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Geographic-Scale Harvest Program to Promote Invasivorism of Bigheaded Carps

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Abstract: Invasive bigheaded carps, genus *Hypophthalmichthys*, are spreading throughout the Mississippi River basin. To explore the efficacy of a consumer-based market (i.e., invasivorism) to manage them, we developed a conceptual model and evaluated three harvest approaches—direct contracted removal, volume-based incentives ("fisher-side" control), and set-quota harvest ("market-side" control). We quantified the efficacy of these approaches and potential population impact in the Illinois River. Contracted removal was effective for suppressing small populations at the edge of the range but cannot support a market. "Fisher-side" removals totaled 225,372 kg in one year. However, participation was low, perhaps due to reporting requirements for fishers. The "market-side", set-quota approach removed >1.3 million kg of bigheaded carp in less than 6 months. Larger, older fish were disproportionately harvested, which may hinder the ability to suppress population growth. Total density declined in one river reach, and harvest may reduce upstream movement toward the invasion fronts. With sufficient market demand, harvest may control bigheaded carp. However, lack of processing infrastructure and supply chain bottlenecks could constrain harvest, particularly at low commodity prices. Given the geographical scale of this invasion and complicated harvest logistics, concerns about economic dependence on invasivorism that encourage stock enhancement are likely unmerited.

Keywords: invasivorism; bigheaded carp; commercial fishing; *Hypophthalmichthys*; Illinois River

1. Introduction

Invasive species threaten biodiversity worldwide [1], costing $120 billion USD annually in the United States [2]. Removal programs may control invasives [3]. For example, humans routinely overharvest fish stocks [4–6]. Thus, controlled harvest may help control invasive populations of fish and other taxa [7–10]. Yet, factors such as time, effort, and expense often limit success [11–13]. Whereas government assistance

is necessary to control invasive species that have low market value such as sea lamprey, *Petromyzon marinus* (Linnaeus; [14]), fishes with commercial value could be marketed to reduce financial burden on government agencies. This consumer-based control of invasive species is popularly called invasivorism. Potential candidates for invasivorism are silver carp *Hypophthalmichthys molitrix* (Valenciennes) and bighead carp, *H. nobilis* (Richardson), collectively known as bigheaded carp. These species invaded the lower Mississippi River basin of the US in the 1970s, expanded northward, are now more abundant in the Illinois River than anywhere else globally [15–17], and may invade the Laurentian Great Lakes via Lake Michigan. Establishment of bigheaded carp in the Great Lakes may jeopardize fisheries valued at $7 billion USD per year [18,19].

Nearly a decade ago, the U.S. Army Corps of Engineers (USACE) explored options to prevent interbasin transfer of aquatic nuisance species (ANS) between the Mississippi River and Great Lakes basins, with bigheaded carp being a primary species of concern and the Chicago Area Waterway System (CAWS) the primary focus area. The CAWS contains five aquatic pathways [20], one of which, the Chicago Sanitary and Shipping Canal (CSSC), is the only permanently open connection between the basins, with Lake Michigan being the recipient Great Lake. The CSSC has previously allowed movement of ANS between the basins [21] and is near the edge of the bigheaded carp range, which is approximately 80 km south downstream in the upper Illinois River [22].

Removal of bigheaded carp is included in all eight management strategies for stopping interbasin movement of these fish [20], and non-structural control plus harvest is the only strategy that can be initiated immediately. Since 2010, contracted removal of greater than 3200 tons of bigheaded carp has occurred near the CAWS in the upper Illinois River, where commercial harvest is prohibited [23]. Removal at this range edge is expected to be agency funded for the foreseeable future [24] and has likely prevented upstream range expansion toward Lake Michigan [22]. In the lower Illinois River from where bigheaded carp in the upper Illinois River derive, commercial harvest is legal. If reliable moderate- to high-value markets can be developed for bigheaded carp in the lower river, exploitation should remain high and reduce upstream migrants via invasivorism. Although the likelihood of reducing bigheaded carp to extinction in such a large, open system is low, the capacity for population suppression and reducing further expansion may be high.

The idea of harvesting near the center of the invading population to reduce densities at range edges is supported by modeling that assesses the influence of harvest and other control measures in lower river reaches where population densities are high. The Spatially Explicit Asian Carp Population (SEAcarP) model [24] links movement probabilities among river pools or reaches with demographic responses to harvest removal to predict the likelihood of population density declines at the edge of the species' range (see Erickson et al. [25] for similar approach with grass carp). The model has been applied to the Illinois River using movement data from Coulter et al. [22], predicting that increasing mortality of bigheaded carp in the lower river will effectively reduce densities at the upstream invasion front.

Stimulating market demand to accomplish control via invasivorism may seem like a simple task. Bigheaded carp are valued food fish in much of the world. With native, wild bigheaded carp stocks threatened or extirpated [26], global demand is now primarily met by aquaculture, with these species being among the most cultured fish in the world [27]. Globally, over 5.3 million tons of silver carp are cultured annually, primarily in China, India, Bangladesh, Iran, the Russian Federation, and Cuba [27]. There may be a high demand for bigheaded carp from the U.S., since consumers in countries such as China are willing to pay a premium price for wild-caught fish [28], and may perceive U.S.-sourced fish as being of a higher quality than cultured products.

