reported as fish captured per sample. In cases where capture methods consisted of multiples of the same gear set together in a series (e.g., tandem hoop net, paired fyke net, paired bongo net), each tandem or paired series was treated as one replicate sample. However, we did not attempt to standardize across distinctly different measures of effort (e.g., effort on the scale of tens of minutes versus tens of hours) because such adjustments would be tenuous at best. Thus, we take a parsimonious approach with the intent of describing general patterns of catches among differing capture gears while preserving their units of effort. All patterns are interpreted in this capacity.

Average, minimum, and maximum catch-per-unit-effort (CPUE) were calculated from pooled mean catch rates of all studies and datasets in which each gear/method was used. Whenever only one data set or one study was available for a gear, the mean CPUE was reported. Gear precision (i.e., the degree of reproducibility of the measurement; Zale et al. 2012) was assessed as relative standard error (RSE = SE/mean × 100) when mean and standard errors were reported or could be calculated. Relative standard error is a unitless measure of dispersion (i.e., how close measurements are to each other) that accounts for the number of samples collected for a capture gear in the calculation of the standard error (i.e., SE = SD / √n). Higher RSE values correspond with lower precision and *vice versa*. All summary statistics were calculated with Program R version 4.0.2 (R Development Core Team 2019).

Management objectives (e.g., detection, monitoring, harvest) vary across the Mississippi River basin with respect to bigheaded carps. For this analysis we focused on gears that reliably (i.e., higher precision; RSE) captured greater numbers (i.e., higher catch rates) of bigheaded carps across differing river strata. Sampling multiple habitats was considered important because riverine environments are comprised of a mosaic of habitat strata and gears that sample multiple habitats would be beneficial to a manager/researcher. Gear by river strata matrices were developed to aid in ranking and assessing gear performance (Figure 1; Gregory et al. 2012). Separate matrices were created for catch rates and precision. Bighead carp and silver carp data were combined (larval gears excluded) as agencies generally manage the two species simultaneously (e.g., ACRCC 2021). Cells within the matrix represented the global mean CPUE or RSE for a given gear-stratum combination. Individual cell values were then assigned a score of 0–4 based on its associated percentile score. If a value with a cell fell within the 0–25th percentile of reported CPUE or RSE values, it was scored as "1"; values in the > 25–50th percentile were scored as "2"; values in the > 50–75th percentile were scored as "3"; values within the > 75–100th percentile were scored as "4". Gears that were not deployed in certain river strata were assigned a score of "0" treating the absence of data as a principal source of uncertainty. For our analysis, higher catch rates were assigned higher scores because values were in the upper percentiles of reported values. For precision (i.e., RSE), values were reverse coded such that low RSE (i.e., high precision) values were assigned higher scores. Once scores were assigned for each gear-strata combination for the catch rate matrix and precision matrix, we then averaged across gear types or across river strata separately for both matrices (Figure 1). The catch rate and precision matrices were combined to integrate the dimensions of gear performance (Figure 1). Respective gear-strata cells from the catch rate matrix and precision average score matrices were first summed to give a combined score (i.e., catch rate + precision; Figure 1, see red cells). Cell scores were then averaged (± SE) across river strata for each gear type and ranked, as well as across gear types and ranked. Average scores for the catch rate matrix, precision matrix, and catch rate + precision matrices were then ranked from lowest to highest and plotted to visually assess gear performance among river strata and across gear types. Correlations between catch rate ranks and precision ranks were examined to see if ranking of one metric influenced the ranking of the other.

Finally, we wanted to account for the labor involved for each gear (Collins et al. 2015). Fisheries gears require differing labor commitments in terms of crew size and time (e.g., overnight sets vs. day trip). For our analysis, we assumed some gears required overnight sets, and thus 2 days of work, whereas

Figure 2. Distribution of bigheaded carp (*Hypophthalmichthys* spp.) data that was included in this study. Shaded portions of the map represent locations included in the analyses with bigheaded carp capture data.

other sampling could occur within a single day. Crew sizes were assumed to be the minimum number of people to safely accomplish the sampling. Based on literature findings, person-days were generalized to the number of people (i.e., crew size) and days (i.e., one or many days) required to deploy and collect a sample (Supplementary material Table S1). The catch rate + precision scores were then divided by person-days to incorporate potential labor costs. Values for this matrix were then averaged across river strata and plotted as previously described.

Results

We identified 27 peer-reviewed studies, two grey literature studies, six agency datasets (DeBoer et al. *unpubl. data*, Hanser et al. *unpubl. data*, Hammen et al. *unpubl. data*, Morris et al. *unpubl. data*, Parkos *unpubl. data*, LaHood et al. *unpubl. data*), and three long-term data repositories (ICMWRG 2020, ORSANCO 2020, LTRMP 2020). The dataset represented collections from 26 distinct locations throughout the United States, most of which occurred within the Mississippi River, its major tributaries (e.g., Missouri River, Illinois River, Ohio River), and smaller rivers and reservoirs within the basin (Figure 2). Twenty-seven capture gears were used to collect bigheaded carps (Table 1). Trammel and gill net were considered active when nets had fish actively herded into the net through percussive sound stimuli with a boat propeller near the water surface or forcefully striking the boat hull (e.g., Butler et al. 2019; Ridgway et al. 2022) and passive if no active herding occurred (e.g., Ridgway et al. 2017).

Table 1. Summary of active and passive sampling gears and attributes used to capture bigheaded carp (*Hypophthalmichthys* spp.) across larval, juvenile, and adult life stages.

