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REVIEW

Emerging control strategies for integrated pest management of invasive carps

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Abstract. Invasive carps are ecologically and economically problematic fish species in many large river basins in the United States and pose a threat to aquatic ecosystems throughout much of North America. Four species of invasive carps: black carp (*Mylopharyngodon piceus*), grass carp (*Ctenopharyngodon idella*), silver carp (*Hypophthalmichthys molitrix*) and bighead carp (*Hypophthalmichthys nobilis*), are particularly concerning for native ecosystems because they occupy and disrupt a variety of food and habitat niches. In response, natural resource agencies are developing integrated pest management (IPM) plans to mitigate invasive carps. Control tools are one key component within a successful IPM program and have been a focal point for development by governmental agencies and academic researchers. For example, behavioural deterrents and barriers that block migratory pathways could limit carps range expansion into new areas, while efficient removal methods could suppress established carp populations. However, control tools are sometimes limited in practice due to uncertainty with deployment, efficacy and availability. This review provides an overview of several emerging modelling approaches and control technologies that could inform and support future invasive carp IPM programs.

Key words: mitigation, pesticide, barrier, deterrent, population model

Introduction

Invasive carp[1] control is a complex issue for fishery and natural resource managers in the United States. Four species of invasive carps: black carp (*Mylopharyngodon piceus* Richardson), grass carp (*Ctenopharyngodon idella* Valenciennes), silver carp (*Hypophthalmichthys molitrix* Valenciennes) and bighead carp (*Hypophthalmichthys nobilis* Richardson), are particularly concerning for native ecosystems because they uniquely occupy and disrupt a broad range of food and habitat niches (Chapman & Hoff 2011). Black carp occupy benthic habitats and predate primarily on macroinvertebrates, such as snails and mussels (Nico et al. 2005). Grass carp are generally found in littoral habitats and consume large amounts of aquatic vegetation (Dibble & Kovalenko 2009).

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[1] *Formerly referred to as Asian carp in the United States. See Kočovský et al. (2018) for historical terminology.*

Silver carp and bigheaded carp, collectively known as bigheaded carps, are large-bodied pelagic fishes that filter feed on planktonic organisms (Kolar et al. 2007). Diverse occupancy of these invasive carps within aquatic ecosystems raises many conservation challenges related to water quality degradation, native and imperilled mollusc species, habitat loss and direct or indirect competition with native fish species. Natural resource agencies recognized this problem and developed a national plan with annual action plans to better understand and control invasive carps in the United States (Conover et al. 2007, ACRCC 2021).

Understanding invasive carp life history characteristics is a necessary first step to develop effective control strategies. Studies have shown that recruitment and survival of invasive carps in the United States is highly dependent on the hydraulic characteristics of large river systems. Invasive carps typically spawn in turbulent areas of rivers during periods of elevated streamflow at 18-28 °C water temperatures (Nico et al. 2005, Kolar et al. 2007). Fertilized eggs enter a critical drift period where hatch success is entirely reliant on the river flows and turbulence to keep eggs in suspension (Fig. 1). Carp eggs are slightly heavier than water (George et al. 2017) and settling of eggs on the streambed can be detrimental to their survival (George et al. 2015). Embryonic development during this period is temperature dependent and larval hatching can take as long as 2.7 days at 18 °C necessitating long river reaches with uninterrupted, turbulent flows (George et al. 2017). While 100 kilometres (km) was previously believed to be a minimum length of drift (Kolar et al. 2007), eggs and larvae have also been found to survive at substantially shorter river lengths (< 25 km) under specific environmental conditions (Murphy & Jackson 2013, Heer et al. 2020). Newly hatched larvae remain reliant on the river and may drift for up to eight more days (at 18 °C; George et al. 2017), but have the capability to swim upwards immediately after hatching (Chapman & George 2011). Lateral swimming and feeding begins at gas bladder inflation and the young fish must exit the turbid and turbulent river to find appropriate nursery habitat with adequate food resources and light penetration to support life at this stage (George et al. 2018). Late larval and early juvenile carp can thus be found most often in shallow, productive backwaters or other low velocity environments (Kolar et al. 2007), where zooplankton and phytoplankton are abundant. Habitat and food requirements may be different for each life stage and species, but invasive carps will continue to seek out suitable habitat and food sources as they develop into adults capable of reproduction. Adults grow quickly and can live up to 10-20 years as they complete annual spawning migrations. Several opportunities exist within this life cycle process from early to adult stages for resource managers to consider control actions that disrupt recruitment, survival and movement patterns (Conover et al. 2007).

Integrated pest management (IPM) programs often rely on effective control tools to successfully manage the target pest (Fredricks et al. 2021). However, limited options presently exist for invasive carps. Harvest is currently the most common invasive carp control method where the concept is to increase fishing mortality above natural mortality to reduce carp survival and abundance (Tsehaye et al. 2013). In the United States, invasive carp harvest typically occurs through commercial fishing, government contracted/subsidized fishing and government agency removal programs. Government contracted fishers, for example, in the State of Illinois have removed large numbers of adult silver and bighead carps annually from the River Illinois to mitigate the risk of population pressure driving upstream movement towards the Laurentian Great Lakes (MacNamara et al. 2016). The benefit of government contracted harvest is that carps can be selectively removed from key areas with nets while native species bycatch are sorted and released back into the water. However, the challenge with harvest as a singular control method is the amount of effort needed to elevate fishing mortality to a level that can cause population declines in large river systems, particularly when exploitation rates are difficult to measure and traditional harvest gears (e.g. gill nets) are often biased towards large adult fish. Although targeted harvest remains the most widely utilized carp control methods for removal, additional tools that expand and support harvest efforts could further equip resource managers to effectively mitigate invasive carps.

Development of new tools to control invasive carps often involves an interdisciplinary and stepwise research process. For example, new ideas usually start with proof-of-concept testing. If results show promise, the next step is to initiate baseline testing at small scales (e.g. laboratory experiments) to allow refined observations in a highly controlled environment. Continued progress can lead to larger scale studies in mesocosm or field settings as