Although recent surveys have suggested that there is potential domestic consumer demand for bigheaded carp as food [29], most US markets are for rendered carp products (meals and oils), as ingredients in livestock and aquaculture feeds [30–32] and as hydrolyzed fertilizers. The current supply of bigheaded carp in US rivers is not a limiting factor in the growth of the industry, but rather the lack of processing plants and reliable domestic markets plus access to existing international markets to monetarily compensate commercial fishers. A well-developed fishery infrastructure does not exist

in the central area of the invasion in the US. Thus, a fishery must be built to implement control via invasivorism.

To determine how a long-term, self-maintained fishery may be developed to control the bigheaded carp invasion, we first developed a broad conceptual supply chain model for economic development of a controlled harvest fishery to promote invasivorism in the Illinois River system, throughout the invaded US, and more broadly for any invaded ecosystem where market-driven consumption is an option. We then evaluated three harvest strategies against invasive bigheaded carp in the upper and lower Illinois River along the conceptual supply chain continuum, quantified the resulting exploitation, and examined economic factors affecting removal by harvest.

The harvest strategies evaluated during 2010 through 2012 were (1) an ongoing contracted harvest program in the upper Illinois River, (2) a "fisher-side" incentives program that offered select commercial fishers progressive economic rewards for participating (i.e., sharing harvest data) and harvesting increasing amounts of bigheaded carp for direct-consumption markets, and (3) a "market-side" incentives program that set a quota-based harvest of bigheaded carp for indirect-consumption markets of fish meal. Harvest removal of fish from populations is often biased toward larger, older individuals, which affects population responses [10]. We hypothesized that a removal effort of this large, geographic-scale magnitude should impact bigheaded carp population demographics including abundance, size structure, and age structure within the study area in the lower Illinois River, and stimulate direct and indirect consumption markets for bigheaded carp, with implications for basin-wide population dynamics and reduced risk to the Great Lakes.

2. Conceptual Model

The commercial fishing industry in the Illinois and Mississippi River basins is significantly reduced from its former past [16], where harvest of mussels and fish peaked in the early 1900s. Much of the fish harvest in this region was for local consumption and as consumer demand waned, river water quality declined, and sedimentation increased, fish harvest as a source of protein and income declined by the 1930s. For a fishery to develop to effectively reduce bigheaded carp from both free flowing and pooled reaches of these and other river systems, industry infrastructure must be reestablished. We propose a simplified conceptual model of bigheaded carp supply, transport, processing, and demand in flowing and non-flowing waters of the US Midwest (Figure 1).

The model identifies major components of a developing fishery for bigheaded carp. The first primary bottleneck to commercial-level invasivorism is the fishers and fishing fleet (Figure 1). The size of the fishing crews, training, time investment, and many other fixed and variable costs influence the reliability and effectiveness of fishing bigheaded carps. At this juncture, fishing is largely conducted by part-time crews with limited gears, because of a lack of funds for purchasing and maintaining boats and equipment. These crews fish for natives and carp, mostly for local businesses or contracted fishing in the upper Illinois River, maintaining local expertise to drive potential harvest expansion. However, with no reliable market for bigheaded carps, capital investment in large, sustained fishing operations will not occur.

The supply of bigheaded carps in the Illinois River and other systems is driven by myriad factors that vary with water body type and location (Figure 1). Lohmeyer and Garvey [33] conducted a recruitment assessment of bigheaded carps in pooled and unpooled reaches of the Upper Mississippi River, finding that recruitment was low but consistent in unpooled reaches and higher and variable in pools (also see Chick et al. [34]). Recruitment variability will affect the reliability of harvest and supply. Harvest will vary with location because of the logistics of reaching fishing locations and transporting fish back to boat landings. Unpooled rivers typically have fewer access points and longer travel times due to their longitudinal geomorphology. Ensuring that harvested bigheaded carps enter a market that provides an economic benefit is necessary to create a system where invasivorism is feasible. Currently, most bigheaded carps removed from the Illinois River system are sold directly to ethnic or local fish markets from the fishers or collected at no cost by fish processors following

agency-contracted removal efforts in the upper Illinois River (see [32]). Harvested bigheaded carps also may be transported by fishers to larger processors, although the number of processors in the region is limited and often geographically distant from harvest areas, making this a costly and often prohibitive option. A second bottleneck to developing market-based invasivorism is ensuring that a steady supply of fresh bigheaded carp is procured by fishers and transported to processors in a way that is safe for the consumer, economical, and efficient.

