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ARTICLE

Simulated Population Responses of Common Carp to Commercial Exploitation

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Abstract

Common carp *Cyprinus carpio* is a widespread invasive species that can become highly abundant and have deleterious ecosystem effects. Thus, aquatic resource managers are interested in controlling common carp populations, but control is difficult, in part, because of the inherent uncertainty as to how populations respond to exploitation. To better understand this response, we evaluated the population dynamics (recruitment, growth, and mortality) of common carp in three natural lakes in eastern South Dakota. Common carp exhibited similar population dynamics across these three systems, which were characterized by consistent recruitment (ages 3–15 being present), fast growth ($K = 0.37\text{--}0.59$), and low mortality ($A = 1\text{--}7\%$). We then modeled the effects of commercial exploitation on size structure, abundance, and egg production to determine its utility as a management tool to control populations. All three populations responded similarly to exploitation simulations in which a 575-mm length restriction represented commercial gear selectivity. Simulated common carp size structure declined modestly (9–37%) in all simulations. The abundance of common carp declined dramatically (28–56% of starting levels) at low levels of exploitation (0–20%), but exploitation greater than 40% had little additive effect, the final populations only being reduced 49–79% despite high exploitation (>90%). At a moderate level of exploitation (40%), maximum lifetime egg production was reduced to 77–89% of starting levels, indicating the potential for recruitment overfishing. Exploitation further reduced common carp size structure, abundance, and egg production when simulations were not size selective. Our results provide insights into the ways in which common carp populations may respond to exploitation. Although commercial exploitation may be able to partially control populations, an integrated removal approach that removes all sizes of common carp has a greater chance of controlling population abundance and reducing the perturbations induced by this invasive species.

Common carp *Cyprinus carpio* originated from the Ponto-Caspian region (Balon 1995) but have been widely distributed across the globe for aquaculture and recreational purposes (Panek 1987). In a myriad of aquatic systems outside their native range, particularly in North America and Australia, common carp form dense populations and negatively affect aquatic ecosystem functions (Parkos et al. 2003; Koehn 2004; Weber and Brown 2009). Common carp are tolerant of a broad range of environmental conditions (Edwards and Twomey 1982; Egertson and Downing 2004; Weber et al. 2010) but often achieve the highest densities (up to 1000 kg/ha) in shallow, eutrophic systems (Panek 1987; Egertson and Downing 2004). At high

densities, common carp have deleterious effects on ecosystems, primarily related to their benthic feeding behaviors that degrade water quality and clarity, reduce aquatic macrophytes, alter invertebrate communities, and reduce the abundance of native fishes (Parkos et al. 2003; Weber and Brown 2009, 2011; Jackson et al. 2010). Thus, aquatic resource managers are extremely interested in controlling this invasive species.

Management strategies for abundant common carp populations are generally aimed at reducing abundance to mitigate their negative effects (Ricker and Gottschalk 1940; Cahoon 1953; Neess et al. 1957). A wide range of control techniques have been attempted with varying success, including water-level

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manipulations (Shields 1957; Verrill and Berry 1995), piscicide treatments (Weier and Starr 1950; Meronek et al. 1996; Bonneau 1999), and removals using various gears (Johnsen and Hasler 1977; Schwartz 1986; Fritz 1987; Stuart et al. 2006). However, commercial removal using large seines appears to be one of the most promising strategies for controlling invasive common carp populations (Ricker and Gottschalk 1941; Rose and Moen 1953; Neess et al. 1957).

While fishery management agencies may do their own removals or contract commercial fisherman to remove common carp from specific systems (i.e., Ricker and Gottschalk 1941; Rose and Moen 1953), a commercial fishing industry does exist for common carp in parts of North America (i.e., Cahoon 1953; Fritz 1987; Hanten and Hanten 2007). Common carp flesh can be processed for human consumption (i.e., fillets, smoked, minced meat, caviar), and the rest of the fish is used for a variety of products (i.e., leather, reproductive hormones, lobster and fish bait, isinglass, bone meal, fish meal, fertilizer; Hanten and Hanten 2007). Commercial harvest of common carp in the USA was high in the early 1900s (19,500,000 kg), declined dramatically during the 1930s, increased during the late 1940s, and then remained relatively stable through the 1970s (Fritz 1987). Most of the common carp harvest in the USA occurs throughout the Midwest (Fritz 1987). In South Dakota, combined annual commercial harvest of common carp, bigmouth buffalo *Ictiobus cyprinellus*, and black bullhead *Ameiurus melas* has ranged from 1,700 kg in 1914 to 1,600,000 in 2002 (Hanten and Hanten 2007). From 2005 to 2010, a single commercial fishing crew annually harvested 147,700–524,500 kg of common carp in 5–10 lakes in eastern South Dakota (E. Moehring, South Dakota Game, Fish and Parks, personal communication).

Systematic, large-scale removals of common carp using commercial seining gear have produced desirable results in the form of increased water clarity, aquatic plant growth, and sport fish production (Ricker and Gottschalk 1941; Cahoon 1953; Rose and Moen 1953; Neess et al. 1957). However, these results may be short-lived because high fecundity (up to 2,000,000 eggs per female; Swee and McCrimmon 1966) and fast growth rates (>500 mm by age 3; Weber et al. 2010) allow populations to quickly rebound following removal efforts. For management strategies to be successful, information is needed to understand how common carp populations respond to exploitation and what level of exploitation is needed to effectively reduce and control their populations.