Approach	Gear	Life stage	Units	Gear attributes
Active	Push net	Eggs, Larvae	density	Single or dual conical nets, 0.5 m diameter, 2.0 m long, 0.8 mm mesh
	Nueston net	Eggs, Larvae	density	1 × 2 m, 500 µm mesh
	Surface plankton net	Eggs, Larvae	density	0.5 diameter opening, 2-m length, 500 µm mesh
	Bongo net	Eggs, Larvae	density	0.6 cm diameter opening, 333 µm mesh
	Cast net	Juvenile	per cast	2.7 m diameter; 10 mm mesh
	Seine–Beach	Juvenile	per haul	10 m length, 3–5 mm mesh
	Seine–Purse	Juvenile	per haul	122 × 3.05 m, with 2.5 cm mesh
	Seine–Contracted	Juvenile, Adult	per haul	Varying set lengths; mesh size range 1.6–5.1 cm
	Trawl–Paupier	Juvenile, Adult	CPUE	Standard amperage adjusted to conductivity, 30 Hz, 15%, 2–4 × 1.5 m frame, 38 mm stretched body mesh to 6 mm mesh cod
	Trawl–Electrified	Juvenile, Adult	CPUE	Amperage adjusted to conductivity, 30 Hz, 15%, 2.13 × 0.9 m frame, 38 mm stretched body mesh to 6 mm mesh cod
	Trawl–Dozer	Juvenile, Adult	CPUE	Two seam; 4.8 m wide × 4.5 m long with 18 mm stretch mesh. Bag 1.8 m; Mesh, 3 mm
	Electrofishing–AC	Juvenile, Adult	CPUE	3-phase, 3 Kw, 230-V, 60 hz; 100–250 V, 3–10 amps, 60–120 hz, 25% Duty cycle, 60–80 pulses/s
	Electrofishing–DC	Juvenile, Adult	CPUE	180–1000 V, 15–60 Hz, 25–50% duty cycle
	Hydroacoustic	Adult	density	Two horizontal-orientated split-beam transducers, 5 pings/s, pulse duration of 0.40 ms, 70 kHz (5 beam angle)–200 kHz (6.6 beam angle)
	Trammel net–Driven	Adult	CPUE	Height, 1.8–3.6 m; Inner panel, 2.5–7.6 cm; Outer panel, 20–34 cm, varying set lengths
	Gill net–Driven	Adult	CPUE	Height, 1.8–3.6 m; Mesh size range: 2.54–25.4 cm; Varying set lengths
Passive	Drift net	Eggs, Larvae	density	0.5 diameter opening, 2-m length, 750 µm mesh, 1-m below surface water
	Bongo net	Eggs, Larvae	density	0.6 cm diameter opening, 333 µm mesh
	Light traps	Larvae	trap night	Cloverleaf array; 25.0 cm tall with 5.0 mm entry slots. Collection pan with 6 holes cover by 250 µm mesh
	Minnow trap	Larvae, juvenile	net night	Trap dimensions, 42 × 19 × 22 cm, baited
	Mini fyke net	Juvenile	net night	4.5 × 0.6 m lead, 0.6 × 1.2 m trap 3 mm mesh; some tandem sets
	Hoop net	Adult	net night	Diameter, 0.6–1.8 m; Mesh range, 3.8–10 cm; Some tandem sets
	Stop log net	Adult	net night	25 × 25 cm wood frames; 0.9 m hoops; 1.9 cm mesh
	Fyke net	Adult	net night	0.9 m × 1.8 m frame with 15.2 m × 1.4 m lead, 1.8 to 3.8 cm bar mesh
	Pound net	Adult	net night	Trap dimensions, 6.1 × 3.1 × 3.1 m; 100 m lead and wings
	Trammel net	Adult	CPUE	Height, 1.8–3.6 m; Inner panel, 2.5–7.6 cm; Outer panel, 20–34 cm, varying set lengths
	Gill net	Adult	CPUE	Height, 1.8–3.6 m; Mesh size range: 2.54–25.4 cm; Varying set lengths

Bighead carp and silver carp

The suite of sampling approaches were identified that captured bighead carp and silver carp across their various life stages (e.g., eggs, larvae, juvenile, adult). Twelve gears generally targeted and captured multiple life stages of bigheaded carp and 14 gears specifically captured a single life stage (Table 1). Sampling approaches were diverse and included modified trawls (e.g., electrified, push, dozer, Paupier), gill and trammel netting that sometimes incorporated herding techniques, seining (e.g., beach/shoreline, purse, contracted commercial), and standard boat electrofishing (e.g., AC, DC) methods. Approaches also varied drastically in the spatial extents or volumes of water sampled. For example, beach seining can capture fish within a few square meters whereas hydroacoustic surveys can enumerate large fish along kilometers of river and within large volumes of water. We noted that gear attributes including mesh sizes, electrofisher settings, and gear dimensions varied among studies.