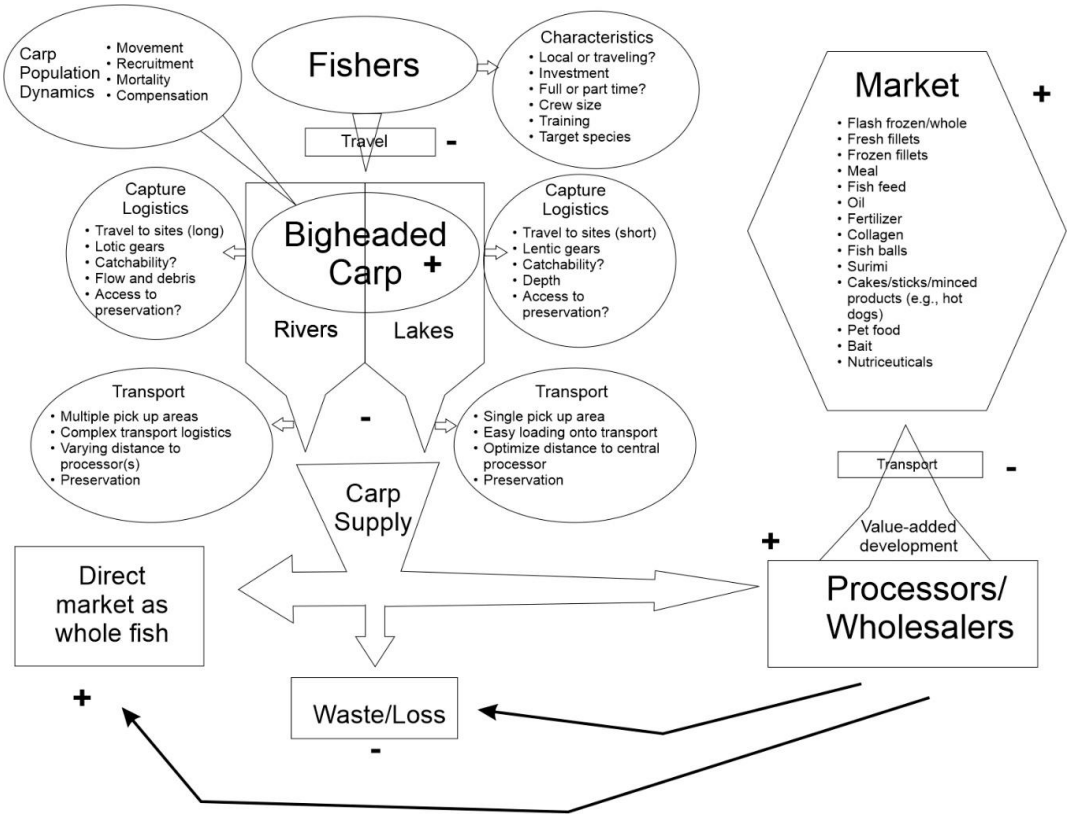

Figure 1. Conceptual model of a fishery for bigheaded carps in the rivers and lakes of the invaded south and north central United States. Economic factors affecting fishers will influence the species composition and biomass of bigheaded carp available to the supply chain. Transportation and markets will drive the level of harvest. Each component along the supply chain has costs (− sign) and economic gains (+) that determine how much fish are removed from the environment.

Providing bigheaded carp-derived products in ways that maximize their value is the goal of wholesalers and processors, where there is clearly global demand for bigheaded carp products. However, costs of setting up local processing facilities is high and potentially risky, while transporting whole fish to existing processors on the coasts or overseas is logistically difficult, involves federal regulation, and is ultimately costly (Figure 1). Creating local demand while developing export and processing facilities is likely the most economically feasible model for establishing harvest as control. However, most investors are wary of supporting such facilities without assurances of dependable supplies of high-quality bigheaded carp from the rivers, which is currently limited by undeveloped fishing capacity, uncertainties about regional fish production, government red tape, and a virtually non-existent transport network.

This conceptual model is not intended to be exhaustive, but it does provide several areas where investments or support may help develop a market for removing bigheaded carp at areas of high density. In the following sections, we describe an effort to stimulate fishing at the "fishing end" and at the "market demand" end of the bigheaded carp supply chain (Figure 1), and the collection of bigheaded carp population demographics through subsampling of commercially harvested carps at the

processing plant, and fishery-independent sampling in the field before and after the harvest programs were implemented.

3. Materials and Methods

The two programs we created to stimulate harvest in the lower Illinois River were compared to the ongoing contracted fishing program in the upper Illinois River [35]. Commercial fishing does not occur in the upper Illinois River at the edge of invaded range, so market-driven removal is not an option in this region (Figure 2). In the lower Illinois River, commercial harvest has occurred for more than a century and has the potential to develop into a control method via invasivorism (Figure 2).