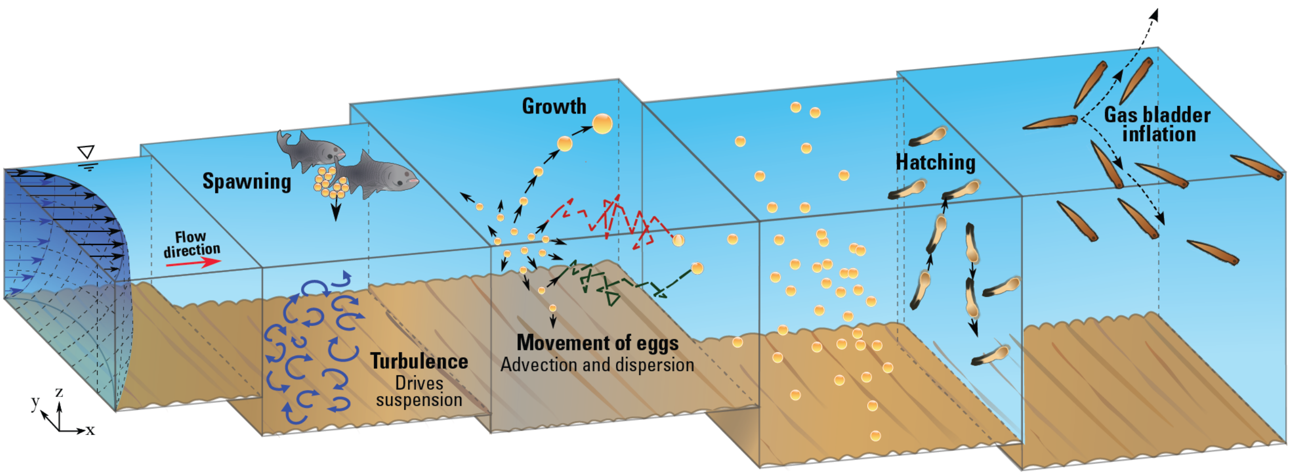

Fig. 1. Conceptual invasive carp early life-stage development process from spawning through gas-bladder inflation shown in the context of a cell-based drift model and physical processes driving transport and dispersion. Life stages shown here led to the development of drift models (FluEgg) and have been used to identify vulnerable life stages for early life history control strategies. Figure modified (with permission) from Garcia et al. (2013).

the understanding of a control technique grows. In parallel to efficacy testing, other technical aspects ranging from engineering, human safety, water quality, hydrology, impacts to navigation, non-target effects, cost-benefit analyses and regulatory compliance warrant consideration. Completion of these research and development milestones produces new control tools that are ready to be tested and evaluated on a management scale in a variety of real-world and adaptive management applications. Many of the control techniques described herein have followed this general research and development process.

The purpose of this review is to synthesize emerging invasive carp control tools that could support future invasive carp IPM plans. Many of the control tools presented in this review have undergone extensive research and field testing, while a few are nascent ideas that are at the early stages of development. This review does not cover the more traditional fishery control techniques (e.g. electric barriers, rotenone) as they are already well described (Dawson & Kolar 2003, Fredricks et al. 2021). Rather, this review synthesizes control strategies that may not be widely found in published literature due to their recency with research, development or application to invasive carps. Control tools described in this review are structured around three broad topics. The first topic covers modelling approaches that can inform invasive carp control efforts and assist managers to make informed decisions regarding application of new control tools. These models serve a range of purposes related to spawning area identification and spawning suitability assessments of rivers (drift modelling); population dynamics of carps in large rivers (population modelling); and decision frameworks to inform the implementation of carp control actions (structured decision making). The second topic covers behavioural and movement control tools that could be used as deterrents and barriers to limit range expansion of invasive carps into new areas. Behavioural controls in this review vary in modes of action and include auditory (acoustic deterrents), multi-modal (BioAcoustic fish fence), tactile (bubble curtains) and chemosensory (carbon dioxide) stimuli. The third topic covers population control tools that can be used to reduce invasive carp abundance in locations where they are established. Population controls include chemical control agents, attractants, physical removal techniques and potential early life history controls. Collectively, models and control tools are described in terms of background research, development stage, and potential application to future invasive carp IPM programs.

Modelling approaches to inform carp control

Drift modelling

Invasive carps are pelagic river spawners that rely upon flowing water to provide sufficient velocity, turbulence and mixing to 1) facilitate egg fertilization, 2) maintain eggs in suspension until hatch and 3) disperse eggs and larvae downstream from the spawning site (Nico et al. 2005, Kolar et al. 2007, Chen et al. 2021). Identifying rivers and reaches that may support spawning of invasive carps may include an assessment to determine if the river/reach hydraulics can support these three primary components of the first stage of recruitment. The primary tool used in such an assessment is a drift model capable of predicting egg and larval drift in a river during the developmental period from fertilization through gas bladder inflation stage (Fig. 1). During the gas bladder inflation stage, carp begin to swim horizontally and actively leave the drift in search of nursery habitat. Most drift models ignore the rapid egg fertilization process and focus primarily on the relatively long egg and/or larval drift periods (e.g. Deters et al. 2013, Garcia et al. 2013, Heer et al. 2020, McDonald & Nelson 2021).

The Fluvial Egg Drift Simulator (FluEgg) is a drift model developed for invasive carps (Garcia et al. 2013). FluEgg combines the physical processes of river flows and particle transport with the biological processes of egg and larval development in a highly adaptable, Lagrangian framework capable of modelling and tracking tens of thousands of individual eggs and larvae over potentially long drift periods (~ 10 days) and reach lengths (> 100 km). Biological development of eggs and larvae are species- and temperature-dependent (Chapman & George 2011, George & Chapman 2013, 2015). FluEgg uses egg and larval growth functions and associated time- and temperature-dependent models of egg density, diameter and fall velocity for each species (Garcia et al. 2013, 2015, George et al. 2017). At the time of this publication, FluEgg is capable of modelling three of the four species of invasive carps. Black carp are expected to be added later as developmental data become available. FluEgg uses a cells-in-series modelling approach that requires the user to discretize a river into a series of reach-wise cells of variable length with uniform channel geometry and hydraulic characteristics within each cell (Garcia et al. 2013). The one-dimensional (1D) input data are used to build three-dimensional (3D) flow fields using open channel flow theory, empirical relations between mean flow and turbulence parameters and observations of transverse and vertical velocity distributions in natural and channelized rivers (Garcia et al. 2013, 2015). A random walk approach is used to account for the stochastic variability in particle motion in each dimension.

FluEgg can be applied to determine if a river or reach has sufficient hydraulic characteristics to support spawning of invasive carps and predict the temporal downstream dispersion of eggs and larvae from a known spawning location at a specific time. FluEgg also has the capability to compute the most probable spawning areas for invasive carp in a river/reach using captured eggs or larvae and either the reverse-time particle tracking (RTPT) algorithm for spawning area identification (Zhu et al. 2018) or a Monte Carlo approach using iterative forward simulations (Embke et al. 2019). While FluEgg can be used without an associated hydraulic model, processing FluEgg with output data from a hydraulic model (1D, 2D or 3D) can improve the accuracy of model predictions. FluEgg can also be used within existing open source hydrodynamic models by incorporating the essential components of FluEgg – such as the time-, temperature- and species-dependent development models – into existing particle transport models (e.g. EFDC + (Heer et al. 2020), Delft 3D (Weeber 2021)). These powerful models allow more accurate FluEgg drift modelling in rivers with highly complex hydrodynamics (e.g. braided rivers) and systems with rivers emptying into deep, thermally stratified lakes or reservoirs.