The sizes of captured carp exhibited notable patterns among gear types and species. Overall, we observed that bighead carp (mean ± SE; 712 ± 266 mm; n = 13,410) tended to be larger than silver carp (503 ± 225 mm; n = 49,749), which

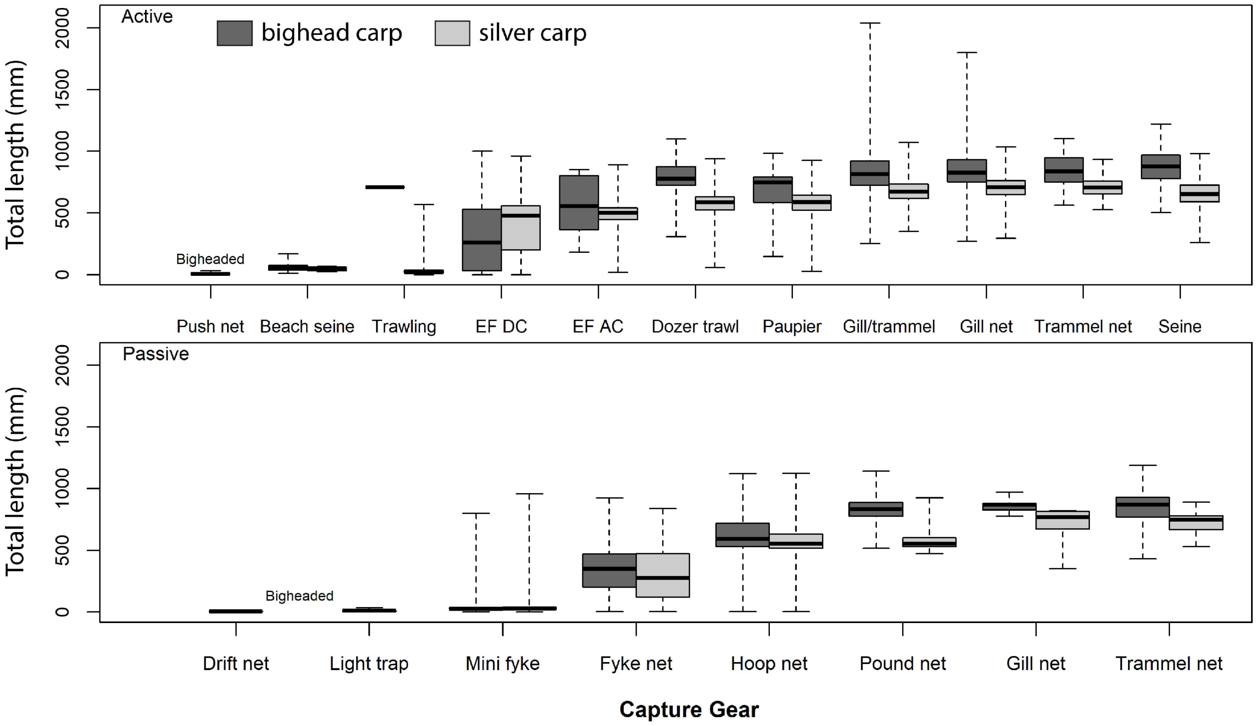

Figure 3. Box-and-whisker plots of the total length (mm) of bighead carp (*Hypophthalmichthys nobilis)* and silver carp (*H. molitrix*) captured using active and passive sampling methods. Whiskers extend to the range of that data. Black lines in each box denote the median length value of that box.

was reflected across most gear types (Figure 3). Furthermore, we observed that some gear types tended to catch larger fish or a wider range of sizes than other gear types. For example, contracted seining by commercial fishers (871 ± 6 mm; *n* = 1,263), gill nets without herding (858 ± 12 mm; *n* = 25) and trammel nets with and without herding (846 ± 8 mm; *n* = 558) generally captured the largest bighead carp and silver carp (Figure 3). Mini-fyke nets (42 ± 1 mm; *n* = 2,680) and beach seining (60 ± 3 mm; *n* = 1,263) generally captured the smallest juvenile bigheaded carp and silver carp (Figure 3).

Catch rates and precision of bighead carp and silver carp varied among gear types (Table 2) and river strata (Table 3). Catch rates of silver carp were generally higher than bighead carp across most gears (Table 2). For example, catch rates from electrofishing (avg. of AC and DC) were considerably higher for silver carp (17.1 CPUE) than for bighead carp (0.05 CPUE). Similarly, catch rates of gill and trammel nets (averaged) were also higher for silver carp (27.6 CPUE) when compared to bighead carp (1.26 CPUE). Catch minimums and maximums also varied considerably and influenced by the sampling approach and the targeted life stages. Seining by contracted fishers yielded the highest bighead carp catch rate (6.3 fish per haul) and highest silver carp catch rate (164.2 fish per haul) among evaluated gears (Table 2). Efforts to drive bigheaded carps into gill and trammel nets generally yielded higher catch rates when compared to passive deployments of the same gear types (Table 2). Boat electrofishing also captured far more silver carp than bighead carp (Table 2).

Table 2. Summary of active and passive fisheries gears used to capture bigheaded carp (*Hypophthalmichthys* spp.) across larval, juvenile, and adult life stages. Catches reflect body sizes (mm; minimum–maximum), catch-per-unit-effort (CPUE), minimum and maximum CPUEs, and the relative standard error (RSE). CPUEs were calculated from pooled data set means. Whenever only one data set was available, the mean CPUE was reported. See Table 1 for gear characteristics.