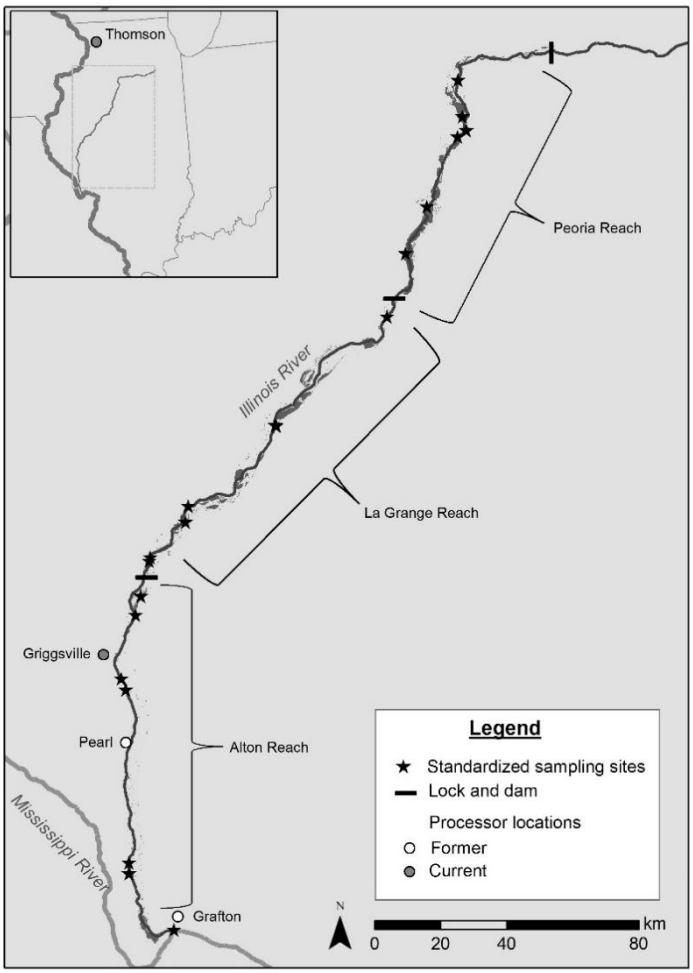

Figure 2. Map of the Illinois River study areas and processing plants during the 2011–2012 study period. Note that Griggsville became non-operational at an unknown time since the study concluded.

3.1. Training, Certification, and Incentives-Based Approach

To accomplish the goals of the "fisher-side" commercial fishing strategy in the lower Illinois River, a stakeholders' meeting was held in Grafton, IL, in the period 20–21 September 2010, during which academic researchers, regulatory authorities, commercial fishers, fish processors, marketers, and distributors discussed using commercial harvest of bigheaded carp in the lower Illinois River as a means of augmenting contracted fishing occurring in the upper river (IISG 2010). Key findings that shaped the design of our removal experiment included the need to (1) improve safety and quality of harvested bigheaded carp as food, (2) properly brand and find markets for the product [29,32], (3) provide financial support for commercial fishers, (4) form a public–private partnership to stimulate harvest, and (5) use associated data to inform an adaptive management framework [36].

We initiated the pilot-scale training, certification, and incentives-based approach to support harvest of bigheaded carp from the lower three reaches of the Illinois River in 2011 to augment the contracted fishing in the upper river (Figure 2). Names of licensed commercial fishers were obtained from the Illinois Commercial Fishing Association (ICFA), and participants were selected by lottery. The training related to (1) safe handling of bigheaded carp for consumption in foreign and domestic markets, (2) licensing and safe operation of commercial fishing vessels, (3) biosecurity practices to prevent transmission of aquatic nuisance species and pathogens, and (4) coordination and sharing of bigheaded carp harvest data with stakeholders.

In addition to receiving $0.42 USD/kg for their catch, incentives for participating fishers included reimbursement for the cost of two ICFA memberships (i.e., fisherperson and deckhand; $100 USD total), the annual Illinois commercial fishing license fee ($35 USD), and net tags required for commercial fishing in Illinois waters ($250 USD). Furthermore, participating fishers received $1000 USD to offset fuel costs after harvesting 22,680 kg of bigheaded carp and $3000 USD to offset gear purchase/repair/replacement costs if they harvested a total of 45,359 kg. For their catch to be eligible for incentives, participating fishers had to report the date/time, location (using a provided handheld GPS), and species composition of their catch. Data had to match information recorded on processor receipts. Only bigheaded carp caught from the Illinois River were considered, and all fish had to be sold to processors for human consumption.

3.2. Set-Quota Harvest Approach

The quota commercial fishing strategy ("market-side") program was conducted in spring 2012, whereby a set-quota fishing effort was implemented to explore the biological and ecological effects of increased bigheaded carp harvest. Following a competitive bidding process, a third-party logistics company (Select Logistics Network, Inc., Clinton, IL, USA) and a local fish processing facility (Big River Fish Company, Pearl, IL, USA) were selected to coordinate the harvest and processing of bigheaded carp at a price of approximately $0.42 USD/kg to fishers, from the lower three reaches of the Illinois River in order to yield up to 453,600 kg of dried fish meal. The bigheaded carp removed through this approach were not eligible for incentives and were processed into fish meal by Protein Products, Gainesville, FL, USA.

3.3. Field and Processor Subsampling

Fisheries are typically highly selective for sizes, ages, and species and thus may have unique impacts on the populations. We visited processing plants approximately every two weeks during the period 1 February 2012 through 8 May 2012 while contracted fishing was occurring. In order to characterize bigheaded carp population demographics within the commercial catch during each biweekly sample, we randomly selected up to 100 silver carp and 100 bighead carp that were harvested from each of the lower three reaches of the Illinois River (depending on availability) and recorded total length (TL) and weight data. Post-cleithra were removed from up to five fish per species per 50 mm length group per river reach for age determination.

We sampled the Illinois River using standardized, fishery-independent sampling to compare bigheaded carp population metrics. We recognized that the sampling was insufficient to detect a fishing impact in such a short time with limited effort. However, we were able to assess annual variability in stock and potential harvest selectivity. Sampling occurred in August 2011 before contracted harvest began and August 2012 after harvest concluded. Sampling was conducted along the main channel of the Illinois River at four fixed locations within each of the three lower pool reaches, as well as nearby backwater lakes and side channels (Figure 2). Pulsed-DC electrofishing transects (Smith-Root GPP 5.0 electrofisher; 15 min each), with two netters, were conducted along each main channel and backwater site during the day. Captured fish were euthanized by immersion in 300 ppm tricaine methanesulfonate (MS-222) until opercular movement ceased. All fish were weighed and measured (total length), and

post-cleithra were collected from a subsample of ten silver carp per 10 mm length group per reach; due to smaller sample sizes, post-cleithra were removed from all collected bighead carp.