Fisheries management revolves around evaluating costs and benefits of multiple management alternatives and deciding what option will best meet management objectives. Modeling can play an integral role in fisheries management by allowing managers to quickly and effectively explore several alternative options, aid in the decision process, and ultimately help select a strategy that is most likely to produce the desired effect (Johnson 1995; Slipke and Maceina 2000). Fishery Analyses and Simulations Tools (FAST; Slipke and Maceina 2000) software is commonly used by fisheries managers to model predicted

effects of several potential management strategies (i.e., length and harvest limits) aimed at maximizing yield, improving size structure, or conserving populations of recreational or commercial value (Maceina et al. 1998; Boxrucker 2002; Quist et al. 2002; Makinster and Paukert 2008; Quist et al. 2010). Conversely, FAST also has potential for evaluating the effects of large-scale removal programs on invasive fish species. Management plans to target population reductions of undesirable species can benefit from an understanding of how populations respond to exploitation but, to our knowledge, have not been modeled with FAST. Mechanical removal of nuisance or invasive species can be an effective means to reduce their abundance (Ricker and Gottschalk 1941; Cahoon 1953; Rose and Moen 1953), but results are highly variable (Meronek et al. 1996) and affected by numerous factors, including demographics, that need to be considered when devising management strategies (Hauser et al. 2006). Thus, FAST models may benefit invasive species management by identifying levels of exploitation where population control and recruitment overfishing may occur. Here, we evaluate population characteristics of common carp in an interconnected glacial lake system in eastern South Dakota. We then use FAST to model the potential effects of commercial exploitation on size structure, abundance, and reproductive potential of common carp and thereby gauge the effect of this control management strategy.

METHODS

Study site.—Information on common carp populations was obtained from Lakes Herman, Madison, and Brant located in Lake County in southeastern South Dakota during 2009. All three lakes are part of an interconnected chain of lakes (Figure 1), but little movement of common carp occurs among these systems (<0.5%; Hennen 2010; M. Weber, South Dakota State University, unpublished data). Lake Brant, the smallest of the three lakes (420 ha), has a mean depth of 3 m (maximum depth of 4.5 m) and a simple basin (shoreline development index = 1.5). Lake Herman, intermediate in size to the other two lakes (521 ha), has a mean depth of 1.5 m, maximum depth of 4 m and a shoreline development index of 1.8. Lake Madison, the largest (1,069 ha) and deepest (mean depth = 2 m, maximum depth = 5 m), has the most complex basin (shoreline development index = 2.2). All lakes have predominately silt bottoms (>70%) and little submerged macrophyte coverage (<1%; Stukel 2003). Fish communities in the three study lakes consist primarily of common carp, yellow perch *Perca flavescens*, walleye *Sander vitreus*, northern pike *Esox lucius*, black crappie *Pomoxis nigromaculatus*, white sucker *Catostomus commersonii*, bigmouth buffalo, smallmouth bass *Micropterus dolomieu*, various *Lepomis* sunfish, white bass *Morone chrysops*, black bullhead, and fathead minnow *Pimephales promelas* (St. Sauver et al. 2009).

Population characteristics.—All common carp were captured May 21–28, 2009, from the three study lakes using a large bag seine (1,200 m long, 5-cm bar mesh). Total length (mm)