Drift models are an applicable tool for natural resource managers to determine which rivers or reaches are potentially suitable to invasive carp spawning (Kočovský et al. 2012, Garcia et al. 2013, 2015, Murphy & Jackson 2013), back-calculate where spawning may be occurring within a river or reach (Deters et al. 2013, Zhu et al. 2018, Embke et al. 2019), predict how eggs and larvae are dispersed downstream from a potential or known spawning site (Garcia et al. 2015, Murphy et al. 2016) and when and where carp reach critical developmental stages (e.g. hatching, gas bladder inflation) following a spawning event (Murphy & Jackson 2013, Garcia et al. 2013, 2015). Such information could be useful for real-time management responses to egg or larval captures to determine locations of possible adult spawning aggregations. The River Sandusky is one example where drift modelling was used in decision making and control efforts. In 2012, simple advection and time-of-travel drift models first indicated the lower River Sandusky could be suitable for grass carp spawning (Kočovský et al. 2012, Murphy & Jackson 2013), a finding later supported by FluEgg simulations (Garcia et al. 2013). Subsequent management-driven monitoring efforts confirmed spawning (Embke et al. 2016) and recruitment (Chapman et al. 2013) of grass carp in the lower River Sandusky. Managers have since used the primary spawning area identified using FluEgg (Embke et al. 2019) as a target harvest location to collect mature grass carp during annual spawning events (Ohio DNR Division of Wildlife 2019). Drift modelling has also informed a study of the feasibility of installing a seasonally operated barrier on the lower River Sandusky to disrupt grass carp spawning (Scurlock et al. 2021). Other model applications could also inform control efforts to predict which rivers might have favourable conditions for future spawning events. The latter approach was used on the River Tennessee as part of a structured decision-making process to identify which reservoirs upstream from the current invasive carp population had hydrologic conditions suitable for recruitment to inform key carp control locations (Post van der Burg et al. 2021; more details provided on structured decision making for the River Tennessee provided in a later section).

Population modelling

Concern that bigheaded carp could successfully invade the Laurentian Great Lakes led to the 2009 creation of the Asian Carp Regional Coordinating Committee (ACRCC) in the United States and Canada (Hansen & Johnson 2010, Cuddington et al. 2014). One subgroup of the ACRCC is the Monitoring and Response Working Group (MRWG), which leads efforts to create a population model to inform management of bigheaded carp in the River Illinois. The River Illinois is a key management location and hydrologic connection between the Mississippi River Basin and the Great Lakes Basin. Currently, an electric barrier system is operated to keep bigheaded carp from spreading from the River Mississippi Basin to the Great Lakes (Moy 1999). However, a robust population model that could inform additional management actions in the River Illinois may be helpful to reduce population pressure on the existing electric barrier.

Initial modelling efforts produced a population model for bigheaded carp in the River Illinois (Tsehaye et al. 2013). This model treated the entire River Illinois as one population, based upon the best available data. However, the River Illinois has a series of locks and dams that obstructs fish movements and creates sub-populations both biologically (e.g. habitat differences between pools) and managerially (e.g. harvest efforts are pool specific). Tsehaye et al. (2013) found that under some conditions, harvest may be able to decrease the invasion risk, but model limitations were not able to identify where harvest efforts would be most beneficial. Subsequent theoretical simulation exercises demonstrated that meta-population dynamics were an important consideration with models to guide invasive species control (Erickson et al. 2018). This is especially true on the River Illinois because recruitment presently only occurs in the lower pools of the river well downstream from the invasion front. Recent movement data for bigheaded carps on the River Illinois facilitated the evaluation of meta-population dynamics for the River Illinois and led to the development of the Spatially Explicit Invasive Carp Population (SEICarP) model (Coulter et al. 2018). The SEICarP model includes movement probabilities among pools of the River Illinois and uses constant demographic data across all pools.

Development of the SEICarP model highlighted the importance of considering meta-population and source-sink dynamics. For example, the U.S. Fish and Wildlife Service (USFWS) reports that harvesting carps in downriver pools (i.e. well below the invasion front) in large rivers may be important for overall population control because recruitment has only been documented in the downriver pools (ACRCC 2019). Carps have generally not been found to successfully spawn in the upriver pools closest to the invasion front. Outputs from SEICarP have also indicated that integration of multiple control methods, such as the combination of harvest and movement barriers, could be more effective than only using one control method (ACRCC 2019). This aligns with the IPM concept where multiple integrated approaches could be considered to effectively control pests.

Robust population models, such as SEICarP, could have implications for carp control beyond the River Illinois. Although SEICarP is currently focused on the River Illinois, other large river basins also could benefit from comprehensive population models. The SEICarP model is intended to be applied on other large rivers with locks and dams to inform control locations and strategies, or to identify data gaps in carp population status or movement probabilities that would be helpful to properly develop a SEICarP model. Efforts are currently underway to document and release the SEICarP model as statistical software for pool specific demographic data (Erickson 2020, Erickson et al. 2021). Public availability of SEICarP may allow resource managers to apply this meta-population model to other rivers where invasive carp are present. Efforts are currently underway to apply SEICarP at locations on the River Mississippi, the River Ohio and the River Tennessee to inform carp management and control actions. Overall, SEICarP is an effort to standardize data collection and population models for invasive carps and may help identify locations for control efforts.

Structured decision making

Invasive carp control is a challenge for fishery and natural resource management agencies that often spans multiple stakeholders and jurisdictions. Structured decision making is an adaptive management process that can be used to reach consensus on control strategies across multiple interest groups (Failing et al. 2013). The structured decision-making process benefits from participation of all stakeholders to develop a decision framework based on uncertainties and objectives (Johnson et al. 2017, Robinson & Fuller 2017). First, the stakeholder group develops a statement that defines the decision to be made and key aspects that go into making the decision. This statement is then used to identify objectives the group hopes to achieve with a decision. Next, the group documents alternative actions and consequences of those actions to meet objectives. Finally, qualitative and/or quantitative analyses are conducted to reach an optimal set of alternative actions to meet objectives based on uncertainty and trade-offs.

There are a few examples where structured decision making has been used to inform invasive carp control. Robinson et al. (2021) conducted a structured decision-making workshop to address invasion of grass carp into Lake Erie, one of the five Laurentian Great Lakes that borders five U.S. states and one Canadian province. Accordingly, the stakeholder group consisted of state, federal, provincial and academic representatives. The group developed a simple decision statement as "a need to develop a strategy for controlling grass carp in Lake Erie to socially and environmentally acceptable levels." Three fundamental objectives were then identified as 1) fulfil public trust responsibility, 2) minimize management associated costs and 3) minimize collateral damage. Alternative actions of removal, barriers, habitat modifications and elimination of population inputs were then identified as possible strategies to control grass carp. Consequences and trade-offs of those alternative actions to meet objectives were then evaluated using expert elicitation and hypothetical models for various management scenarios. Outcomes from this process identified combinations of control actions that could best meet management objectives and highlighted key uncertainties with grass carp data gaps that could become focal points for future research and monitoring.

A similar decision analysis process was used on the River Tennessee to prioritize locations for invasive carp control actions. Beginning in 2020, the Tennessee Valley Authority (TVA) conducted an Environmental Assessment for invasive carp barriers at nine lock structures along the River Tennessee. A structured decision-making workshop was coordinated to inform decisions on barrier type and placement within the context of TVA's environmental assessment (Post van der Burg et al. 2021). The stakeholder group was composed of representatives from state and federal agencies with interest and authority on the River Tennessee system. A decision statement was then developed specifically based on the TVA's Environmental Assessment to "recommend where and what type of barriers should be placed to control invasive carps within the River Tennessee system." Five objectives were then identified as 1) minimize carp abundance and distribution, 2) maximize public satisfaction, 3) minimize impact to lock operation, 4) minimize impact to native species and 5) minimize cost. Alternative actions of acoustic barriers, multi-modal barriers, electric barriers, carbon dioxide barriers, no barrier and targeted removal (i.e. overharvest) were set as potential control strategies. Consequences of those actions were then evaluated based on four population growth models for carp in the River Tennessee ranging from low growth, moderate growth, high growth and high growth with depensation threshold. Results indicated that targeted removal and placement of barriers in lower portions of the River Tennessee were generally the most optimal control strategies based on hypothetical models run over 20-year projections (Post van der Burg et al. 2021). Overall, outcomes from this process were considered successful as they met the timelines and information needs for the TVA's Environmental Assessment.