To determine age, post-cleithra were sectioned transversely across the center with a 1.5 amp diamond-blade low-speed isomet saw (Buehler, Lake Bluff, IL, USA) following Johal et al. [37]. Two independent readers used side illumination from an MI-150 fiber optic light (Dolan-Jenner Industries, Boxborough, MA, USA); if disagreement between readers could not be resolved, the sample was omitted. Age distributions were developed for the entire dataset using an age–length key [38].

Electrofishing catch per unit effort was compared between 2011 and 2012 for silver and bighead carp by reach and for all reaches combined using paired *t*-tests with each site being treated as the unit of replication. All statistical analyses were conducted using SAS 9.2. (SAS Institute, Cary, NC, USA). An alpha level of 0.05 was used to judge statistical significance.

4. Results

4.1. Training, Certification, and Incentives Approach

Although the fishers harvested bigheaded carp from the Illinois River (Figure 2), the "fisher-side" data collection and fish removal goals of the 2011 incentives approach were not fully achieved. Despite the promise of incentive payments, commercial fishers infrequently reported data such as fishing location (GPS coordinates). Of the ten commercial fishers enrolled in the incentives program, only three fully participated, providing GPS locations and dates related to their fishing efforts. These individuals harvested a combined total of 225,372 kg of bigheaded carp from the Illinois River, and received a total of $8000 USD in incentive payments. Although they technically fulfilled the obligations of the incentives program, review of the data revealed the GPS coordinates provided were typically locations of boat access ramps from which they launched, not the precise locations of harvest. This provided little detailed information other than from which river reach fish were harvested. Harvest effect in the Illinois River was likely minimal due to the low harvest quantities.

4.2. Set-Quota Harvest and Processor Subsampling Approach

The "market-side" fishing approach, with a goal of harvesting enough bigheaded carp to yield an open order of 453,600 kg of dried fish meal, was successful in meeting removal and data goals. Between 25 January 2012 and 11 June 2012, commercial fishers harvested 805,878 kg of bigheaded carp from the Alton reach, 223,910 kg from the La Grange reach, and 276,559 kg from the Peoria reach, for a total of 1,306,346 kg, which yielded enough dried meal to meet the contracted goal.

4.3. Bigheaded Carp Standardized Sampling Catch Rates Pre- and Post-Harvest

Mean silver carp electrofishing CPUE for the three lower reaches of the Illinois River combined had a 2011 rate of 100.4 fish/h (SE = 14.6) and 2012 rate of 81.0 fish/h (SE = 17.4). This difference was not significant ($t_{17} = 1.60$; $p = 0.128$). Silver carp mean CPUE declined from 2011 to 2012 in the Alton reach by nearly half ($t_5 = -3.77$; $p = 0.01$; Table 1), but was not significantly different for the La Grange reach ($t_6 = -1.53$; $p = 0.18$) or the Peoria reach ($t_4 = 0.33$; $p = 0.76$; Table 1). Mean bighead carp CPUE was not different from 2011 to 2012 for the lower three reaches of the Illinois River combined ($t_{19} = 1.12$; $p = 0.28$) or among reaches ($t_6 \leq 1.05$; $p \geq 0.34$). Overall bighead carp CPUE was 2.9 fish/h in 2011 (SE = 2.3) and 0.3 fish/h in 2012 (SE = 0.2) among all reaches.

Table 1. Standardized densities (mean fish electrofished per hour; catch per unit effort, CPUE) of silver carp in each reach pool of the Illinois River before (2011) and after (2012) harvesting occurred.

Year	Reach	N Sites	Silver Carp Mean CPUE	SE
2011	Alton	7	61.6	10.7
	LaGrange	7	107.3	27.3
	Peoria	6	126.7	23.2
2012	Alton	6	33.3	10.8
	LaGrange	7	75.5	15.6
	Peoria	5	147.1	46.1

4.4. Size and Length at Age

Comparisons of length frequency distributions and length at age from commercially harvested and electrofished silver carp in 2011 and 2012 demonstrated the size selectivity of commercial gears. The length frequency histogram comparing commercial harvest to standardized sampling showed a bimodal distribution of commercially caught silver and bighead carp (Figure 3). Examination of the age frequency of silver carp showed over 25% of commercially harvested silver carp were age 5 and older, compared to just over 7% of silver carp collected during standardized sampling (Figure 4), with harvested fish having larger length at age than fish in the standard samples.