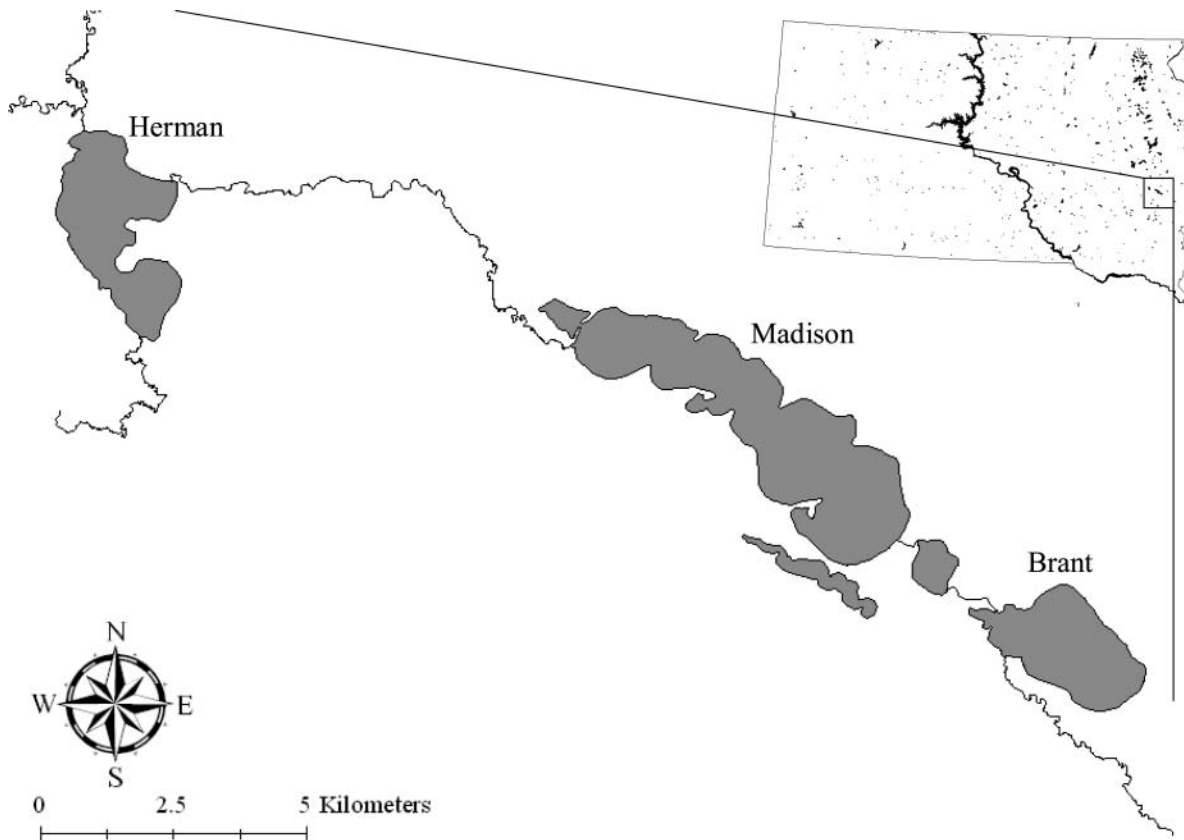


FIGURE 1. Locations of Lakes Herman, Madison, and Brant in southeastern South Dakota, where common carp population data was collected.

and weight (g) were measured, gender was determined, and the dorsal spine was removed from approximately 100 individuals from each population. Dorsal spines were air dried for 2 weeks, and transverse sections (0.8-mm width) were removed from the distal portion of the spine using a low-speed Isomet saw. Dorsal spines have been deemed an acceptable aging structure for common carp (Weber and Brown, in press). Annuli were counted under a dissecting microscope by three independent readers that were experienced with aging common carp spines. If the age estimates differed among the three readers, the spine was reevaluated by all readers until there was unanimous agreement.

A von Bertalanffy growth function was used to describe the growth of common carp, namely,

$$L_t = L_{\infty}[1 - e^{-K(t-t_0)}],$$

where L_t = length at time t , L_{∞} = the theoretical maximum length of common carp in the population, K = the growth coefficient, and t_0 = time when length would theoretically equal 0 mm. Initial fitting of von Bertalanffy models to the data resulted in illogical intercept (t_0) estimates, probably due to the low numbers of fish captured less than age 3 ($n = 15$). Consequently, t_0 was fixed at zero when deriving k and L_{∞} from the von Bertalanffy models and in all simulations. Parameter esti-

mates from the length–weight relationships and von Bertalanffy growth equations were obtained using FAST (Slipke and Maceina 2000) and subsequently used in modeling simulations. Total annual mortality (A) was estimated using Heincke's method (Everhart et al. 1975):

$$A = 1 - [(n - n_0)n^{-1}],$$

where n is the total of all age frequencies in the sample, including the first fully recruited age, and n_0 is the frequency of the first fully recruited age. The size structure of each population was assessed by calculating the proportional size distribution (PSD = 100[number of fish ≥ 410 mm]/number of fish ≥ 280 mm [or $N_{\geq 280}$]), proportional size distribution of preferred-length fish (PSD-P = 100[number of fish ≥ 530 mm]/ $N_{\geq 280}$) and proportional size distribution of memorable-length fish (PSD-M = 100[number of fish ≥ 660 mm]/ $N_{\geq 280}$; Neumann et al., in press).

Population simulations.—The effect of commercial exploitation on common carp size structure, abundance, and spawning potential ratio was evaluated using the dynamic pool option in FAST over a 100-year period because it includes population size among its output variables (Slipke and Maceina 2000). Conditional natural mortality (CM; natural mortality in the absence of fishing mortality) and conditional fishing mortality (CF; the

exploitation rate in the absence of natural mortality) can be manipulated to evaluate multiple levels of exploitation on fish populations. Varying mortality rates were used to derive estimates of instantaneous rate of fishing mortality ($F = -\log_e[1 - CF]$) and natural mortality ($M = -\log_e[1 - CM]$) and are used as variables in the Beverton–Holt equilibrium model (Slipke and Maceina 2000). Common carp are a long lived species (about 21 years; this study) and mortality is perceived to be relatively low (1–7%; this study). Thus, we modeled fixed rates of CM at 5% and 15% to evaluate a realistic range of natural mortality rates. Because FAST does not allow direct inputs of exploitation, we manipulated CF values to obtain estimates of exploitation from 0% to 95% at 5% intervals.

To evaluate the potential for commercial fishing to achieve recruitment overfishing of common carp populations, we assessed spawning potential ratio (Goodyear 1993) at varying levels of exploitation. Spawning potential ratio (SPR) is a tool originally developed for use in marine environments to determine the critical number of adults needed to produce recruits under Ricker or Beverton–Holt models (Hillborn and Walters 1992). Assuming density-dependent growth and survival do not occur, potential recruit fecundity (P) is defined as the number of eggs that could be produced by an average recruit in the population. Potential fecundity was estimated as

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

where n is the number of ages in an unfished population, E_i is the mean fecundity of females of age i , and $S_{ij} = e^{-(F_{ij} + M_{ij})}$ or the density-dependent annual survival probabilities of females of age i when age j , where F_{ij} is the instantaneous fishing mortality rate of females from age i to age j and M_{ij} is the instantaneous natural mortality rate of females from age i to age j (Goodyear 1993). The SPR (i.e., $100[P_{\text{fished}}/P_{\text{unfished}}]$) has a maximum value of 100 and decreases toward 0 as exploitation increases. Reducing SPR below 10–20% of maximum (when $CF = 0$) has been suggested as a threshold where adult spawners are removed below potential recruitment levels (Goodyear 1993; Slipke et al. 2002). Because an SPR level of 20% is typically designed to protect important recreational or commercially valuable fish stocks and may be conservative (Goodyear 1993; Slipke et al. 2002), we set our target at 10–20% of maximum. To estimate SPR, we derived a linear common carp fecundity–length relationship (number of eggs = $2,139.79[\text{length in mm}] - 1,025,284$; M. Weber, South Dakota State University, unpublished data) developed for these systems to estimate average egg production. We assumed that fish were sexually mature by age 3 (Panek 1987; Bajer and Sorensen 2010) and spawned on an annual basis. Population sex ratio approximated 50 males:50 females in all three lakes.