Species	Type	Gear	Unit of effort	Length (min–max)	CPUE	CPUE(min-max)	RSE	Ref.*
Silver Carp	Active	Cast net	Fish per sample	96–160	0.03	0.03 – 0.03	–	1
		EF–AC	Fish per hour	20–890	16.6	16.6–16.6	–	2
		EF–DC	Fish per hour	1–1140	17.6	0.00–475.9	27	1:14,34
		Gill net–driven	Fish per 182 m of net	310–1036	3.7	0.00–83.7	56	5,13,15
		Gill/trammel–driven	Fish per 182 m of net	352–1000	37.5	26.0–72.9	25	5
		Trammel net–driven	Fish per 182 m of net	527–933	41.6	11.5–69.9	29	5
		Hydroacoustics	Fish captured per 100 m^3 of water	400–1120	1.8	0.2–3.6	37	16:18
		Seine–beach	Fish per sample	25–67	0.04	0.0–99.5	66	3, 6
		Seine–contracted	Fish per sample	356–980	164.2	0.0–1140.5	60	5
		Seine–purse	Fish per sample	–	7.3	0.6–14.0	92	6
		Trawl	Fish per sample	10–570	0.0	0.0–0.0	–	3
		Trawl–Dozer	Fish per hour	10–869	70.9	58.7–336.8	58	9, 10
		Trawl–Paupier	Fish per hour	200–960	64.7	7.0–209.2	52	9, 10, 19
	Passive	Fyke net	Fish per net night	130–837	0.04	0.0–0.3	43	3, 21
		Gill net	Fish per 182 m of net	320–1052	0.25	0.0–20.8	49	1,3,6,8,14,15,34
		Trammel net	Fish per 182 m of net	500–900	0.06	0.0–0.1	80	3, 14, 23
		Hoop net	Fish per net night	180–941	0.03	0.0–8.5	60	1,3,5,11,12,14,21,
		Minnow trap	Fish per net night	–	0.00	0.0–0.0	–	11
		Mini fyke	Fish per net night	1–640	10.9	0.0–604.9	58	3,6,8,11,14
		Pound net	Fish per net night	662–1010	19.5	2.9–38.9	45	5, 21
		Stop log net	Fish per net night	–	0.9	0.9–0.9	–	23
Bighead Carp	Active	Cast net	Fish per sample	–	0.00	0.0–0.0	–	24
		EF–AC	Fish per hour	183–859	0.02	0.2–0.2	–	2
		EF–DC	Fish per hour	1–1140	0.08	0.0–2.3	39	2,3,4,7,8,11,14,24,25, 34
		Gill net	Fish per 182 m of net	397–2039	0.4	0.0–5.0	57	5,15,25
		Gill/trammel	Fish per 182 m of net	252–1800	2.0	0.1–4.0	57	5
		Trammel	Fish per 182 m of net	1045–1103	1.4	0.2–2.9	53	5
		Hydroacoustic	Fish captured per 100 m^3 of water	400–1200	0.3	0.1–0.9	50	17,18
		Seine–beach	Fish per sample	10–170	0.3	0.0–4.17	72	5,26
		Seine–contracted	Fish per sample	503–1220	6.3	0.0–63.9	59	5
		Trawl	Fish per sample	710–710	0.0	0.0–0.1	–	3
	Passive	Fyke net	Fish per net night	100–922	0.1	0.0–1.0	41	3,21
		Gill net	Fish per 182 m of net	1072–1323	0.2	0.0–0.4	28	3,8,14,15,24,34
		Trammel net	Fish per 182 m of net	480–1200	0.4	0.0–0.7	97	3,22
		Hoop net	Fish per net night	1200–1385	0.02	0.0–0.7	30	3,5,24,21,11,14
		Minnow trap	Fish per net night	–	–	–	–	11
		Mini fyke	Fish per net night	1–800	0.2	0.0–1.6	37	3,8,11,14
		Pound net	Fish per net night	517–1141	2.6	0.0–13.0	64	5,21
		Stop log net	Fish per net night	–	0.4	0.4–0.4	–	23
Bigheaded Carp	Active	Bongo net	Fish captured per 100 m^3 of water	–	0.8	0.0–261.6	82	27, 28, 29
		Push net	Fish captured per 100 m^3 of water	3–32	4.2	0.2–1335.1	94	30, 31
		Hydroacoustic	Fish captured per 100 m^3 of water	400–1200	0.2	0.4–261.6	39	17, 32
	Passive	Driftnet	Fish captured per 100 m^3 of water	3–8	0.4	0.0–0.9	54	30, 31
		Light trap	Fish per net night	6–35	9.06	0.0–9.1	100	31,33

*References: (1) Ridgway and Bettoli 2017; (2) DeBoer et al. *unpublished data*; (3) LTRMP 2020; (4) ORSANCO 2020; (5) ICMRWG 2020; (6) Collins et al. 2017; (7) Bouska et al. 2017; (8) Eggleton et al. 2010; (9) Hammen et al. 2019; (10) Hammen et al. *unpublished data* ; (11) Hayer et al. 2014; (12) Stuck et al. 2015; (13) Sullivan et al. 2017; (14) Wanner and Klumb 2009; (15) Butler et al. 2018; (16) Coulter et al. 2019; (17) MacNamara et al. 2016; (18) MacNamara et al. 2018; (19) Ridgway et al. 2020; (21) Collins et al. 2015; (22) Williamson and Garvey 2005; (23) Schultz et al. 2007; (24) Ridgway 2016; (25) Sullivan 2016; (26) Lohmeyer and Garvey 2008; (27) DeGrandchamp et al. 2007; (28) Deters et al. 2013; (29) Schrank et al. 2001; (30) Schaick et al. 2023; (31) Roth et al. 2023; (32) Coulter et al. 2018; (33) La Hood et al. *unpublished data*; (34) Morris et al. *unpublished data.*

Table 3. Summary of catch per unit effort of *Hypophthalmichthys* spp. across larval, juvenile, and adult life stages among the various habitat strata found in this literature review. Comparison of catch rates among rows should be done with caution as units of effort may vary (e.g., number per time vs. number per length of net) and are not be directly comparable. Habitat strata: BW = Backwater; IMP = Impoundment; MC = Main channel; SC = Secondary channel; TW = Tailwater.