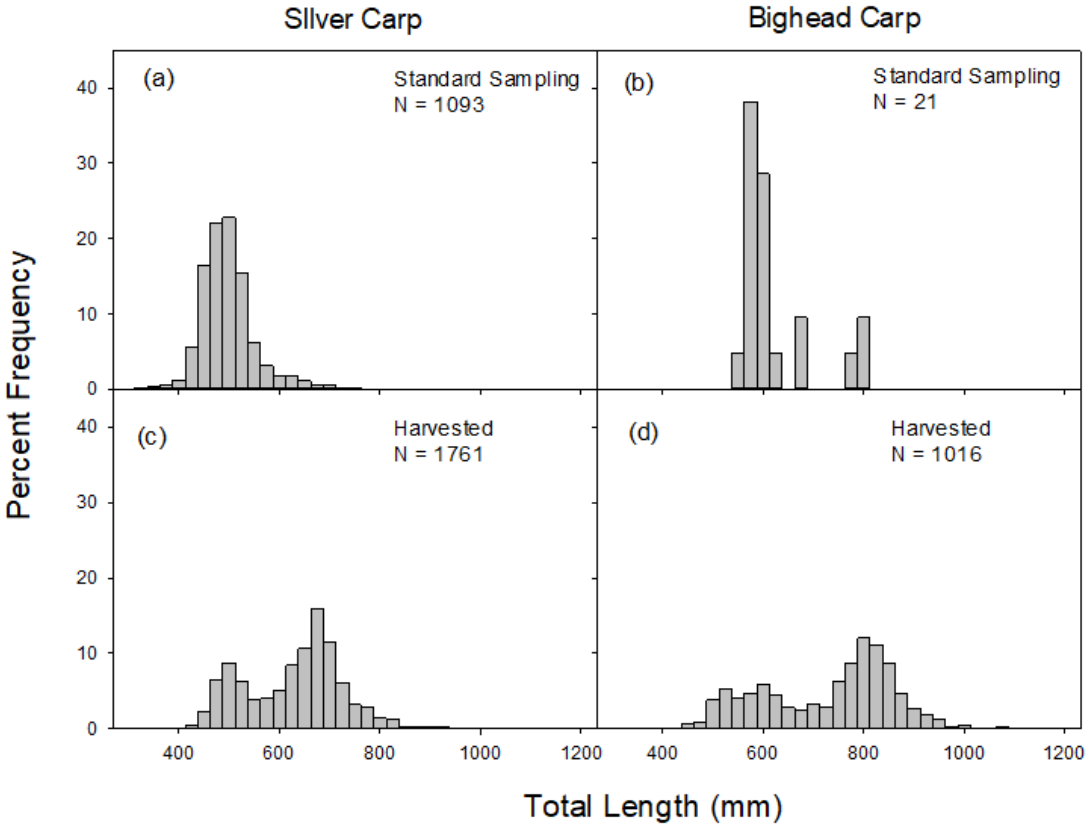

Figure 3. Percent frequency of total lengths of (**a**) silver carp and (**b**) bighead carp sampled with standardized gear (upper panels) and harvested by fishers (**c**,**d**) in the lower Illinois River during 2012.

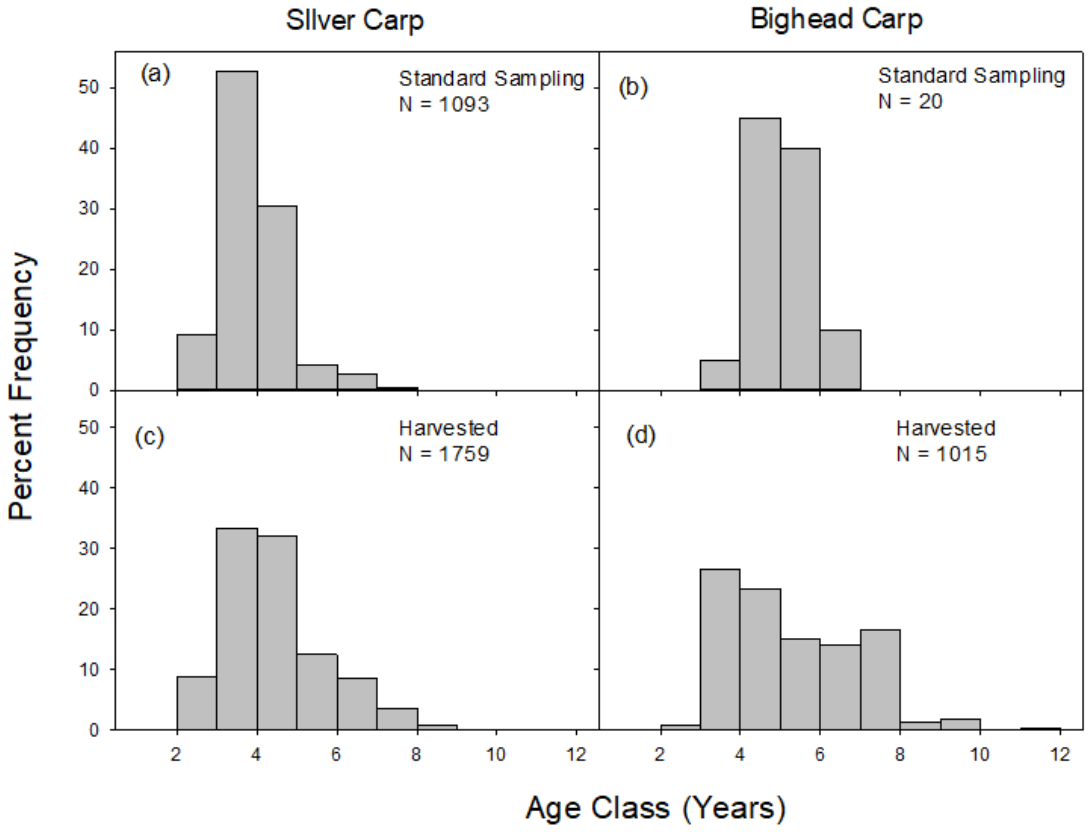

Figure 4. Percent frequency of ages of (**a**) silver carp and (**b**) bighead carp sampled with standardized gear and harvested by fishers (**c**,**d**) in the lower Illinois River during 2012.

