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Research Article

Use of exploitation simulation models for silver carp (*Hypophthalmichthys molitrix*) populations in several Midwestern U.S. rivers

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Abstract

Management of silver carp *Hypophthalmichthys molitrix* has become a growing concern for multiple state and federal entities. Commercial fishing may have the greatest potential to control silver carp. However, for a management action to be successful, the level of exploitation required to reduce silver carp populations must be quantified. Therefore, silver carp were collected from Midwestern U.S. rivers (i.e., Upper, Middle, and Lower Mississippi, Missouri, Illinois, Ohio, and Wabash rivers) to obtain population dynamics (i.e., recruitment, growth and mortality). Parameters obtained from population demographics were used to simulate exploitation levels using a spawning potential ratio (SPR) approach to determine target size and the amount of exploitation needed to recruitment overfish silver carp within each river system. Overall, we determined that silver carp populations (regardless of river) must be exploited at a small size (i.e., 27–33% of population exploited at ≥300 mm or 33–44% exploited at ≥400 mm), in order to reduce SPR to 0.2, which is identified as a threshold for recruitment overfishing. However, an understanding of the impacts of small mesh sizes on native species and an incentive program for commercial fisherman to promote catch of small fish is needed. This study provides federal and state agencies levels of exploitation and a target size required to effectively reduce silver carp populations in multiple rivers.

Key words: *Hypophthalmichthys molitrix*, invasive species control, exploitation, population dynamics

Introduction

Silver carp *Hypophthalmichthys molitrix* Valenciennes, 1844 were introduced to North America from Asia and subsequently entered Midwestern U.S. rivers in the early 1980s (Freeze and Henderson 1982). Since then, silver carp have rapidly expanded their range throughout the Mississippi River basin (Kolar et al. 2007). Such rapid and successful expansion of invasive species (i.e., silver carp) is attributed to tolerance of a wide range of environmental conditions, high efficiency of feeding, high fecundity, rapid growth rates, lack of natural predators and ability to rapidly acclimate to novel ecosystems (Ehrlich 1984; Lodge 1993; Cudmore and Mandrak 2004; Kolar et al. 2005).

Since the invasion of silver carp in the Illinois and Mississippi Rivers, condition and abundance of bigmouth buffalo *Ictiobus cyprinellus* and condition of gizzard shad *Dorosoma cepedianum* have declined (Irons et al. 2007). These interactions have created great concern regarding the potential effects of silver carp populations on aquatic communities throughout North America. Risk assessments suggest silver carp may cause substantial ecological and economical damage (Mandrak and Cudmore 2004; Nico et al. 2005; Kolar et al. 2005; Kolar et al. 2007; Chapman and Hoff 2011), prompting the Aquatic Nuisance Species Task Force (ANS Task Force) to form the Asian Carp Working Group (ACWG) to develop a national management plan and control measures for silver carp (Conover et al. 2007). The ANS Task Force

is an intergovernmental organization committed to prevent and control aquatic invasive species (ANS Task Force 2011). A goal of the ACWG plan is to control silver carp through exploitation (Conover et al. 2007). However, knowledge of how silver carp populations will respond to exploitation in North America is limited to the Illinois River (Conover et al. 2007; Tsehaye et al. 2013).

Conover et al. (2007) stated that commercial fishing has great potential to reducing silver carp populations in North America. To evaluate the influences of exploitation on population trajectories of silver carp, a thorough understanding of population dynamics is needed. Quantitative parameters are critical for developing harvest quotas which will reduce invasive species populations. Fishery Analysis and Model Simulator (FAMS; Slipke and Maceina 2010) software has been traditionally used to model several harvest length limits and creel limits in order to prevent recruit-ment overfishing (Quist et al. 2002; Slipke and Maceina 2010). However, FAMS models, such as spawning potential ratio (SPR), have also been used to determine exploitation levels required to achieve reduced abundance of individuals in a population (recruitment overfishing; Weber et al. 2011). The SPR model assesses the accumulation of somatic or gonadal tissue accruing in the population (via von Bertalanffy growth model) and the age-specific loss of biomass (e.g., natural mortality) from the population (Ricker 1975). Ultimately, SPR models have potential to assist in identifying the most cost efficient management decisions for successfully reducing silver carp populations.