Age-structure analysis indicated that common carp in these systems exhibited consistent recruitment. However, common

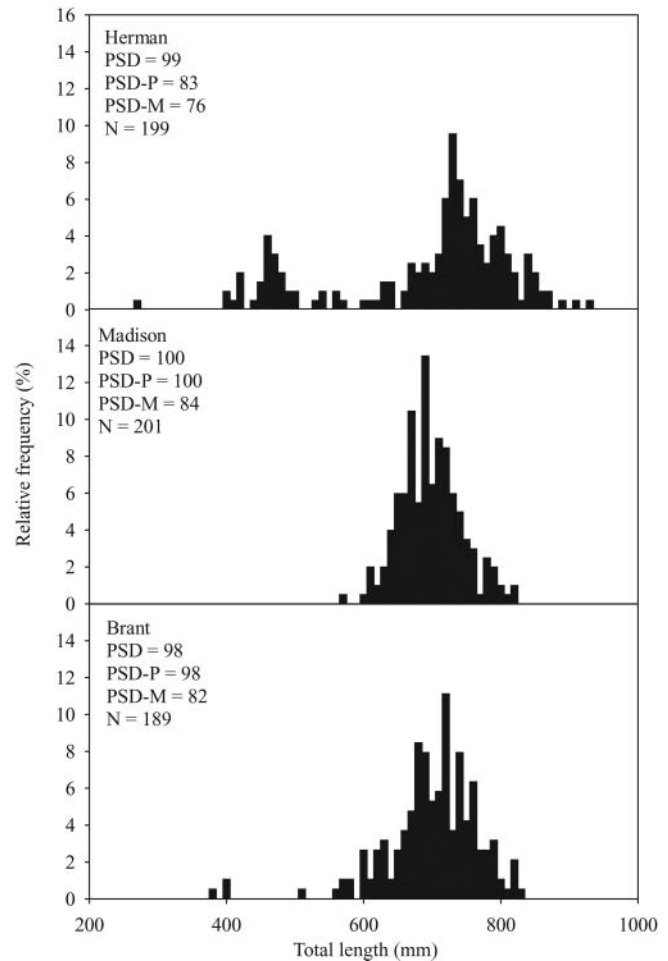


FIGURE 2. Length frequency histograms, size structure indices, and sample size (N) for common carp sampled from Lakes Herman, Madison, and Brant using a 1,200-m, 5-cm-bar-mesh bag seine. Size structure indices included the proportional size distribution ($PSD = 100[\text{number of fish} \geq 410 \text{ mm}]/\text{number of fish} \geq 280 \text{ mm}$ [or $N_{\geq 280}$]), the proportional size distribution of preferred-length fish ($PSD-P = 100[\text{number of fish} \geq 530 \text{ mm}]/N_{\geq 280}$), and the proportional size distribution of memorable-length fish ($PSD-M = 100[\text{number of fish} \geq 660 \text{ mm}]/N_{\geq 280}$).

carp have also been shown to exhibit cyclic recruitment displaying strong year-classes every second year (Phelps et al. 2008). Therefore, to make our models more broadly applicable and to understand how control strategies may be affected by recruitment patterns, we ran all models using both the fixed recruitment option and sequentially varied recruitment with strong year-classes every second year that were three times the average year-class (Phelps et al. 2008). All simulations were started with an initial population size of 1,000 recruits. For simulations evaluating commercial exploitation, we applied a 575-mm minimum length restriction because few individuals smaller than this size were captured by commercial fishing gear (Figure 2). To evaluate how populations would respond to multi-faceted management strategies using alternative removal methods that were not size-selective, we also simulated exploitation on Lake

TABLE 1. Population parameter estimates for common carp populations sampled in Lakes Herman, Madison, and Brant. These estimates were employed in Fishery Analyses and Simulations Tools (FAST) simulation models.

Variable	Description	Population		
		Herman	Madison	Brant
β_0	Intercept of \log_{10} weight–length regression	–5.59	–4.63	–4.90
β_1	Slope of \log_{10} weight–length regression	3.24	2.92	3.01
L_∞	Theoretical maximum length (mm)	778	728	738
K	Growth coefficient (rate at which fish approach L_∞)	0.368	0.589	0.387
t_0	Length of fish at theoretical time 0 (years)	0	0	0
Age_{max}	Oldest fish sampled (years)	21	15	20
A	Total annual mortality (%)	7	2	1

Herman without the 575-mm length restriction. The procedures detailed above resulted in a total of 14 simulations with data from three populations with simulated consistent and cyclic recruitment under exploitation scenarios of 0–95%.