5. Discussion

Our "experimental" approach toward stimulating invasivorism in the lower Illinois River yielded important information about how to effectively and economically remove large quantities of bigheaded carp and potentially other invasive species. There are three examples for comparison.

First, the completely subsidized, decade-long contracted removal program in the upper Illinois River is an example of one extreme where market demand for fish does not drive harvest, although harvested bigheaded carps are acquired for free by processors. As we noted earlier, this approach has likely prevented density increases in the upper river, although societal, taxpayer costs are high and bigheaded carp densities continually rebound as fish immigrate from downstream [17]. Along the supply chain model we developed, this approach is completely decoupled from fish availability, market needs, or economic costs and benefits of fishing. Because processors obtain fish at no cost, there is no need to develop a consistent demand for fish. Without contracted removal at the range edge, populations will build in the upper river, greatly increasing the probability of movement toward the CAWS and potentially into Lake Michigan and the other Great Lakes.

The second approach we conducted at the "fisher side" of the model was considered unsuccessful. In the lower Illinois River, when it came to enlisting fishers to assist in the collection of data, the incentive levels did not substantially increase fishing, with our participants not complying. Non-compliant fishers may have placed a greater value on their proprietary information (i.e., fishing locations and methods) than what they could gain from the incentives program. Providing incentives without confirming information about fishing location, effort, and species composition may lead to potential misinformation about the source of the fish, compromising the efficacy of control programs where targeted harvest is necessary. Any successful fisheries management program requires significant buy in and compliance by fishers [39], and this was not accomplished with this approach. In summary,

for this incentives program to work, stakeholders need to work together to reduce impediments to compensation and information sharing, which will require considerable effort, time, and resources.

The third approach we conducted at the "market side" of the conceptual model was considered a success, with our removal goal achieved within 6 months. Creating a fish meal demand using a logistics company to arrange transport and processing allowed fishers to quickly deploy and meet the market price we set. The processor was required by contract to ensure that the source of catch by fishers was recorded accurately, allowing us to match catch data with field-derived sampling. Presumably, this scenario shows that, if demand increased with prices similar to those we set ($0.42 USD/kg), consistent fishing would occur. At the time, prices for bigheaded carp commodities were approximately half of what we set ($0.26 USD/kg) for fish intended for rendering or other industrial purposes (personal communication, Lisa McKee, Big River Fish Co.; personal communication, Gray Magee Jr., CEO, American Heartland Fish Product LLC, Grafton, IL, USA). Fishers also likely preferred the increased income (i.e., they were paid directly by the processor) over the paperwork and documentation necessary to meet incentive benchmarks set in the "fisher-side" approach (i.e., funding required application).

The experimental large-scale removal approaches we instituted during the first half of 2012 were at that time the primary market for bigheaded carp on the Illinois River. The State of Illinois had contracted with China to export over 13.6 million kg annually for direct consumption [40]; however, this volume was not exported due to the lack of fish processing infrastructure and logistic difficulties in transportation and distribution. At the time of the project, "market side"-driven harvest appeared to stimulate the expansion of the bigheaded carp fisheries in the region, at least temporarily. Big River Fish Company subsequently relocated to a larger facility in Griggsville, IL. Upon reopening in 2013, they purchased significant amounts of bigheaded carp for direct consumption markets in China (personal communication, Lisa McKee, Big River Fish Company). Despite this promising start, this processor appeared to have closed permanently by 2020. Schaefer Fisheries in northern Illinois (Thomson, IL, USA, Figure 2) purchased bigheaded carp for domestic direct consumption markets, and for use in liquid organic fertilizer [41]. Direct consumption purchases by this processor have declined since a fire burned the original building in 2015 and reduced capacity for manufacture of bigheaded carp food products such as hotdogs and extruded meats [41,42]. A rendering facility operated by American Heartland Fish Products LLC opened in Grafton, IL near the confluence of the Illinois and Mississippi Rivers in May 2014 (Figure 2). This facility was processing up to 27,000 kg of bigheaded carp per day into fish oil and fish meal until noxious odor violations led to its closure (personal communication, Gray Magee Jr., CEO, American Heartland Fish Product LLC). Other processors and distributors have opened in the region since the early 2010s, with varied success and capacity [32]. Despite continued interest among stakeholders in elevating market demand for bigheaded carp from the Illinois River and other inland waters, harvest has fluctuated rather than increased in the lower Illinois River since 2010 (Figure 5). Likely contributing to the lack of increased harvest, market prices have remained relatively unchanged since the inception of this project [32].

Population modeling suggests that, to deplete bigheaded carp populations in the Illinois River, all age classes must be targeted for removal [10]. Although a large amount of bigheaded carp biomass was removed in 2012, no large-scale removal of bigheaded carp under 500 mm total length occurred. Based on processor subsampling and informal surveys, we determined that a limited number of commercial fishers appeared to use seines or other gears which would harvest all sizes of bigheaded carp. The majority of fishers used gill, trammel or hoop nets that target larger fish. Not only were commercial fishers harvesting larger, older fish, compared to standardized sampling, but they were also harvesting the largest fish within younger age classes. This is supported by the lack of a bimodal distribution in the age-frequency histogram of commercially harvested fish. As an alternative to the collapse approach, the SEAcarP model suggests that market-based fishing in the lower river will effectively reduce densities of carp near the edge of the invaded range in the upper river [24]. This allows for more effective contracted removal efforts at the range edge and reduces the probability of a breach through barrier systems.