Some challenges still exist with decision analytics and invasive carp control efforts. New invasions often result in a request for rapid response from the public and resource managers to address the emerging carp problem. However, new invasions also lack information or data on key aspects of carp movement and population dynamics that are necessary to inform control efforts. Lack of information can result in high levels of uncertainty during the decision analysis process and influence the reliability of the outcome. In most cases, data gaps are overcome by expert elicitation where informed estimates are used in lieu of actual data (Johnson et al. 2017), or by using hypothetical models that encompass plausible scenarios and uncertainty (e.g. see the four differing population growth models in Post van der Burg et al. 2021). Regardless, these gaps frequently exist with new invasions and present challenges to the decision process that may need to be addressed through subsequent research and monitoring. Fortunately, structured decision making is an adaptive process that is meant to adjust optimal actions based on new or better information as it becomes available. While decision analysis may not solve all carp problems, it presents a framework that can help inform carp control efforts.

Behavioural and movement controls

Underwater acoustic deterrent systems (uADS)

Scientists have recognized that fish use sound to communicate (Bass & Ladich 2008), and the underwater soundscape (i.e. the biological and human-generated acoustic components of the environment; see Lindseth & Lobel 2018 for a review) also influences fish behaviour (Fay & Popper 2000, Popper & Hawkins 2019, Putland et al. 2019). Fish may respond to these environmental and human-generated sounds in a variety of ways, including moving away from sounds that are either uncomfortable or elicit an escape response (Cox et al. 2018). The use of human-generated sound to modulate fish behaviour is not new (Popper & Carlson 1998). The U.S. Department of the Interior collaborated with the U.S. Navy and U.S. Army Corps of Engineers (USACE) in the late 1940's to test underwater acoustic deterrents of varying frequencies and amplitudes on fish (Burner & Moore 1953). Applied acoustic research for management of salmonids and cyprinids followed, largely with the goal of increasing successful smolt migration and keeping fish away from water intake structures or hydropower facilities (e.g. Maes et al. 2004, Sonny et al. 2006, Jesus et al. 2018). Underwater acoustic stimuli (i.e. underwater sounds) are now being explored as possible invasive carp deterrents.

Invasive carps are ostariophysans and possess a Weberian apparatus consisting of ossicles linking the inner ear and swim bladder (Lovell et al. 2006, Patty 2020), and therefore, enhancing their ability to detect sound pressure (Popper & Carlson 1998, Lovell et al. 2006). Many native Midwestern and Great Lakes fishes lack this adaptation (Putland et al. 2019). Anatomical and physiological differences among species indicates that auditory stimuli could be an effective deterrent to invasive carp movement with limited influence on most native fishes. Initial pond studies demonstrated that playbacks of complex sounds (i.e. recorded from a 100-hp boat motor) were effective to coerce silver carp back-and-forth (i.e. described as a ping-pong effect) within a confined pond (Vetter et al. 2015). Interestingly, pure tones of a single frequency and amplitude were not shown to elicit the same repeatable repellent or startle behaviours. Subsequent studies in outdoor ponds confirmed this behavioural responses with bighead carp to complex sounds through discrete and repeated sound exposures (Vetter et al. 2017, Murchy et al. 2017). Promising results from these proof-of-concept studies led to a recommendation for this technology to be tested longer-term on invasive carps and native fishes at larger management-relevant scales.

In March 2021, an experimental underwater acoustic deterrent system (uADS) was deployed in the downstream lock approach of lock no. 19 on the River Mississippi near Keokuk, Iowa (Fig. 2). Baseline acoustic analyses were conducted before installation to determine the ambient soundscape of the lock approach and confirmed that lock approaches might pose challenges to a successful acoustic deterrent because of their loud and complex nature (Putland et al. 2021). However, lock no. 19 was identified for assessing an experimental acoustic deterrent on invasive carps' behaviour at management-relevant scales and locations because the dam associated with the lock is an impassable high-head dam that limits upstream fish passage to the lock (i.e. upstream passage is not possible through the spillway). This location is important for resource managers to limit the source of invasive carp from the middle and lower portions of the River Mississippi from freely moving into the upper River Mississippi where carp abundances are currently low or non-existent (Jackson & Runstrom 2018). Invasive carps and native fishes commonly make upstream passage through the lock (Fritts et al. 2021), thus providing the opportunity to evaluate the behavioural responses of fish to an experimental acoustic deterrent at this location. The uADS that was deployed consists of 16 underwater transducers located in the downstream lock approach that play acoustic deterrent stimuli half of the time (i.e. on-off treatments). Invasive carp and native species behaviour near the deterrent are being studied

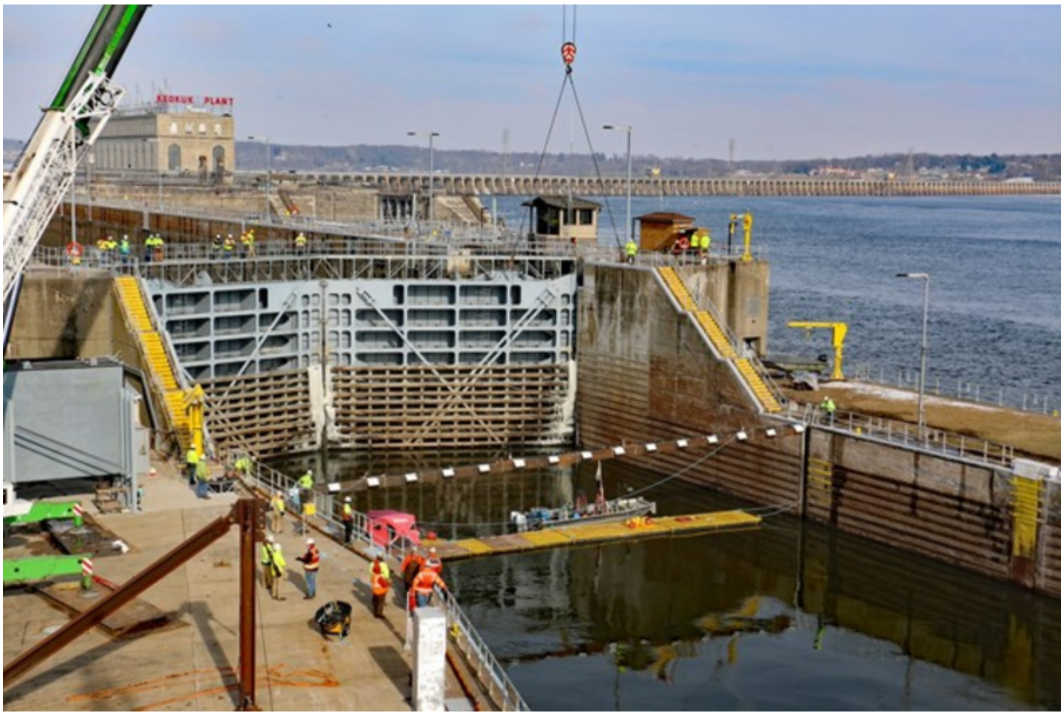

Fig. 2. Underwater acoustic deterrent system (uADS) being installed into the downstream approach channel at lock no. 19 on the River Mississippi near Keokuk, Iowa. The uADS prototype was lowered into a water discharge lateral at the bottom of the channel. The experimental system is planned to operate up to three years for a research study to evaluate its effectiveness at reducing upstream passage of invasive carps (photo Mark Cornish – U.S. Army Corps of Engineers, used with permission).

using acoustic telemetry to determine deterrent effectiveness and possible limitations. This ongoing evaluation is being conducted in the lock approach channel during the normal navigation season (approximately March through December) for up to three years to encompass the anticipated range of environmental conditions that could affect the operation and effectiveness of the uADS.