Baseline silver carp population demographics were collected from several Midwestern U.S. rivers to develop river specific exploitation models. These rivers were selected because they contain established silver carp populations (Conover et al. 2007). Population demographic information was used to simulate exploitation levels using SPR models. The SPR models were then used to determine target size (e.g., minimum length at harvest) and the amount of exploitation required to recruitment overfish the population within each river. The current study will provide federal and state agencies with the information needed to reduce silver carp populations.

Methods

Silver carp were collected from the Illinois River (river kilometers [rkm] 128.7–254), Missouri River (rkm 0–80), Ohio River (rkm 1479–1579), Wabash River (rkm 0–108), Upper Mississippi River (rkm 323–388.6), Middle Mississippi River (rkm 0–128.7), and Lower Mississippi River (rkm 1362–1534) during September and October 2011 using daytime boat electrofishing. Total length and weight were collected; gender was determined by dissection, and otoliths (lapilli) were removed from 100 or more individuals from each river. Two experienced otolith readers independently recorded the number of annuli from each lapillus. If age estimates differed between readers for an individual structure, both readers reviewed the structure together until a consensus was reached. The structure was excluded from further analysis if a consensus was not reached. Methods for processing silver carp otoliths are further described in Seibert and Phelps (2013).

Silver carp growth was modeled using the von Bertalanffy equation:

$$L_t = L_\infty (1 - e^{-k\,(t - to)}),$$

where L_∞ = maximum theoretical length (length infinity) that can be obtained, k = Brody growth coefficient, t = time or age in years, t_o = is the time in years when length would theoretically be equal to zero and e = exponent for natural logarithms. Growth was estimated for silver carp populations using FAMS (Slipke and Maceina 2010). For von Bertalanffy growth equations, L_∞ was set at the largest length of silver carp caught during this study. Length-weight regressions for each population were calculated using FAMS and were used for population modeling. FAMS uses a linearized relationship of length-weight regressions:

$$\log_{10}(W) = a + b^{*}\log_{10}(L),$$

in order to simplify this computation; where W = weight, L = length, a = intercept value and b = slope. Instantaneous mortality (Z) was estimated from the descending limb of each silver carp population based on the catch-curve analysis in FAMS. Total annual mortality was calculated using the following equation in catch-curve analysis using FAMS:

$$\mathrm{Ln}(N_t) = \ln(N_0) - Z(t),$$

where N = number of fish, t = time and Z = rate of change in N. Age-structure analysis indicated that silver carp populations exhibited consistent recruitment.

We used the yield-per-recruit modeling option in FAMS (Slipke and Maceina 2010). FAMS uses the Jones (1957) modification of the Beverton–Holt equilibrium yield equation found in Ricker

(1975) for their yield-per-recruit model. This equation was rearranged by Slipke and Maceina (2010) to:

$$Y = \frac{F * N_t * e^{(z*r)} * W_\infty}{K} [\beta(X, P, Q)] - [\beta(X_1, P, Q)]$$

Where:
F = instantaneous rate of fishing mortality;
N_t = the number of recruits entering the fishery at some minimum length at time (*t*);
Z = instantaneous rate of total mortality;
r = time in years to recruit to the fishery (tr - to);
W_∞ = maximum theoretical weight derived from predicting this weight using L4 and the weight-to-length regression equation;
K = is the growth coefficient in the von Bertalanffy growth equation;
β = incomplete Beta function;
X = e^{-Kr};
X_1 = $e^{-k\,(Maxage\,-\,to)}$ and Max age is the maximum age of the population;
P = Z/K; and
Q = slope of the weight-length relation + 1.

Within the yield per recruit model, the static spawning potential ratio (SPR) option in was used. This modeling approach assumes fixed recruitment and all simulations were started with an initial population size of 1,000 recruits. This allows the evaluation of the relative influence of many exploitation rates simultaneously (Slipke and Maceina 2010). Goodyear (1993) defined potential recruit fecundity (P) as the number of eggs that could be produced by an average recruit in the population, assuming density-dependent growth and survival do not occur. Potential fecundity was estimated as:

$$P = \sum_{i=1}^{n} E_i \prod_{j=0}^{i=1} S_{ij},$$

Where:
N = number of ages in the unfished population;
E_i = mean fecundity of females of age *i* in the absence of density-dependent growth;
S_{ij} = e $^{(-(Fij\,+\,Mij))}$, the density-independent annual survival probabilities of females of age *i* when age *j*;
F_{ij} = the fishing mortality rate of females of age *i* when age *j*; and
M_{ij} = the natural mortality rate of females of age *i* when age *j*. (Goodyear 1993).