Species	Type	Gear	BW	IMP	MC	SC	TW
BHC	Active	Cast net	–	0.00	–	–	–
		EF–AC	–	–	0.02	–	–
		EF–DC	0.04	0.00	0.08	0.08	0.00
		Gill net	1.15	0.00	0.24	0.42	5.0
		Gill/trammel net	4.03	2.00	0.30	0.10	–
		Trammel net	2.99	1.39	0.26	0.24	–
		Hydroacoustic	0.85	–	0.23	–	–
		Seine–beach	0.01	–	0.55	0.35	–
		Seine–contracted	32.77	–	3.15	31.25	–
		Trawling	–	–	0.00	0.00	0.04
	Passive	Gill net	0.00	0.13	0.19	0.37	–
		Hoop net	0.04	0.06	0.01	0.03	0.09
		Mini fyke	0.25	0.15	0.16	0.56	1.60
		Minnow traps	–	–	0.0	–	–
		Pound net	8.93	–	0.0	–	–
		Trammel net	–	0.74	0.01	–	–
		Trap net	0.40	0.09	0.04	0.00	0.96
SCP	Active	Cast net	–	0.03	–	–	–
		EF–AC	–	–	16.59	–	–
		EF–DC	17.29	18.67	16.59	25.87	161.28
		Gill net	16.15	0.00	3.16	83.72	2.67
		Gill/trammel net	31.65	26.00	38.86	72.88	–
		Trammel net	41.61	44.84	11.46	69.98	–
		Seine–beach	34.50	–	0.01	0.06	–
		Seine–contracted	236.81	–	82.08	1140.50	–
		Seine–purse	14.00	–	0.59	–	–
		Trawl–dozer	64.77	–	336.82	–	–
		Trawl–Paupier	27.48	101.88	–	–	–
		Trawling	–	–	0.00	0.00	0.00
	Passive	Gill net	0.25	5.00	0.25	0.30	–
		Hoop net	0.00	0.08	0.03	0.02	0.04
		Mini fyke	10.85	42.18	5.55	7.47	604.92
		Minnow traps	–	–	0.00	–	–
		Pound net	35.92	2.86	–	–	–
		Trammel net	–	0.11	0.01	–	–
		Trap net	0.06	0.06	0.03	0.01	0.11
Both	Active	Bongo net	1.30	–	0.23	261.63	–
		Hydroacoustics	–	–	0.63	–	–
		Push net	–	–	4.24	–	–
	Passive	Driftnet	–	–	0.10	–	–
		Light trap	–	9.06	–	0.00	–

All bigheaded carp species combined

All gears where captures were reported as "bigheaded carp" were described as capturing eggs and larvae, except hydroacoustic surveys which reported adults. No studies reported mean catch rates of eggs for bigheaded carp. One study reported maximum egg density (Coulter et al. 2016) and another reported egg catch standardized by river discharge and pooled across three species of spawning carps (bighead carp, silver carp, grass carp; Parkos et al. 2023). Thus, catch rate indices and size structure descriptions of bigheaded carp do not include eggs. For larval gears with lengths measurements, light traps captured bigheaded carps from 6 to 35 mm (mean ± SE = 9 ± 1 mm; n = 1,767), push nets from 3 to 32 mm (9 ± 1 mm n = 84), and drift nets from 3 to 8 mm (5 ± 1 mm; n = 42). For adults, hydroacoustic surveys detected individuals from approximately 400 to 1200 mm in length (Table 2). Notably, hydroacoustic surveys detect but do not capture fish, and need information from capture methods to approximate bigheaded carp numbers and sizes. Push nets had a higher maximum catch rate of 1335 ind. per 100 m^3 of water (Table 2). Light traps (9.06 ind. per trap night) and benthic drift nets had the lowest (0.40 ind. per 100 m^3 of water; Table 2) catch rates.

Gear comparison matrices

Ranking matrices identified several gears that consistently outperformed others (Figure 4a–d). In terms of catch rates, DC electrofishing, mini-fyke nets, gill/trammel nets, and seining yielded the highest-ranking scores across all habitat strata (Figure 4a). Ranking of gears in terms of sampling precision yielded similar results as DC electrofishing was ranked first, followed by driven trammel nets, fyke nets, then hoop nets (Figure 4b). Combining scores from the catch rate and precision matrices resulted in the same suite of gears performing best (Figure 4c). Comparison of catch rate to precision (RSE) revealed correlations for mean scores (averaged across strata; n = 16, r = 0.71, P = 0.002) and rank scores (rank among gears; n = 16, r = 0.67, P = 0.004), indicating that gears that scored better in terms of catch rates also tended to be more precise in our scoring scheme. Adjusting catch rate + precision scores to incorporate labor effort shifted rankings to mainly gears that can be completed by 2 persons in a single day (Figure 4d).

Ranking matrices also identified some river strata that scored higher (i.e., cell values averaged across gears for a given river strata) than others in terms of catch rates, precision, and their combined scores (Figure 5). Active sampling in main channel boarders and tributaries scored higher than passive sampling approaches (Figure 5a). For the remaining river strata, average scores were similar between active and passive sampling approaches. Passive sampling in dam tailwaters scored slightly higher than active sampling (Figure 5a). The patterns observed for catch rates were also observed in scores of sampling precision (Figure 5b) and the summed scores of catch rate + precision (Figure 5c).