BioAcoustic fish fence (BAFF)

The BAFF (fish guidance systems Ltd., Fareham, United Kingdom) is a fish deterrent system that combines air bubble curtains, proprietary acoustic stimuli and light to produce a multi-sensory field to deter and guide fish (Welton et al. 2002, Taylor et al. 2005, Perry et al. 2014). Field evaluations have demonstrated that downstream migrating juvenile salmonids (i.e. smolts) and estuarine clupeids can be effectively deterred by a BAFF, diverting their movement path to another downstream channel (Welton et al. 2002, Maes et al. 2004, Perry et al. 2014). An initial small-scale test of the BAFF stimuli on bighead carp in a hatchery raceway demonstrated a high percentage of deterrence (i.e. 95%; Taylor et al. 2005). A more recent laboratory study assessed the effectiveness of multi-frequency acoustic signals, including the proprietary cyclic signal of the BAFF and the sound of a 40-hp outboard motor, with and without bubble curtains, at deterring juvenile common carp (*Cyprinus carpio* Linnaeus), largemouth bass (*Micropterus salmoides* Lacépède), and bighead carp (Dennis et al. 2019). The results from this study indicated that the proprietary sound of the BAFF was more effective than the sound of a 40-hp boat motor, and that the coupled stimuli (i.e. either of the multi-frequency signals with bubble curtains) was more effective at deterring fish than the acoustic stimuli or bubble curtains alone. This work also indicated that fish did not habituate to the stimuli, and that largemouth bass were less responsive to the combined stimuli than bighead carp or common carp (Dennis et al. 2019).

The first field evaluation of the BAFF with invasive carps was conducted in a shallow stream in the River Illinois watershed (Ruebush et al. 2012). This study indicated that the BAFF is an effective deterrent for wild invasive carps, but conclusions were limited by the relatively short duration and small-scale of that study. Subsequently, a large-scale field test of the BAFF was initiated in 2019 in the downstream lock approach channel at Barkley lock and Dam near the Rivers Grand, Kentucky (Fig. 3). Barkley Lock and Dam was identified by managers as a strategic management point for controlling invasive carp

Fig. 3. An experimental BioAcoustic fish fence (BAFF) in operation at the downstream approach channel of Barkley lock on the River Cumberland near Grand Rivers, Kentucky. Photograph shows the air-bubble curtain when the system is turned on. The BAFF is planned to be operated for up to three years for a research study to evaluate its effectiveness to reduce upstream passage of invasive carps.

because populations downstream are greater than populations upstream and fish must use the lock to move upstream past the dam (Post van der Burg et al. 2021). This location is important for resource managers to cut off the source of invasive carps in the Ohio River Basin from migrating into the Tennessee River Basin. The primary objective of the field test at Barkley lock and Dam is to evaluate the effectiveness of a BAFF at preventing telemetered silver carp from moving upstream past the BAFF and into the lock chamber under the wide range of environmental conditions that occur at the site. Three native fish species (paddlefish *Polyodon spathula* Walbaum; smallmouth buffalo *Ictiobus bubalus* Rafinesque; freshwater drum *Aplodinotus grunniens* Rafinesque) are also telemetered as part of the BAFF evaluation to determine potential effects to native fishes.

The Barkley lock and Dam is a first attempt to characterize the biotic and abiotic factors, such as barge traffic, lock and dam operations, water depth and seasonality, on BAFF effectiveness at deterring invasive carp. The bubble curtain component of the BAFF may be affected by water depth, in that increased water depth may cause air bubbles to disperse or coalesce near the surface and diminish the uniformity of the bubble curtain (Dennis et al. 2019). BAFF technology, particularly the bubble curtain component, may function best in locations with low water velocity. The discharge valves for the Barkley lock chamber empty outside of the downstream lock approach channel; therefore, water turbulence is less likely to interfere with the bubble curtain integrity at Barkley lock and Dam compared to other sites where the lock discharges into the lock approach channel. The field test at Barkley lock and Dam is expected to be completed by 2023 and may advance the understanding of the effectiveness and feasibility of the BAFF at management-relevant scales and locations for invasive carps.

Oblique bubble screens as two-way dispersal barriers

Bubble screens or curtains have been shown under laboratory conditions to inhibit passage of bigheaded carp with greater than 80% efficacy (Zielinski & Sorensen 2016, Dennis et al. 2019). However, bubble screen research and applications to date have exclusively been unidirectional, designed to stop either upstream or downstream movement or to guide migratory fish. Oblique bubble screens (OBS), such as those used in the BAFF system, are generally deployed across a channel at an angle to the flow (e.g. 45 degrees). This oblique orientation allows a bubble screen to guide upstream-moving fish away from exclusion zones and toward potential collection/trapping zones near the upstream-most bank (Scurlock et al. 2021). In addition, the oblique orientation can redirect downstream-drifting particulates in the water column to the downstream-most bank where they can be collected (actively or passively). Recent pilot studies have demonstrated a mean efficacy of 86% in trapping and collecting plastic particles greater than 1 mm from flowing rivers and canals (https://thegreatbubblebarrier.com; Kools et al. 2021). While primarily developed for capture of plastics (Ehrhorn 2017, Spaargaren 2018), this emerging technology appears to be well-suited for application to trapping of drifting eggs and larvae from invasive carp spawning. Bubble screens could also trap drifting native fish eggs and/or larvae, which may be an important consideration in appropriate sites for this technology. If proven effective at removing a substantial percentage of invasive carp eggs and larvae from the drift, an oblique bubble screen system may be able to both entrain and inhibit downstream dispersal of eggs and larvae while also deterring the upstream movement of adult carp attempting to reach spawning areas, thus providing managers with an option for a two-way dispersal barrier that could be operated seasonally.