RESULTS

Population Characteristics

Data were collected from 598 common carp from the three lakes ranging between 274 and 933 mm total length (TL; Figure 2). Size structure was large but similar among the three populations ($\text{PSD} = 98\text{--}100$, $\text{PSD-P} = 83\text{--}100$, $\text{PSD-M} = 76\text{--}84$; Figure 2). Most fish sampled (83%) were greater than 650 mm TL, but few (8%) were greater than 800 mm TL. Weights of common carp (230–12,680 g) in lakes Madison and Brant were similar for a given length but slightly larger than those in Lake Herman (Table 1). Growth rates of common carp were also generally similar among all three populations. Common carp in Lake Madison had a larger growth coefficient, whereas those in Lake Herman had a larger theoretical maximum length (Table 1). Pooled age and growth information from all populations resulted in a von Bertalanffy growth equation of $L_t = 751[1 - e^{-0.409(t - 0)}]$. Common carp in Lake Madison experienced shorter longevity than did those in Lakes Brant and Herman, and total annual mortality was low for all populations (1–7%, Table 1).

Population Simulations

The predicted size structure of common carp populations declined only modestly with increases in exploitation at a 575-mm length restriction (Figure 3). When $\text{CM} = 5\%$, PSD-P declined 30–33% for populations with consistent recruitment and 9–37% for populations with cyclic recruitment as exploitation increase from 0% to 95%. When $\text{CM} = 15\%$, PSD-P declined 28–29% for populations with consistent recruitment and 27–35% for populations with cyclic recruitment as exploitation increased from 0% to 95%.

Low levels of exploitation dramatically reduced the number of common carp in each population (Figure 4). Populations

simulated with consistent recruitment resulted in fewer individuals in the population compared with simulations with cyclic recruitment. When recruitment was consistent and $\text{CM} = 5\%$, number of common carp in the population declined 33–35% as exploitation increased from 0% to 10% and decreased an additional 15–18% (i.e., to 48–53%) as exploitation increased from 10% to 20%. When CM increased to 15%, population abundance declined 18–22% as exploitation increased from 0% to 10% and decreased an additional 10–14% (i.e., to 28–36%) when exploitation increased from 10% to 20%. Similar results were obtained when populations were simulated with cyclic recruitment (Figure 4). Despite extremely high simulated exploitation (90%), common carp populations were only reduced 49–79% of initial abundance.

Exploitation also had a dramatic effect on SPR (Figure 5). For populations with consistent recruitment and $\text{CM} = 5\%$, SPR was reduced to 25–32% at 20% exploitation, and SPR fell below 10% when exploitation surpassed 40–50%. For populations with consistent recruitment at $\text{CM} = 15\%$, SPR was reduced to 38–41% at 20% exploitation, and SPR fell below 10% when exploitation surpassed 63–93%. When populations were simulated with cyclic recruitment, SPR responded similarly (Figure 5).

Effects of exploitation without the 575-mm length restriction on the common carp population in Lake Herman were more dramatic. Without size-selectivity imposed upon removal efforts, common carp size structure, abundance, and spawning potential ratio declined more dramatically and to lower values compared with size-selective removal methods (Figure 6). Common carp size structure was reduced by 50% when exploitation was 32–53%, and abundance was reduced 54–71% when exploitation was only 20%. Additionally, SPR fell below 20% at 17–22% exploitation and to below 10% at 24–31% exploitation.

DISCUSSION

Population Characteristics

Common carp in these three eastern South Dakota lakes exhibited similar population characteristics across systems that were described by consistent recruitment, fast growth, large

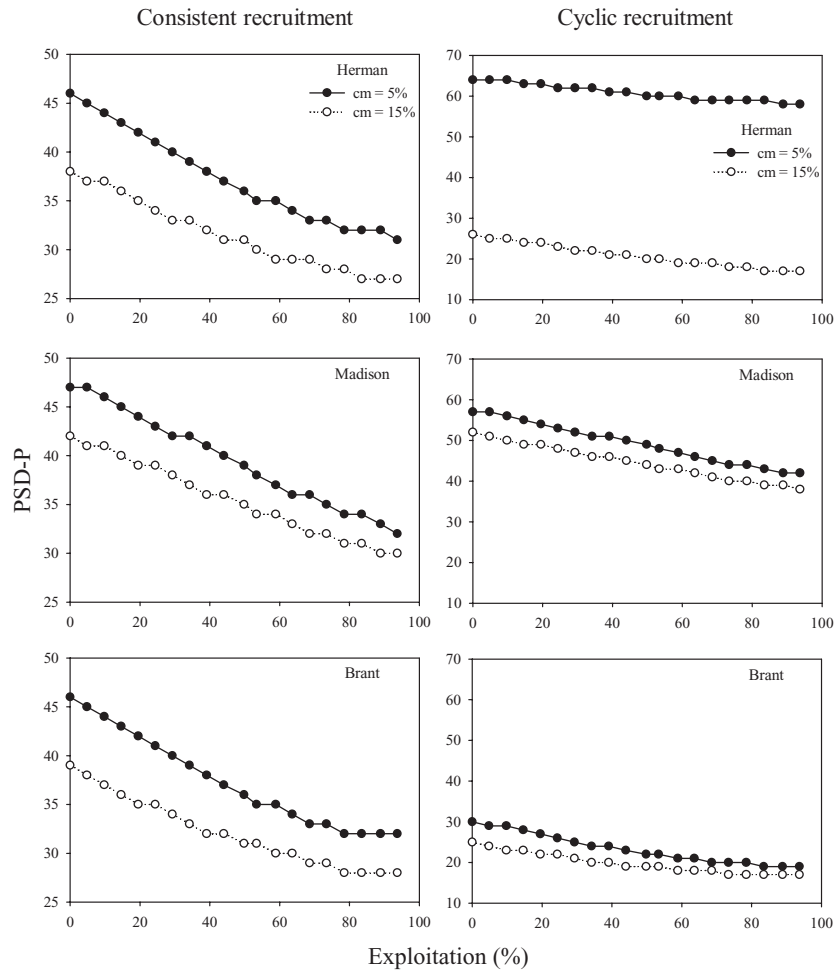


FIGURE 3. Simulated proportional size distribution of preferred-length (PSD-P; see Figure 2) common carp populations in Lakes Herman, Madison, and Brant under consistent (left panels) and cyclic (right panels) recruitment rates (note the differing y-axis scales) and conditional natural mortality (cm) rates of 5% and 15% with size selective removal.