Discussion

Our synthesis of bigheaded carp catches (i.e., catch rates, precision of abundance estimates, and size biases) from the various gears should aid, in part, in the strategic management of bigheaded carp populations across North America. A survey of published literature and agency reports revealed numerous sampling options for fisheries scientists depending on target life stage and budget. Such gears reflected a suite of conventional sampling gears

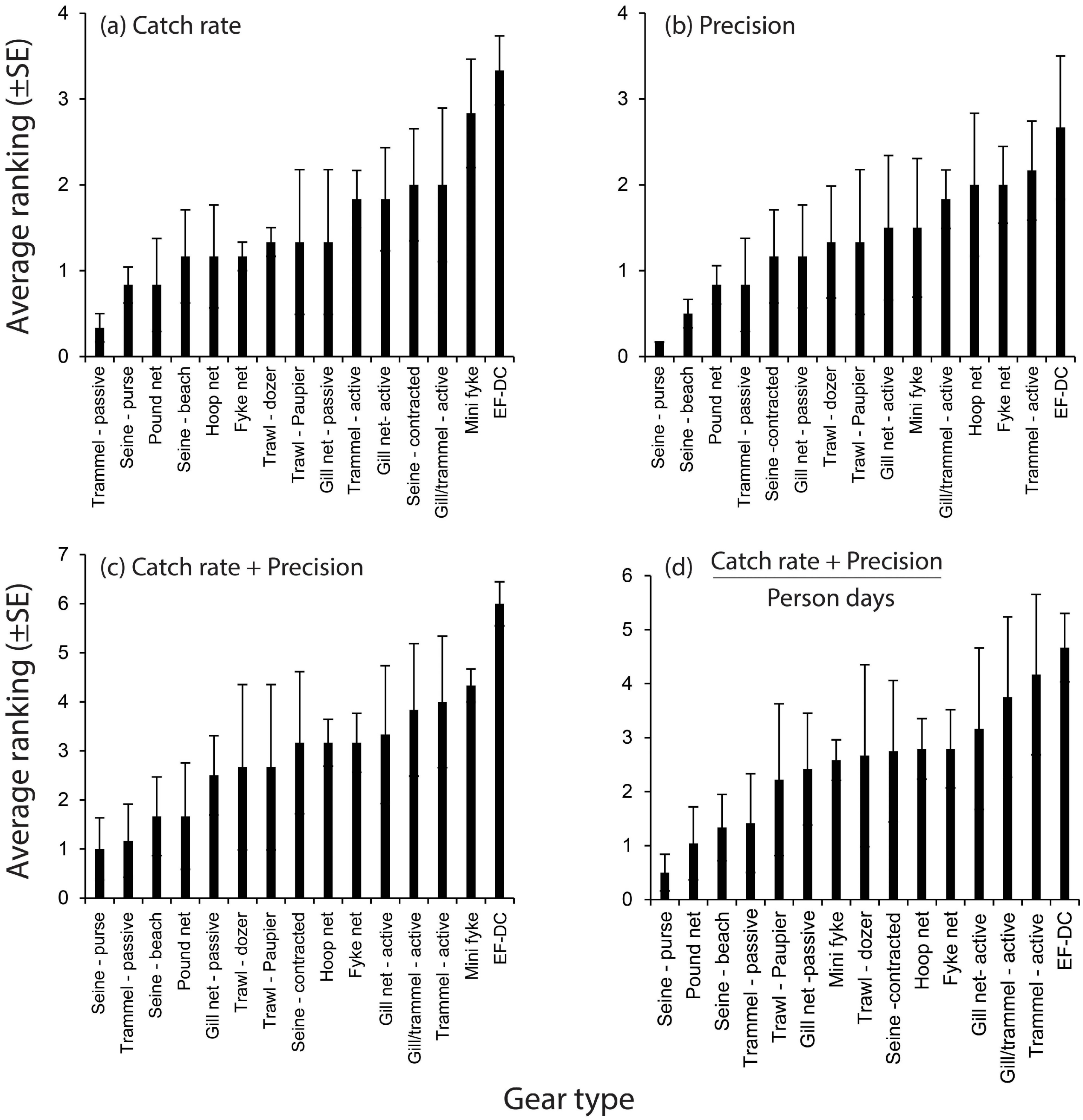

Figure 4. Ranked bigheaded carp (*Hypophthalmichthys* spp.) catches in capture gears based on (a) catch rates, (b) precision (relative standard error), (c) catch rates + precision, and (d) catch rates + precision scores adjusted by labor (person days). Errors bars are 1 standard error for the averaged ranking for each gear type.

(e.g., hoop nets, gill nets, electrofishing), custom designed equipment (e.g., Paupier trawl), and the combination of differing sampling approaches (e.g., herding fish into nets). Among gears, we observed a gradient of body sizes captured, with some gears better suited to capturing large adults and others that spanned juvenile and adult life stages and others that are best suited for larvae. Additionally, we observed that catch rates of silver carp were generally three times higher than bighead carp across all reported data. These differences in relative abundance are likely because silver carp outnumber bighead carp in many locations (e.g., Collins et al. 2015; Bouska et al. 2017; MacNamara et al. 2016, 2018). Overall, direct current electrofishing, gill netting, and trammel