SPR is defined as SPR = $P_{fished}/P_{unfished}$ and has a maximum value of 1 and decreases toward 0 as exploitation increases. A more comprehensive review of SPR can be found in Goodyear (1993).

Using FAMS, SPR was assessed for various exploitation rates in 5% intervals, (i.e., 5% – 95%) with fish of varying target harvest lengths (e.g., 300, 400, 500, and 600 mm). Spawning potential ratio is an index used to define the critical number of adults needed to maintain recruitment in the population and was originally used to protect marine populations from recruitment overfishing (Goodyear 1993). A SPR level of 0.2 was used, as this is the threshold for recruitment overfishing in resilient fish populations (Goodyear 1993; Slipke et al. 2002; Weber et al. 2011). Growth, mortality, maximum age, length-weight regression, and male to female ratios from each silver carp population were used. The Hoenig method in FAMS was used to determine conditional natural mortality (Cm) for each population (Hoenig 1983). Fecundity-length estimates were adapted for silver carp from Baerwaldt and Garvey (Southern Illinois University of Carbondale, unpublished data). It was assumed that fish were sexually mature by age-3 and spawned on an annual basis (Kolar 2005).

Results

A total of 931 silver carp ranging from 173–914 mm total length, were collected from the seven Midwestern U.S. rivers (Figure 1). Silver Carp collected from the Ohio, Upper Mississippi, and Missouri rivers exhibited a wide range of sizes, whereas the Middle Mississippi and Lower Mississippi rivers were comprised of medium to large individuals (Figure 1). The Wabash River population structure was dominated by large individuals and the Illinois River was made up of predominantly smaller individuals (Figure 1). Brody growth coefficients were greatest in the Wabash River, followed by the Lower Mississippi, Illinois, Ohio, Middle Mississippi, Upper Mississippi, and Missouri River populations, respectively (range = 0.27–0.176 K; Table 1). Silver carp populations exhibited annual mortality rates ranging from 42–77% (Figure 2). Maximum age observed for silver carp populations ranged from 8 to 13 years, with the Wabash River population having the greatest maximum age observed (Table 1; Figure 2).

For silver carp populations simulated with a targeted harvest length of 600 mm, only the Wabash River (i.e., 87%) had a possibility of reaching the SPR threshold of 0.2 needed to initiate recruitment overfishing through exploitation (Figure 3). All other

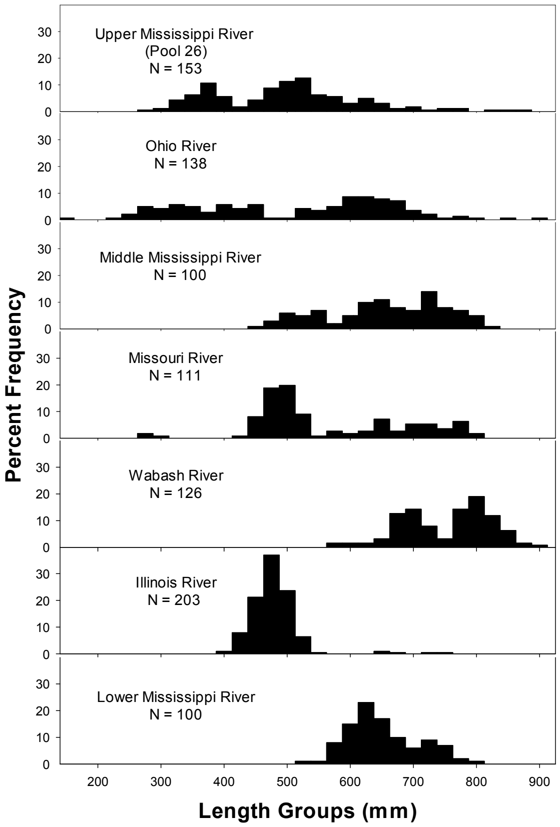

Figure 1. Length-frequency distribution of silver carp (by 25-mm length groups) collected from several Midwestern U.S. rivers via electrofishing during the fall of 2011. N = number of individuals.