size structure, longevity, and low natural mortality. Common carp populations were composed of primarily older individuals and recruitment was relatively consistent. Recruitment of common carp has been shown to be consistent in some systems (Starrett and Fritz 1965; Karatas et al. 2007) and erratic or cyclic in others, potentially influenced by climatic events and predation (Phelps et al. 2008; Bajer and Sorensen 2010). Growth rates and size structure of common carp in these systems are similar to other systems throughout the region (Weber et al. 2010) but appear to be faster than across much of their range. Growth rates identified here are some of the fastest in North America (Jackson et al. 2008) and are faster than many populations in Europe (Fernandez-Delgado 1990). Common carp in Australia have similar rates of growth but attain smaller maximum size (Vilizzi and Walker 1999), whereas common carp in the Mediterranean have lower growth rates but attain larger maximum sizes (Treer et al. 2003). Outside of catastrophic events (i.e., hypoxia, disease), total annual mortality of common carp is low (<10%). Maximum ages of common carp in

the region have been reported at 24 (Phelps et al. 2007) and 34 (Bajer and Sorensen 2010) years, although common carp in some areas have been suggested to reach 50 years of age (Panek 1987).

Population Simulations

Traditionally, FAST models have been used to identify successful harvest restrictions and prevent overexploitation of fishes with recreational or commercial value. Our results demonstrate that FAST models can also provide insights into how invasive populations may respond to exploitation and may be used to identify levels of exploitation where effective population control may occur. Our simulations predict that exploitation only has a minor effect on common carp size structure. Only a few scenarios where exploitation was high resulted in significant declines in common carp size structure, probably because fast growth rates and low natural mortality prevent size structure from being reduced. Fast growth rates, low natural mortality, and high fecundity also made it difficult to substantially reduce

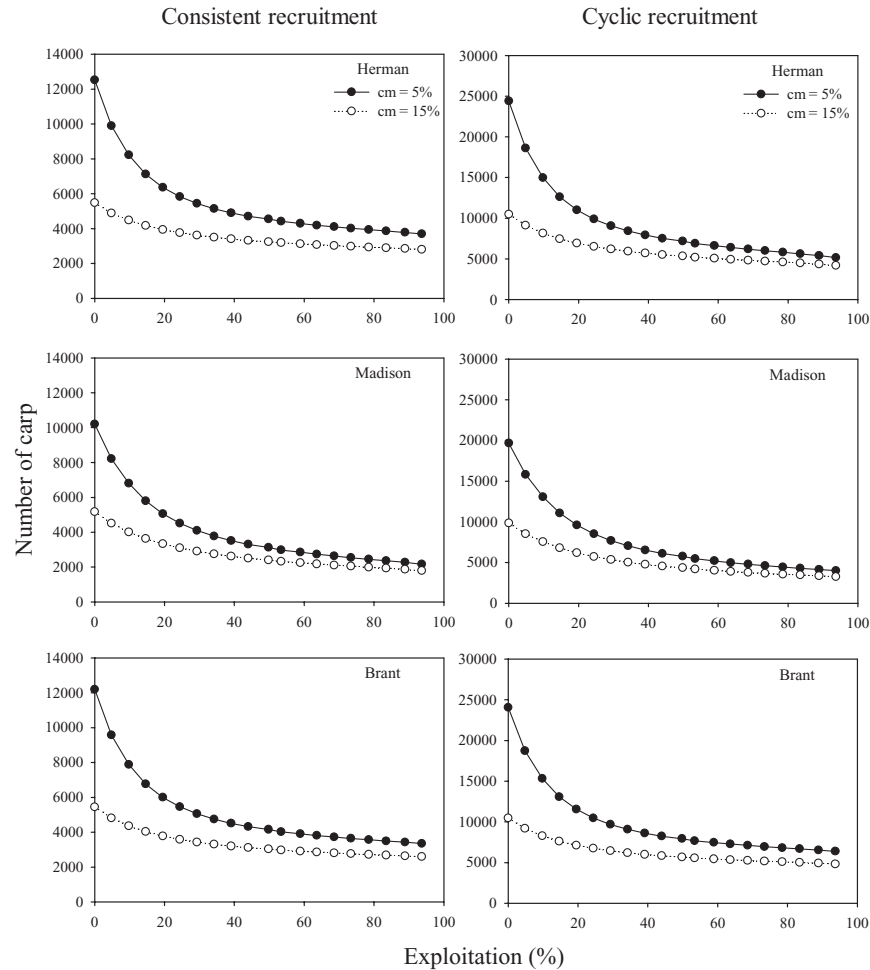


FIGURE 4. Simulated number of common carp remaining in Lakes Herman, Madison, and Brant under consistent (left panels) and cyclic (right panels) recruitment rates (note the differing y-axis scales) and conditional natural mortality (cm) rates of 5% and 15%.

common carp abundance. Common carp abundance substantially declined as exploitation increased from 0% to 20% and marginally declined from 20% to 40% exploitation, but beyond 40% exploitation, effects of exploitation were limited. Thus, managers attempting to control common carp abundance with gears that select for large-bodied individuals may realize few benefits from increasing exploitation beyond 40%.