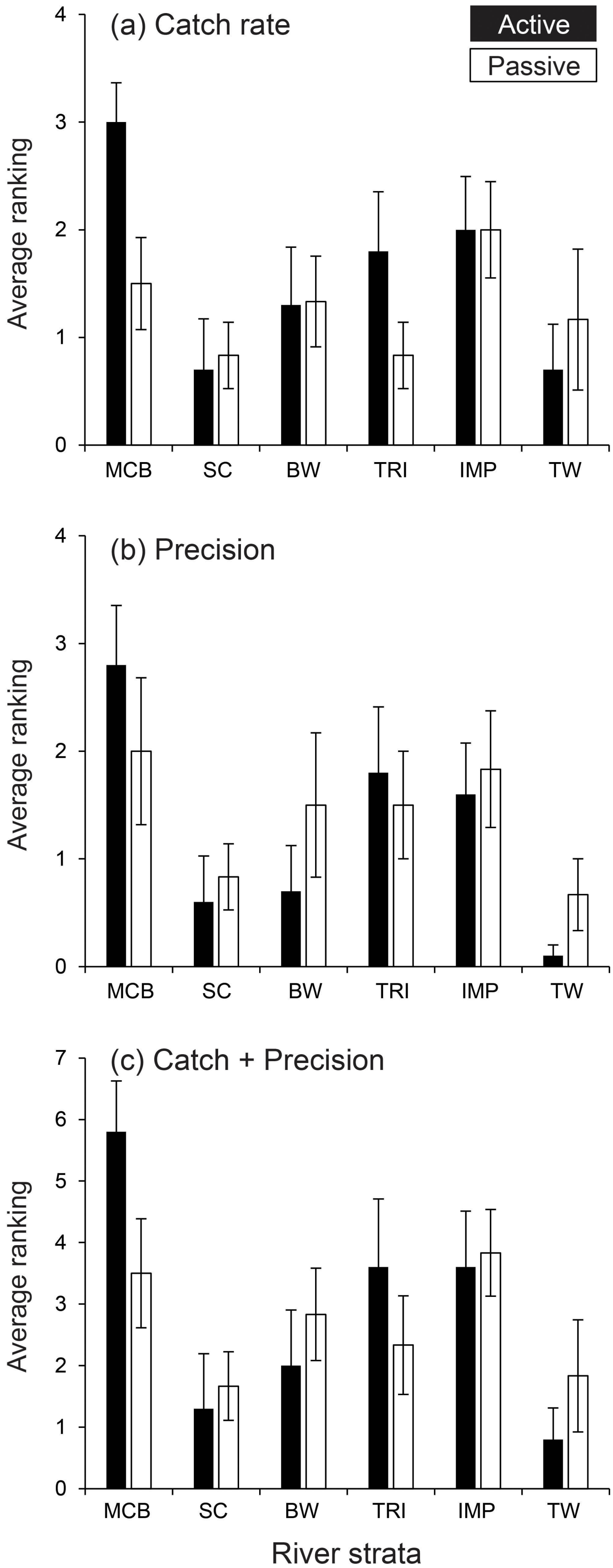

Figure 5. Ranked bigheaded carp (*Hypophthalmichthys* spp.) catches among river strata based on (a) catch rates, (b) precision (relative standard error), and (c) catch rates + precision. Errors bars are 1 standard error for the averaged ranking for each gear type. Habitat strata are abbreviated according to Wilcox 1993. BW = Backwater, IMP = Impounded, MCB = Main channel border, SC = Secondary channel, TRI = tributary TW = Tailwater.

netting tended to score highest in our gear comparison when targeting adult life stages. These also happen to be some of the most common means of capturing carp among fisheries biologists. Notably, our summary encompassed studies spanning the Mississippi River basin, which included areas where bigheaded carp were in high and low abundance, during the early and late stages of the invasion. Consequently, management objectives varied from early detection to assessments of gear effectiveness for differing life stages of bigheaded carp. In the following paragraphs, we discuss our findings in the context of broader management programs to control bigheaded carp populations.

The management and control of bigheaded carp populations is a unifying goal across their invaded range in North America. As part of the broader strategic management of bigheaded carp populations, fisheries scientists are tasked with addressing key areas including developing effective deterrent technologies, mass removal efforts, implementing early detection measures, and developing statistical models with strong inference, to name a few (Chapman et al. 2023). Progress towards this goal is challenging as some locations prioritize early detection and others prioritize the harvest and removal of large numbers of fish. Removal efforts would generally benefit from gears with high catch rates whereas monitoring and detection efforts would require precise catch rates that accurately represent bigheaded carp abundance. Within a given objective, strategies may vary with respect to the gears used by fisheries biologists. For example, the removal of bigheaded carp can be accomplished by small groups of scientists while sampling, contractually via commercial fishers, or through coordinated and systematic removal efforts that can require a combination of fisheries gears and methods (Chapman et al. 2023). In such cases, the use of one or many gears may be required to accomplish the management objective. Fortunately, most capture gears that targeted bigheaded carp were able to collect them, with DC-electrofishing (Wanner and Klumb 2009; Eggleton et al 2010; Hayer et al. 2014; Ridgway 2016; Sullivan 2016; Sullivan et al. 2017; Bouska et al. 2017), mini-fyke net (Hayer et al. 2014; Wanner and Klumb 2009), gill and/or trammel netting (Williamson and Garvey 2005; Wanner and Klumb 2009; Ridgway 2016; Sullivan 2016; Sullivan et al. 2017; Butler et al. 2019; ICMRWG 2020), and contracted seining (ICMRWG 2020) scoring high when ranked by catch rate alone or catch rate and precision together. When incorporating labor metrics (i.e., person-days), active sampling methods like electrofishing or herding into gill and/or trammel nets scored higher in our ranking system as these sampling events can be accomplished by fewer individuals within a shorter time frame. Fisheries managers must determine which capture gear(s) best meets their specific objectives.

Our analysis likely favored more generalized capture gears compared to specialized methods (e.g., gears developed for specific fish sizes, habitat types, or species). For example, boat electrofishing and gill/trammel netting are common and reliable sampling approaches used by fisheries scientists in large river and reservoir settings. Moreover, these approaches can sample across a range of river strata, making them a relatively robust means of fish sampling. Capture gears not yet deployed in a river strata would receive lower rankings in our assessment. For example, pound nets have been shown to catch large numbers of bigheaded carp, but their large size makes them vulnerable to net drag and floating debris in environments outside of backwater habitats (Collins et al. 2015). Other capture gears such as the electrified dozer trawl and Paupier trawl have been evaluated in a limited number of habitat stratums (e.g., river channel borders and backwater; Hammen et al. 2019; Ridgway et al. 2020), lowering their ranking despite being potentially useful in other habitats, such as open water portions of the main channel. Using specialized gears to achieve specific objectives and exploring the use of novel gears in previously untested habitats could provide additional information for this kind of gear comparison.