Recent laboratory experiments are starting to evaluate the efficacy of an OBS system for trapping invasive carp eggs and larvae using synthetic grass carp eggs and larvae (plastic particles matched in size and density to live eggs and larvae). While no extensive studies have been completed at the time of this publication, Prada et al. (2018, 2020) have shown that egg and larvae transport are largely affected by flow obstructions. Building upon the work of Prada et al. (2018, 2020), the initial OBS efficacy testing is focused on grass carp, the only species of invasive carp known to be reproducing in the Great Lakes (Chapman et al. 2013, Embke et al. 2016). Recently, a feasibility study initiated by the Great Lakes Fishery Commission identified the BAFF system as one of two options for a seasonal barrier on the River Sandusky to limit grass carp reproduction and increase harvest of mature adults (Scurlock et al. 2021). Results of this study may directly inform the design of such a system and allow it to act as a 2-way dispersal barrier with targeted disruption of reproduction across multiple life stages. Furthermore, results are expected to be applicable to bigheaded carps based on similar egg and larvae characteristics (George et al. 2017) and proven response to bubble screens (Zielinski & Sorensen 2016). Potential effects on native species with spawning and/or drift periods that overlap with invasive carps can also be identified and assessed in this study. Because turbulence features generated by the OBS may also alter sediment and oxygen dynamics downstream of the system, monitoring of water quality to identify optimal configurations that improve barrier efficiency and reduce environmental effects is warranted.

If proven effective in capturing synthetic grass carp eggs and larvae in 2021, the laboratory study may be repeated with live grass carp eggs and larvae in 2022. This future study is dependent upon success of laboratory studies in 2021 and includes design and testing of an optimized, two-way OBS system for inhibiting upstream passage of motivated adult grass carp and trapping and removal of grass carp eggs and larvae from the downstream drift in 2022. If these laboratory studies yield promising results, outdoor field-scale trials are planned to be completed in 2023 and effects on native species would be assessed.

Carbon dioxide behavioural deterrents

The use of pesticides to control aquatic nuisance species is routine practice across fishery and natural resource management. Pesticide applications, such as rotenone, are often intended to kill and remove unwanted species and have been used extensively for invasive carp control (Rach et al. 2009, Fredricks et al. 2021). However, pesticides can also be applied for other beneficial purposes. By definition, a pesticide is any registered chemical that is approved to prevent, destroy, repel or mitigate a pest (USEPA 2013). Pesticides that are chemosensory deterrents (i.e. chemicals that repel or deter pests) are not widely considered in most invasive carp IPM plans but could provide an additional strategy to reduce or block carp movement.

Carbon dioxide (CO_2) mixed into water is one example of a chemosensory deterrent for invasive carps. An increasing body of literature has demonstrated that fishes sense and avoid areas with elevated CO_2 concentrations at laboratory (Kates et al. 2012, Cupp et al. 2017b, Tix et al. 2018), pond (Donaldson et al. 2016, Cupp et al. 2017a, 2021) and limited field scales (Cupp et al. 2018b). Behavioural responses to CO_2 are generally consistent across fish species, life-stage and water temperatures, with little evidence of acclimation to the chemical stimulus (Suski 2020). At higher CO_2 concentrations or during prolonged exposure, fish can also become narcotized. Narcotization results in the involuntary loss of swimming function and partial to full loss of equilibrium as fish reach deeper levels of sedation (Tix et al. 2018). Collectively, the repellent and immobilization effect of CO_2 on carp behaviour could be exploited as a barrier to limit their spread through key chokepoints in river systems into new areas, disrupt spawning migrations, or limit movement of larvae from spawning to nursery areas.

Most published studies on carp and CO_2 have focused on its potential application at locks and dams (Fig. 4). Carbon dioxide, like uADS and BAFF, is a deterrent option at these locations to potentially reduce carp passage without causing disruption to navigation or lock operation. Several engineering designs for CO_2 injection systems that are unobstructive to vessels and lock gates

Fig. 4. Installation of an experimental carbon dioxide (CO_2) deterrent system at lock #2 on the River Fox near Kaukauna, Wisconsin. Photograph shows gas distribution piping on bottom and side of lock chamber. This system was temporarily installed for research purposes in 2019 to evaluate gas system engineering and performance within navigation lock chambers.

currently exist (Fig. 4; Zolper et al. 2019). One common method uses differential pressures to infuse CO_2 into water. Water from the lock is pumped into a pressurized mixing chamber while CO_2 at a slightly higher pressure is simultaneously injected into the mixing chamber to achieve supersaturated concentrations (e.g. 1,000-2,000 mg/L) prior to being distributed back to the lock. This recirculating process continues until complete mixing and target CO_2 concentrations in the lock are achieved. A second method involves direct gas injection within the application site. Carbon dioxide gas is applied directly into water via aeration using microbubble porous diffusers. Liquid CO_2 storage systems coupled with gas vaporization make either application system viable for large-scale application. Both CO_2 injection methods are used worldwide for wastewater and effluent water treatment processes and have been adapted to control invasive carps (Zolper et al. 2019).

Pesticide use in the United States is closely regulated by USEPA and state agencies. In 2019, a major milestone was completed when CO_2 was registered by the USEPA under the name Carbon Dioxide-Carp (USEPA 2019). Certain state and federal governmental agencies are now approved to use Carbon Dioxide-Carp as a behavioural deterrent for silver, bighead, grass, and black carps. The pesticide label prescribes target concentrations of 100-150 mg/L CO_2 to induce avoidance behaviours during treatment applications. Approval of CO_2 as an aquatic pesticide for behavioural control expands the potential uses for chemicals in IPM plans and could potentially supplement or complement other invasive carp barriers. Current efforts are focused on state level registrations and regulatory compliance with the Clean Water Act for National Environmental Policy Act (NEPA) permits.

Population controls

Carbon dioxide lethal applications

The second approved use for Carbon Dioxide-Carp is its registration as a conventional pesticide. Carbon Dioxide-Carp is approved for applications under ice to kill any aquatic nuisance species, including invasive carps (USEPA 2019). The pesticide label prescribes a target concentration of 200 mg/L CO_2 for a minimum of 96 hours to kill unwanted pests. This application pattern aligns closely with other pesticides (e.g. rotenone) when the intent is to remove a wide range of nuisance species or unwanted pests using lethal means, particularly due to its non-selectivity across species and taxa (Treanor et al. 2017).

Studies have shown that CO_2 can be an effective pesticide when applied to kill invasive carps. This concept was first tested on invasive carps overwintered in outdoor fish rearing ponds (Cupp et al. 2017c). After ice cover had fully formed, CO_2 gas was injected into each pond at two different concentrations. Fish survival was determined at pond harvest and ponds treated with the highest concentrations of CO_2 had complete mortality of bigheaded carp relative to > 80% survival for those same species in untreated control ponds. Underwater video recordings confirmed that most mortalities occurred within 1-2 days after treatment application (A. Cupp, USGS, pers. observ.). Maximum CO_2 concentrations were reached quickly within ponds using common aeration equipment, and ice cover enhanced treatments by holding CO_2 in solution for several weeks after treatment application. Results supported potential for CO_2 as a lethal control technique for invasive fish removal.

A similar experimental design evaluated the use of dry ice as another CO_2 delivery method (Cupp et al. 2018a). Dry ice is solid state CO_2 that sublimes directly into a gas form when applied into water. Invasive carps were again overwintered in outdoor ponds that were treated with incremental CO_2 concentrations. Results confirmed that dry ice was a simple and effective CO_2 delivery method to eradicate bigheaded carp from experimental ponds. Collectively, both studies showed potential for CO_2 as a lethal control using gaseous and dry ice formulations to deliver CO_2 and kill invasive carps.