Spawning potential ratio is typically used to provide a fishery conservation strategy for managers to ensure that stocks are not depleted to the point of recruitment overfishing (Goodyear 1993). For nuisance or invasive species, reducing spawning potential ratios below replacement levels may be used to define management strategies for control purposes because it can lead to population decline and extirpation. Generally, minimum spawning potential ratios are set at no less than 20–30% for marine species and 10–20% for freshwater species to maintain populations (Goodyear 1993; Slipke et al. 2002). Reducing SPR below these thresholds may reduce the abundance of age-0 individuals produced (Slipke et al. 2002) and regulate recruitment.

Exploitation needed to achieve our target SPR level was slightly higher than exploitation needed to reduce common carp abundance because of the low SPR target values we identified. Our simulations revealed that SPR was often reduced to 10–20% when exploitation ranged from 40% to 60%, suggesting that it may be possible to induce recruitment overfishing of common carp populations, thereby reducing their abundance. Groupers (*Serranidae*) and striped bass *Morone saxatilis* have experienced dramatic population declines when SPR fell below 10% (Huntsman et al. 1999; Slipke and Maceina 2000). Additionally, evidence for recruitment overfishing has been documented for several freshwater species, including yellow perch (Eshenroder 1977), walleye (Anthony and Jorgensen 1977), and lake whitefish *Coregonus clupeaformis* (Walker et al. 1993), suggesting that recruitment overfishing of common carp may also be feasible.

Exploitation of common carp may be high enough in some instances to observe predicted effects. Commercial exploitation of common carp in these three study populations varied from

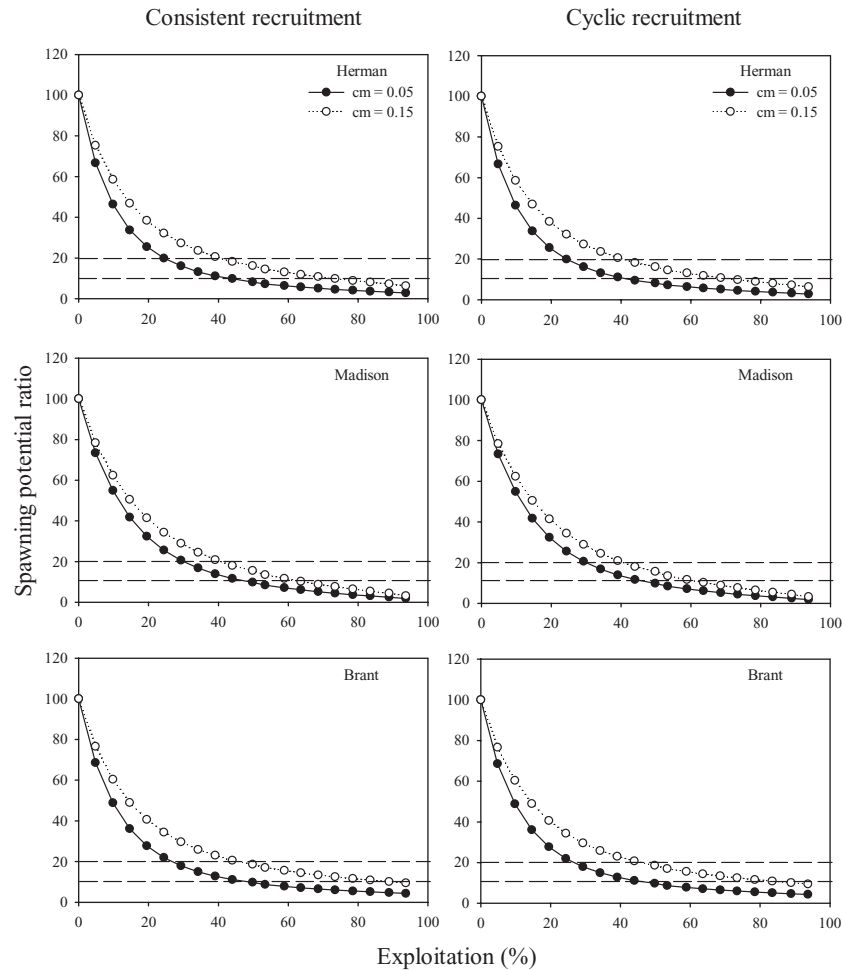


FIGURE 5. Simulated spawning potential ratios (SPRs) for common carp populations in Lakes Herman, Madison, and Brant under consistent (left panels) and cyclic (right panels) recruitment rates and conditional natural mortality (cm) rates of 5% and 15%. The horizontal dashed lines represent 80% and 90% reductions in SPR with size selective removal.