Size distributions of captured bigheaded carps differed among capture gears. The largest and smallest individuals were most often represented in passive gears whereas intermediate lengths groups were more completely characterized in active gears. Capture efficiencies tend to be lowest for fish at the extreme end of size distributions (i.e., very small or large; Peterson and Paukert 2009) with activity levels of smaller individuals lower compared to larger individuals (Hogue and Pegg 2009). Therefore, less active and rarer individuals may be more likely to be captured by gears sampling over a longer period of time (hours to days) compared to shorter time intervals (seconds to minutes; Parkos et al. 2019). Size discrepancies among capture gear may also have been caused in part by the life stage targeted by researchers and managers with each gear type. Based on reported study objectives or gear specifications (e.g., mesh size), most passively fished gears focused on sampling adult-sized fish or subadult-sized fish separately, whereas active gears focused on adult and subadult bigheaded carps simultaneously (~ 81% of gears, see Table 1). Although bighead carp and silver carp are managed together, size-selective sampling biases may arise. Thus, it might be prudent to develop a multi-gear sampling regime to mitigate any potential biases.

Variation in the ability of gears to capture bigheaded carp have been observed. In the Missouri River, Wanner and Klumb (2009) found that hoop nets and mini-fyke nets captured the most bighead carp and push trawls and gill nets captured the majority of silver carp. Collins et al. (2015, 2017) conducted comparisons of several gears in the Illinois River and noted differences among gears in the sizes of bigheaded carp captured as well as the labor required. Roth et al. (2023) compared larval sampling techniques and found that push trawls were most effective at capturing larval bigheaded carp, but each gear examined showed unique strengths. Bongo nets (DeGrandchamp et al. 2007; Deters et al. 2012), plankton nets

(Schrank et al 2001), and light traps (La Hood et al. 2023) also demonstrated potential for sampling larval bigheaded depending on the river strata and system size sampled. Innovative techniques, such as herding (Butler et al 2019; Ridgway et al. 2023) and modified electrofishing techniques (Bouska et al. 2017; Hammen et al. 2019; Ridgway et al. 2020), have shown promise as modifications to traditional fisheries techniques and have led to increases in capture efficiency of bigheaded carp. These findings further emphasize that no one gear will be able to effectively sample all sizes and species of bigheaded carp.

Innovative and synergistic sampling approaches have been used to enhance the detection and capture of bigheaded carp. For example, herding fishes into entrapment or entanglement has been shown to improve catch rates and detection probability (Butler et al. 2019; Ridgway et al. 2022), minimizing some gear bias and generally improving capture gear performance. At larger scales, a Chinese unified fishing technique has been used where fish deterrents or stimuli (e.g., complex sound, block net) have been used to direct fish into nets (e.g., gill nets, electrofishing, pound nets, and seining) to remove large quantities of bigheaded carp in a short period of time (Irons 2016; Cupp et al. 2021; Chapman et al. 2023). Other technologies like side-scan sonar units can be used to determine suitable placement of some capture gears to improve catch rates or assess potential interactions of bigheaded carp with capture gear (Lawson et al. 2020). Combining multiple techniques or modifying capture gears could improve detectability in areas of low abundances, increase overall catch, reduce gear avoidance, supplement standard monitoring, or further improve standard sampling (e.g., accuracy, catch rates, detection). However, more work is needed to assess these approaches across large and mid-sized rivers.

This synthesis brings together information from disparate sources on the performance of capture gears used to collect bigheaded carp across a variety of riverine habitat types. It is our hope that the provided information can guide the development of control, detection, and monitoring programs for bigheaded carp (ACRCC 2021; Chapman et al. 2023). We recommend that future assessments focus on capture and detection probabilities across the carp invasion fronts to evaluate gear sampling accuracy. Detection probability (Hoffman et al. 2016; Butler et al. 2018, 2019) and assessments of gear accuracy (Peterson and Paukert 2009; Bodine et al. 2013) are important considerations for capture gears used in monitoring programs. Finally, we urge managers to consider how the selection of differing capture gears may influence by-catch of other aquatic organisms. For example, gears intended to capture bigheaded carps may also capture fishes of greatest conservation concern, creating a scenario where the management of one species creates conflict with the conservation of another. Addressing each of these issues should alleviate additional uncertainties and lead to more informed and effective decision making in the management of invasive bigheaded carp in North American waters and beyond (Chapman et al. 2023).

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Author's contribution

NJL: research conceptualization; sample design and methodology; data analysis and interpretation; roles/writing – original draft; writing – review and editing. SFC: research conceptualization; sample design and methodology; investigation and data collection; data analysis and interpretation; roles/writing – original draft; writing – review and editing. JJH: research conceptualization; sample design and methodology; investigation and data collection; roles/writing – original draft; writing – review and editing. JJP: research conceptualization; sample design and methodology, roles/writing – original draft; writing – review and editing.

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Supplementary material

The following supplementary material is available for this article:

Table S1. Generalized assessment of labor days for the deployment and collection of fisheries gears.

This material is available as part of online article from:
http://www.reabic.net/journals/mbi/2024/Supplements/MBI_2024_Lederman_etal_SupplementaryMaterial.pdf