Ice cover is one limiting aspect of carbon dioxide-carp as a lethal control for invasive carps. Northern portions of the United States routinely experience ice cover during winter months. Recent expansion of carps into the Upper River Mississippi and Missouri River Basins could allow CO_2 to be incorporated into IPM plans as a general pesticide (Larson et al. 2017). However, ice cover is rare or non-existent in southern portions of the United States making CO_2 not a practical lethal control option in those areas. Researchers and managers have initiated discussions with regulatory agencies to expand the pesticide label and remove the ice cover restriction. For example, CO_2 lethality with various fish species has already been documented across a range of water temperatures (Cupp et al. 2020). This indicates that CO_2 could be used as a lethal control during open water applications at higher water temperatures if target concentrations can be achieved without the aid of ice cover. Ice cover is not a restriction for Carbon Dioxide-Carp when applied as a behavioural control and engineering research for that purpose has shown that open water treatments are possible depending on the volume and physical dynamics of the mixing zone. If the ice cover restriction is removed for lethal control applications, CO_2 could add another option to the general broad-spectrum pesticides available in the United States.

Attractants

Invasive carp attractants are generally an understudied approach to enhance control actions. Attractants that congregate carps in specific areas could be used by resource managers to increase efficiency with harvest removal efforts (described in next section) or facilitate the delivery of targeted pesticide applications. Food attractant formulations could also be developed that have a high degree of specificity towards carps and minimize the possible non-target consumption (Jensen et al. 2011). Limited information exists on the application of attractants for invasive carp control, but recent studies with food attractants, pheromones and pesticide-laden particles are trending research in this direction (Claus & Sorensen 2017, Poole et al. 2018, Sorensen et al. 2019).

Food attractants and pheromones are two options being explored to attract invasive carps. Research has found that an algal formulation of *Spirulina* and *Chlorella* elicited a strong feeding response in bigheaded carps (Claus & Sorensen 2017). Bigheaded carps are planktonic filter feeders, and these algal formulations overlap with natural diet and particle sizes that carps consume in the wild (Jensen et al. 2011). Feeding events using these attractants under controlled settings have been shown to sustain active feeding for up to 45 minutes (R. Calfee, USGS, pers. observ.). Similarly, reproductive pheromones can also result in attractant and congregating behaviours (Hara 1992). Pheromones research has been initiated that has focused on determining species-specific sex pheromones from silver carp with the intention to isolate certain pheromones that can be utilized to attract wild carps (Sorensen et al. 2019). Encouraging results from initial research may lead to testing in field settings over the next few years. If successful in field settings, the ability for resource managers to congregate invasive carps using food attractants and/or pheromones could provide an opportunity for other control actions to be deployed.

Food attractants are also being explored as a mechanism to deliver pesticides to invasive carps. Ongoing research is exploring methods to develop a carp-specific control bait that, when paired with the algal attractant, has the potential to increase ingestion by invasive carps.

A successful proof-of-concept application of a pesticide encapsulated bait formulation was recently reported using common carp (Poole et al. 2018). Corn baits containing antimycin-A (ANT-A; a pesticide previously registered with USEPA that has since expired) encapsulated in a microparticle formulation induced partial mortality in common carp (37-46%) but not in yellow perch (*Perca flavescens* Mitchill) and bluegill (*Lepomis macrochirus* Rafinesque) during mixed species exposures. This indicated that mortality was a result of common carp consuming the pesticide-encapsulated bait rather than ANT-A leaching into water (Poole et al. 2018). Considerably more research on attractants would be necessary before this strategy could be considered for management purposes, particularly to determine the effects to native species with similar diet overlap (Walleser et al. 2014). Field research would also be critical to understand whether wild invasive carps are susceptible to attractants under real-world conditions where food availability is not a limiting factor.

Mass removal

Harvest is currently the primary method used by resource managers to address invasive carp populations in the United States. However, some challenges still exist with conventional harvest approaches related to fishing effort, limited numbers of fishers, poor efficiency with traditional gears and gear bias towards large fish. Mass removal is a supplemental approach to conventional harvest that focuses on removing large quantities of fish over short periods of time (Chapman 2020, Ridgway et al. 2021). These mass removal efforts could be deployed supplementally with long-standing harvest strategies to increase efficiency or as a standalone method to quickly remove invasive carps from certain areas. Methods are currently being developed and tested for mass harvest techniques that could be utilized in a variety of situations.

For the purpose of this review, mass removal is defined as the artificial concentration of invasive carps for harvest. Mass removal can be achieved by attracting or actively herding large numbers of fish to a specific location or into harvest gear (Fig. 5). This approach is particularly useful for bigheaded carps that are pelagic planktivores with limited affiliation to a specific home range and can be driven long distances. Driving techniques developed for bigheaded carps are similar to mass harvest in China with the "unified method" that is currently being adapted for applications in the United States (Li & Xu 1995). Versions of the unified method (also translated as the "united method" or "joint fishing method") exist for both deep and shallow Chinese water bodies and they incorporate several gear types to fish an entire lake or reservoir, or a large portion of a lake or reservoir, with the intention to capture a large proportion of the target fish. Multiple boats are used to herd and concentrate bigheaded carp into confined areas where they are harvested with large trap gears or seines. In shallow water bodies, such as natural floodplain lakes of the Yangtze River Basin, harvest goals may be as high as 85% of the target fish population (Li & Xu 1995). Similar methods used in the United States have most resembled the shallow water methods, because of the reliance on block nets that fill the entire water column. Bigheaded carp are driven from sections or "cells" and kept from returning with block nets. Fish are systematically driven in a stepwise fashion into a smaller and smaller portion of the water body where they are concentrated for capture. In Chinese shallow lakes, this process may take months, and the capture devices are usually large trap nets, fished regularly throughout the process to remove fish as they are concentrated.

In the United States, because of the goals of increasing the speed of harvest, herding of the fish may occur over days or weeks. Technology has since been incorporated, such as using underwater loudspeakers and specially modified electrofishing gear, to expedite the driving process (Ridgway et al. 2021). Side scan sonar has also been utilized for real-time evaluation of fish school position to assist in the timing of block net placement. The final harvest method usually incorporates a large seine, sometimes supplemented by entanglement netting, to remove fish as quickly as possible (Fig. 5).

The unified method with these modifications has become known as the "modified unified method" or MUM. The MUM has been utilized for management purposes in Illinois and versions have been successfully trialled at Creve Coeur Lake in Missouri (Fig. 5) and in embayments of Kentucky Lake in Kentucky. Carp drives have been trialled in the Dresden Island pool of the River Illinois that are more similar to the deep water unified method (Li & Xu 1995), without the use of block netting but using driving methods to concentrate fish over a long distance for gill netting. Versions of the MUM were also used in 2021 in Pool 8 of the River Mississippi to successfully capture invasive carp at

Fig. 5. Mass removal from a modified unified method (MUM) event in Creve Coeur Lake near St. Louis, Missouri. Silver carp were driven into a final collection area and contained within a large seine for sorting and removal. Approximately 108,000 kg of silver carp were removed from the lake during this multi-day process (photo Kevin Muenks – Missouri Department of Conservation, used with permission).

a location where abundances were extremely low. This application in Pool 8 was useful for monitoring purposes and may result in early detection or rapid response actions in those areas. Continued research would be beneficial to refine MUM methods and techniques, but resource managers could consider current MUM techniques as an available tool to support population control efforts.