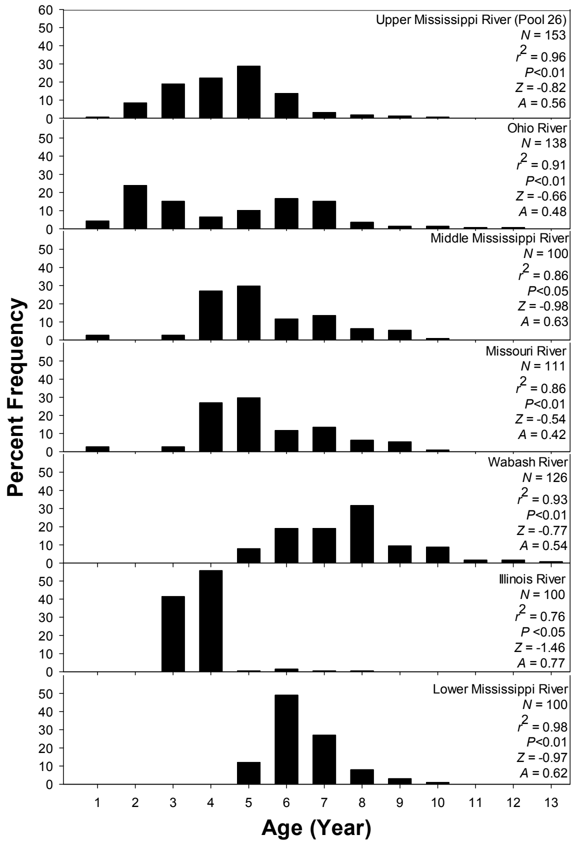

Figure 2. Age-frequency distributions of silver carp collected from several Midwestern U.S. rivers via electrofishing during the fall of 2011. Age structure indices include number of fish (N=), catch-curve regression (r^2), significance of regression (P), instantaneous mortality (Z), and Total annual mortality (A).

populations required greater than 99% exploitation to initiate recruitment overfishing. Silver carp populations were assessed under a simulated 500 mm target length, and required rates of exploitation ranging from 49–76% to reach the SPR threshold. Silver carp populations simulated with a minimum target length of 400 mm, required rates of exploitation ranging from 33–44% to reach the SPR threshold. The Lower Mississippi River required the lowest exploitation rate while the Illinois River required the highest. When silver carp populations were simulated with a 300 mm target harvest length, all rivers required 27–33% exploitation to reach the SPR threshold. While, the Wabash River required the least amount of exploitation while the Illinois River would require the highest degree of exploitation to reach the SPR threshold.

Discussion

Silver carp among these Midwestern U.S. rivers exhibited similar population characteristics such as consistent recruitment, fast growth, longevity, and high mortality. Other studies in Midwestern rivers have also observed fast growth (Williamson and Garvey 2005; Irons et al. 2011; Tsehaye et al. 2013), longevity (8 years old, Illinois River, Tsehaye et al. 2013), and high mortality (Tsehaye et al. 2013). However, higher maximum ages (i.e., 13 years old) were observed in the present study, and were similar to the ages of silver carp in their native range (up to 15 years old, Berg 1964; Kolar 2005). The parameters generated in this study were based on electrofishing and gear avoidance is probable because of the evasive nature of silver carp. Qualitative observations during this study support

Table 1. Parameters for silver carp populations used for spawning potential ratio modeling from several Midwestern rivers during the fall of 2011 via boat electrofishing.

Parameter	Description	Illinois	Wabash	Missouri	Ohio	UMR	MMR	LMR
B_0	Intercept	-5.124	-5.957	-4.37	-5.03	-4.898	-4.659	-4.595
B_1	Slope	3.042	3.349	2.76	3.011	2.966	2.88	2.86
$L\infty$	Theoretical maximum length at time = ∞ (mm)	920	920	920	920	920	920	920
t_0	Theoretical time when length = 0 (years)[a]	-0.063	0.682	-1.009	-0.443	-0.944	-0.744	0.512
K	Growth coefficient[a]	0.218	0.27	0.176	0.199	0.197	0.198	0.226
Age_{max}	Maximum age observed	8	13	10	12	10	10	10
Cm	Conditional natural mortality[b]	0.41	0.28	0.34	0.30	0.34	0.34	0.34

[a]Parameters of the von Bertalanffy growth curve.
[b]Calculated by the Hoenig method.