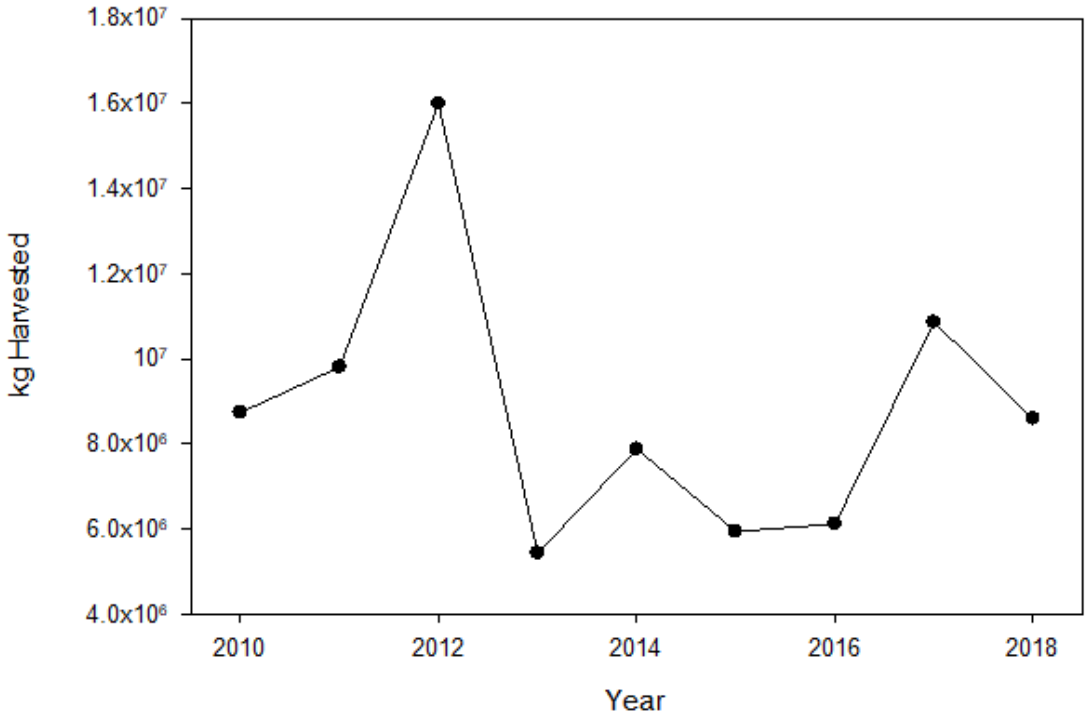

Figure 5. Total biomass in kg of bigheaded carp harvested from the lower Illinois River during the 2010–2018 period, derived from Illinois Department of Natural Resources records [43].

6. Conclusions

Bigheaded carp standing stock and biomass will vary among river reaches and years as a function of variable recruitment, emigration, immigration, harvest impacts, and environmental conditions. In our study, silver carp densities in the Alton Pool did decline, whereas they did not in the other reaches, perhaps because Alton Pool was in proximity to the contracted processor and received greater than 60% of the total harvest. However, without control reaches, more intensive sampling, and multiple years, it is impossible to infer a direct, causal relationship. With sufficient market demand, commercial harvest may control bigheaded carp. However, lack of processing infrastructure and supply chain bottlenecks could constrain harvest, particularly at low commodity prices. Whether a commercial harvest approach to fighting bigheaded carp will be successful can only be assessed over time. Any such evaluation must consider that once a nuisance species becomes an economic resource or a part of local culture, it may no longer be considered a nuisance, but an asset. This could result in pressure to maintain the species or even expand its range to uninvaded regions [9,44], causing a paradox for managers trying to restrict or prevent the spread of certain invasives or mitigate their effects on native species and ecosystems (see Settle et al. [45], and a related discussion on socioeconomic feedbacks of invasive lake trout control in Yellowstone Lake [3]). Given the large, geographical scale of this invasion and complicated harvest logistics, concerns about economic dependence on invasivorism that encourage stock enhancement are likely unmerited.

While harvest-driven extirpation is unlikely, more realistic reduction and control benchmarks might be achieved, although the nature of such benchmarks has yet to be fully articulated. Identifying bigheaded carp density thresholds that would lessen their impacts on native ecosystems or reduce the risk of density-dependent upstream movement toward the Great Lakes or other uninvaded regions are options. Once population goals are determined, management agencies must monitor market prices relative to population densities. If harvest can achieve significant decreases in bigheaded carp density, flexibility in the fishery to move to other river reaches where bigheaded carps are abundant or switch to alternative stocks would be necessary to maintain stability. It is likely that higher (possibly subsidized) prices for bigheaded carp would be needed to compensate for the greater effort necessary to maintain

harvest levels in a declining abundance scenario. Nonetheless, partially subsidized fishing may still be a more cost-effective, efficient, and publicly acceptable means of bigheaded carp control. Agencies must be prepared to provide the economic flexibility and stability necessary in a widespread, complex region such as the Mississippi River basin to ensure that removal by harvest remains robust to maintain control through time without creating unintended dependencies.

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