Early life history control strategies

Early life history is a critical period for fish that is characterized by high and variable mortality rates (Houde 1989). To manage sustainable fisheries, resource managers often seek to reduce mortality and improve recruitment rates for native species conservation (e.g. Chen et al. 2021). However, for invasive species, early life history offers opportunities for population control. Management application of research on the early life stages of invasive carps has mostly focused on risk assessment, such as determination of systems where invasive carp might be able to successfully recruit (Kocovsky et al. 2012, Murphy & Jackson 2013, Garcia et al. 2015, Heer et al. 2019, 2021), or the spawning locations of eggs that were captured in the drift (Deters et al. 2013, Embke et al. 2019). The FluEgg model (Garcia et al. 2013), as described above, was created and later modified (Zhu et al. 2018) to increase the accuracy and usefulness of those types of applications. Capture of early life stages is also useful in early detection, and in determination of what systems or ranges invasive carps are reproductive (Embke et al. 2016, Larson et al. 2017). Research on grass carp and bigheaded carp larval identification and staging, development of models of developmental rate based on temperature (George & Chapman 2013, 2015) and on the physical characteristics and requirements of eggs (George et al. 2015, 2017) have been important for those management applications. Similar early life history assessments of black carp have not yet been completed. To date, there have been few, if any, management actions to reduce recruitment of invasive carps by focusing on the early life stages. Nevertheless, there is potential for direct control of invasive carps by exploiting their complex requirements for survival of eggs and fry, or the behaviours, movements, and habitat selection of carp larvae or age-0 individuals.

Management actions that target early life stages might then address survival at any of these stages

(Fig. 1). Actions focused on the embryonic stages that drift in rivers could be targeted by engineering methods that affect drift conditions, or by causing spawning to occur in locations that do not have appropriate downstream conditions for survival of the eggs or larvae. Engineered areas of very high turbulence could be designed to damage eggs in the drift (Prada et al. 2020) or areas of very low turbulence might be engineered to increase mortality through settling of the eggs (George et al. 2015). While larvae prior to gas bladder inflation are not subject to settling under low turbulence conditions because of their vertical swimming capabilities and have some ability to avoid the areas of highest turbulence (Prada et al. 2020, Tinoco et al. 2020), it is unknown if the conditions in the drift might be required by the larvae for other reasons that might be exploited for control. There are no known locations where recruitment has occurred without relatively turbid and turbulent conditions for that period of the carp life cycle. The pre-gas bladder-inflation larvae have limited response to stimuli (George & Chapman 2015, George et al. 2018) and are likely mostly sightless, thus have limited ability to avoid predators. Eggs and larvae drifting in turbid and high energy systems are protected from predation by the conditions of the system (George et al. 2017), but if turbulence and turbidity are reduced as a result of moving from a riverine to a lentic environment, those larvae may have limited or no defence from sight-feeding predators such as small fish or invertebrates. If drift conditions are required for substantial survival of pre-gas-bladder-inflation larvae, it triples the minimum length of river required for recruitment compared to the length required for eggs, and also triples the length of river that might be available for engineering controls that capitalize on the drifting period of the life cycle. Tinoco et al. (2020) and Prada et al. (2018) investigated hydraulic aspects of egg and larval drift; further studies in those areas could potentially be used for engineering of flows or structures that hinder the natural transport and movement of carp eggs and larvae in the drift, for example, as discussed earlier, bubble curtains that harvest or cause mortality of eggs and larvae. Further research would be helpful to understand the requirements of the drifting stages of larvae, which may enlighten management of invasive carp populations.

The requirement to move from the river to nursery habitats may provide opportunities to intercept the larvae at this transitional stage, or larvae and post-larvae stages might be controlled within the nursery areas. Larval swimming abilities change rapidly during this settlement period (George et al. 2018), and control mechanisms can be informed by the ontogeny of those abilities. Access to quality off-channel nursery areas might be controlled by physically blocking access to those areas during peak carp spawning seasons, or by repelling the larvae through chemical or acoustic means. Current efforts are underway to determine detection and behavioural response to different sensory stimuli during the larval settlement period. If cues that attract carp to these areas can be determined, these can be replicated to attract or altered to repel larvae from specific areas. Nursery areas to which larvae have been attracted might then be drained, harvested, or subjected to pesticides to induce mortality. Other control methods within these nursery areas may include stocking desirable predators.

Rather than attempting to directly affect survival and recruitment through management actions, another option would be to encourage adult invasive carp to spawn in locations that already lack adequate conditions downstream to support development of eggs or larvae, rather than in places where spawning would result in successful recruitment. Such encouragement could take the form of spawning pheromone attractants, engineering of attractive hydrologic conditions for spawning activity, or barriers to prevent or reduce migration to alternative, more potentially successful, spawning locations.

Control of carp in early life stages has not yet been applied by managers, but Tsehaye et al. (2013) found that addressing multiple life stages would likely be necessary for adequate control of invasive carps. Early life controls would have to be tailored to the location, habitats, and possibly the native fishes and other organisms present; what works in one basin or river may be useless or even detrimental in another basin. Successful use of early life controls would benefit from experimentation and more precise knowledge of the biology of the early life stages (including ontogeny and response to abiotic factors) and the appropriate scale to target before the most useful methods can be implemented. Nevertheless, opportunities for control of invasive carps by addressing the early life stages likely exist and may one day become an important component of invasive carp control.

Next steps

Development of new control tools and refinement of existing applications may expand the ability for resource management agencies to address invasive carp in the United States. Continued inter-agency collaboration and communication between researchers and resource managers across large river basins will be important to identify research strategies that align with management goals and priorities outlined in the national plan (Conover et al. 2007, Newcomb et al. 2021). Standardized long-term monitoring to evaluate the performance of control strategies implemented for management actions will also be important, particularly for spatial and temporal scenarios not captured during previous research. Continuity with data collection across technologies and geographical areas may allow practical comparisons to be made and help inform structured decisions making processes and adaptive management. Control techniques described in this review could evolve as new information is learned and data gaps are addressed.

Another technical aspect to consider is regulatory compliance. Distribution of carps throughout the United States spans multiple states and jurisdictions (Rasmussen 2011). Permits and regulations may vary across states and river basins which could determine how some control techniques (e.g. pesticides) are applied. Frequent communication with regulatory authorities could be helpful to understand how new techniques might be regulated and how the potential environmental and administrative cost of implementing a control measure would compare to the environmental benefit of controlling invasive carps.

Lastly, a large data gap exists in published literature regarding combinations of control technologies. This review presented each control as an individual technique or strategy and did not synergistically consider how each technology could be combined with others. However, IPM by name is an integrated approach to managing invasive pests, and it is likely that many of these techniques could be combined to enhance invasive carp control. Understanding how to best apply or combine techniques may be important to developing the best comprehensive control strategy for invasive carps and help meet goals outlined in the National Plan (Conover et al. 2007).

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