this notion given the extraordinary swimming and leaping ability of silver carp. Other studies have suggested similar biases with electrofishing and suggest an understanding of this uncertainty must be recognized (Sass et al. 2010; Irons et al. 2011; Moy 2011). Only as of recent have silver carp population evaluations become an area of focus; thus, formalized gear efficacy studies have not yet been conducted. However, a recent report completed by Illinois Natural History Survey (Butler et al. 2013) compared the efficacy of gill nets, hoop nets, and trammel nets for capturing silver carp. The authors suggest that electrofishing was the most effective gear at capturing a wide range of sizes and ages of silver carp (Butler et al. 2013).

Population characteristics of silver carp were used to evaluate a target size and levels of exploitation required to recruitment overfish silver carp populations in Midwestern U.S. rivers. Conventionally, FAMS models have been utilized to prevent overexploitation of fishes through determining harvest restrictions. However, recently FAMS models have been used to determine the relative proportion of the population that should be exploited to effectively control invasive species (i.e., common carp *Cyprinus carpio* Linnaeus, 1758; Weber et al. 2011). Using the population parameters estimated in this study, it was determined that moderate levels of exploitation are needed to effectively reduce silver carp populations. The results indicate that it is essential to establish a target length in order to significantly impact silver carp populations. Fast growth rates, high mortality, relatively fast generation time, and high fecundity exhibited by this species is likely the reason for the exploitation levels needed to achieve recruitment overfishing.

Based on each model, harvesting fish ≥500 mm would not effectively recruitment overfish all populations. Specifically, it was predicted that 76% exploitation of silver carp ≥500mm would be required to recruitment overfish the Illinois River population (highest ambient densities of silver carp in the world, Sass et al. 2010). Similarly, Tsehaye et al. (2013) stated that an exploitation rate of 70% would collapse the population; however, targeting all size classes of silver carp would be essential to achieve this. Achieving this level of exploitation would be extremely difficult though, a target length of ≥400 mm resulted in 33–44% exploitation to reach the SPR threshold for all Midwestern U.S. rivers in this study. Furthermore, a target length of ≥300 mm indicated an even lower exploitation rate needed to reach the SPR threshold. Although the exploitation rate at this size range (≥300mm) is considerably low, it is based on a proportion of the fish harvested of that size and greater, and does not indicate a reduced number of fish needed to be harvested.

Targeting fish ≥300 mm in length is likely undesirable for commercial fishermen because payment is dependent on weight (not individual fish). Targeting larger fish limits the amount of time spent handling and processing fish as well as the amount of bycatch “fouling” their nets, and ultimately results in better utilization of their