0% to 40% annually (M. Weber, South Dakota State University, unpublished data), while a study in Wisconsin documented 60% exploitation (Neess et al. 1957). Based on our simulations, these levels of exploitation have an effect on common carp populations. When exploitation is low, additional control techniques may be incorporated to increase exploitation of common carp. For instance, common carp often form large seasonal aggregations (Penne and Pierce 2008; Hennen 2010), which may be targeted for removal. However, our simulations also reveal that even with extreme levels of annual exploitation using commercial fishing gear (up to 95%), 20–50% of common carp population abundance may remain. Thus, regardless of the level of commercial exploitation via large seines, our simulations suggest that common carp populations may only be partially controlled using gears that select for large-bodied individuals. However, significant reductions of highly abundant common carp populations should result in improvements in ecological conditions (i.e., Ricker and Gottschalk 1941; Rose and Moen 1953; Cahoon 1953; Neess et al. 1957).

Model simulations, such as those presented here, can assist managers identify meaningful biological reference points where growth and recruitment overfishing of invasive species are likely to occur. Because our modeling produced similar results across all three populations under varying recruitment patterns, growth rates, and natural mortality rates, results may be broadly applicable to other common carp populations with comparable population characteristics. Previous modeling has indicated that long-lived common carp populations are best controlled through mechanical removal, whereas short-lived populations are best controlled by reducing recruitment (Brown and Walker 2004). However, size-selective removals, such as the one evaluated here, may only reduce populations by up to 60% (Brown and Walker 2004). Our results support that hypothesis. We based our models on the utility of commercial seining, a popular management tool (Cahn 1929; Rose and Moen 1953; Meronek et al. 1996) to reduce common carp populations. Similar to most gears, commercial seines appear to be size selective. Only individuals greater than 575 mm were effectively captured using

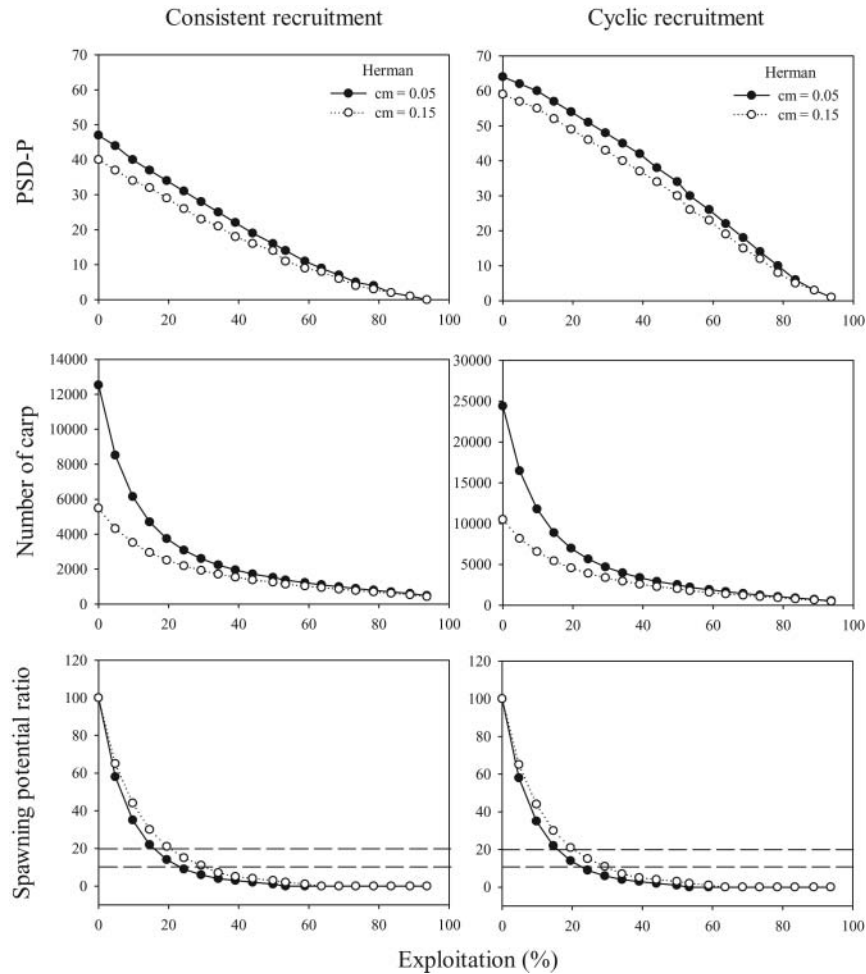


FIGURE 6. Simulated proportional size distribution of preferred-length (PSD-P; see Figure 2) common carp in Lake Herman, the number of carp in the population, and their spawning potential ratio (SPR) under consistent (left panels) and cyclic (right panels) recruitment rates, conditional natural mortality (cm) rates of 5% and 15%, and varying levels of exploitation without size selection. The horizontal dashed lines in the bottom panels represent 80% and 90% reductions in SPR.

a bag seine with a 5-cm bar mesh. In the three systems evaluated, 575-mm common carp were approximately age 4 and sexually mature. Thus, size selective commercial fishing for common carp functions as a minimum length limit that protects small-bodied, immature individuals. However, additional simulations run for the Lake Herman population without size selectivity were more promising for common carp control. Common carp size structure, abundance, and SPR were dramatically reduced at 20% exploitation by not selectively removing only larger individuals. Schwartz (1986) and Stuart et al. (2006) describe using traps and Pinto et al. (2005) describe using gill nets and electrofishing to remove common carp less than 575 mm. If other gears that target smaller-bodied individuals (e.g., rotenone spot-treatments, traps, predator introductions) are used in conjunction with seining, lower levels of exploitation will be needed to control common carp populations. Thus, management strategies that incorporate alternative control techniques, in addition to large-scale ongoing adult removals, may achieve

the greatest success at controlling common carp populations in shallow lakes.

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