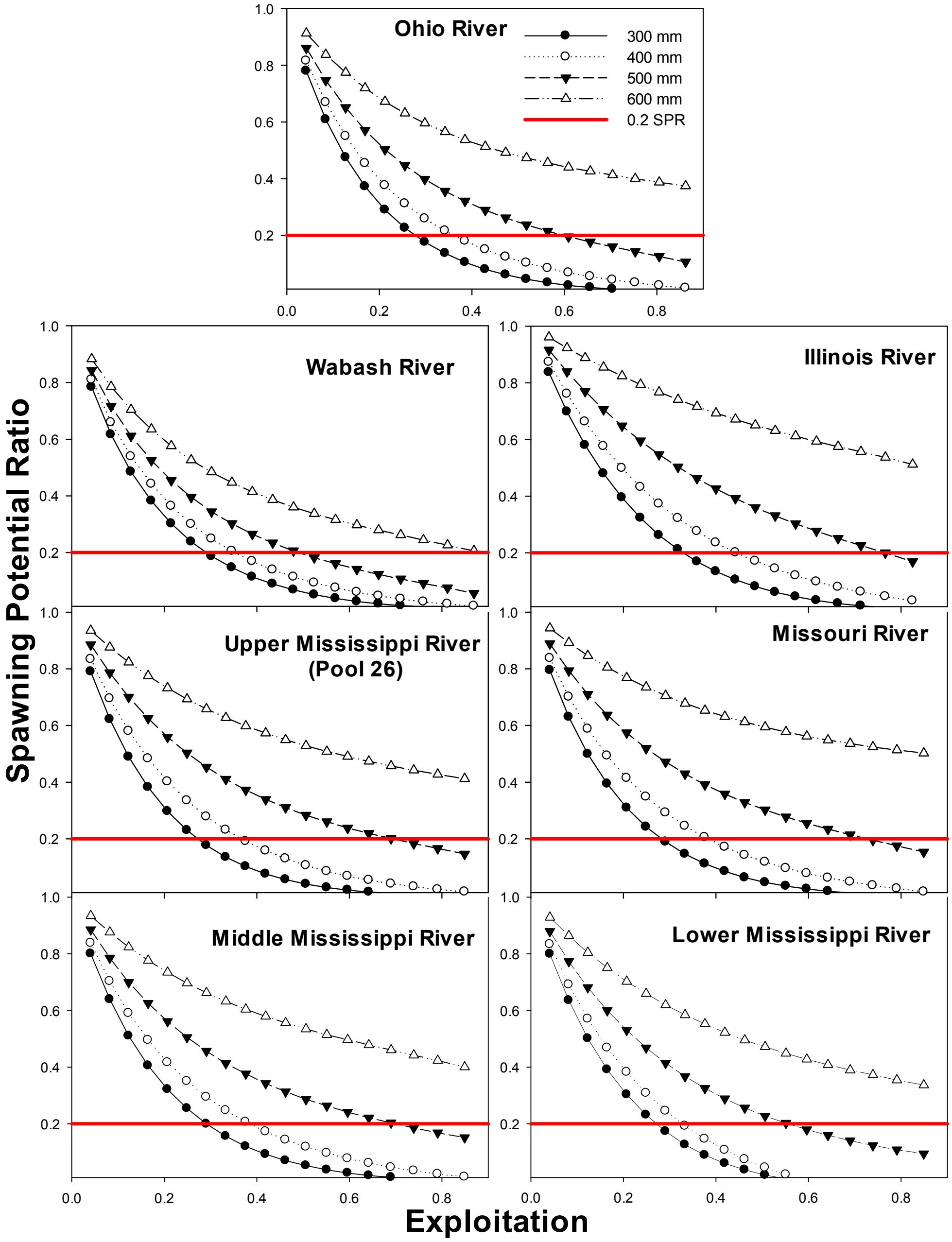

Figure 3. Spawning potential ratio (SPR) models for several Midwestern U.S. rivers with varying minimum lengths of harvest (i.e., target length; 300-600 mm). SPR of 20% (red line) indicates threshold needed to recruitment overfish silver carp populations.

time (Bettoli and Scholten 2006). An increase in mortality of native species may result from bycatch when using smaller mesh sizes (Bettoli and Scholten 2006). For example, Bettoli and Scholten (2006) noted that high mortality of native fish species was observed seasonally when caught as bycatch in nets. Therefore, after evaluation, it may be possible to target smaller sized silver carp seasonally with little impact on the native fish species.

The potential to recruitment overfish similar invasive species has been well documented. Specifically, Weber et al. (2011) found that

intermediate levels of exploitation at a smaller target length would potentially result in recruitment overfishing of common carp. Recruitment overfishing has also been observed for several freshwater fish species including yellow perch *Perca flavescens* Mitchill, 1814 (Eshenroder 1977), walleye *Sander vitreum* Mitchill, 1818 (Anthony and Jorgensen 1977), and lake whitefish *Coregonus clupeaformis* Mitchill, 1818 (Walker et al. 1993). These fish species exhibit some of the similar r-selected characteristics of silver carp, suggesting that recruitment overfishing of these populations may be achievable. Conversely, population equilibriums are rare for invasive populations that may still be growing, receiving migrants, or populations that are being intensively harvested. Therefore, in order to maintain low levels of silver carp, exploitation would need to be continued even after an apparent reduction of the population is observed.

This study provides federal and state agencies the amount of exploitation likely needed to reduce silver carp populations in the Illinois, Missouri, Ohio, Wabash, and Mississippi rivers. The models used provide insight into the most efficient size range (i.e., ≥300 mm or ≥400 mm) to effectively control silver carp populations in multiple large rivers. However, further research is needed to determine the impact of smaller mesh sizes on native fauna. It is also important to identify possible markets for small silver carp. Additionally, given the connectivity among rivers, exploitation is needed within all of these reaches to maintain low levels of silver carp. To ensure management is efficient and effective, silver carp population dynamics and levels of exploitation will need to be continuously monitored.

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