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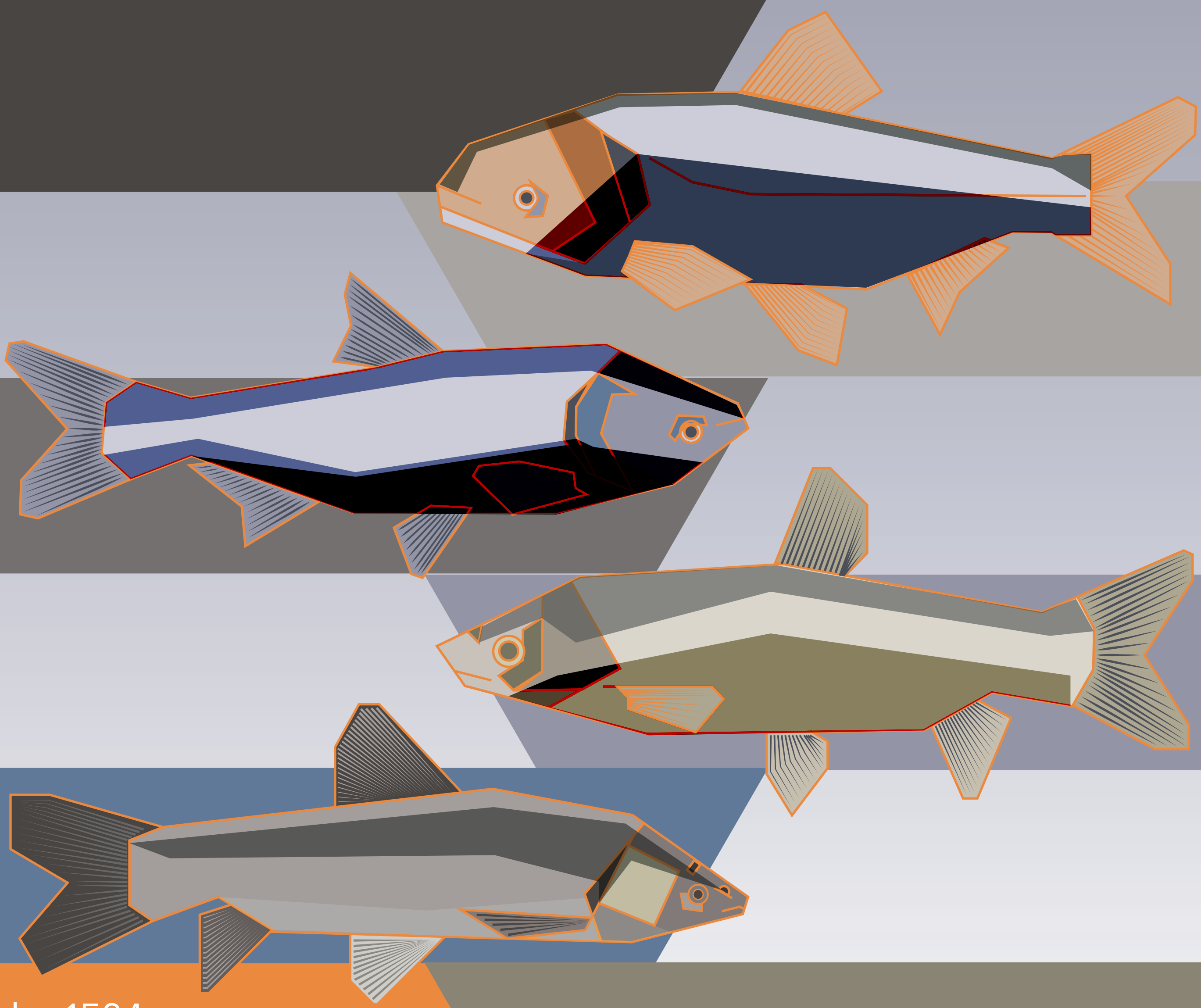
U.S. Geological Survey Invasive Carp Strategic Framework, 2023–27



Circular 1504

U.S. Department of the Interior
U.S. Geological Survey

Front cover. From top to bottom: *Hypophthalmichthys nobilis* (bighead carp), *H. molitrix* (silver carp), *Ctenopharyngodon idella* (grass carp), and *Mylopharyngodon piceus* (black carp). Digital illustration by David Bruce, U.S. Geological Survey.

Back cover. *M. piceus* (black carp). Digital illustration by David Bruce, U.S. Geological Survey.

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By Duane Chapman, Jon Amberg, Robin Calfee, Enrika Hlavacek, Jon Hortness, P. Ryan Jackson, David C. Kazyak, Brent Knights, and James Roberts

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Contents

Figures

Tables

Abbreviations

eDNA	environmental deoxyribonucleic acid
IPM	integrated pest management
MICRA	Mississippi Interstate Cooperative Resource Association
RNAi	ribonucleic acid interference
SDM	structured decision making
USGS	U.S. Geological Survey

Key Terms

bigheaded carp
A collective term for *Hypophthalmichthys nobilis* (bighead carp) and *H. molitrix* (silver carp).

environmental deoxyribonucleic acid (eDNA)
Organismal deoxyribonucleic acid (DNA) found in the environment.

integrated pest management
An approach that uses biological, cultural, physical, and chemical tools in a way that reduces risks to human health, the environment, and the economy. It is a science-based decision-making process that incorporates management goals, consensus building, biology, monitoring, environmental factors, and selection of the best available technology to achieve desired outcomes while managing effects on nontarget species and the environment and preventing unacceptable levels of damage.

invasive carp
A collective term for bighead carp, *Mylopharyngodon piceus* (black carp), *Ctenopharyngodon idella* (grass carp), and silver carp. Also known as "Asian carp" and "four major Chinese carp."

invasive species
With regard to a particular ecosystem, a non-native organism whose introduction causes or is likely to cause economic or environmental harm or harm to human, animal, or plant health (3 CFR 13751).

structured decision making (SDM)
An approach to identify and evaluate natural resource management alternatives. SDM incorporates decision theory and risk analysis and input from experts, interested parties, and decision makers to deal with complexity and uncertainty. SDM may include consideration of management alternatives, tradeoffs, and consequences, as well as inclusion of values-based input (Compass Resource Management, 2013).

United States
The 50 States; the District of Columbia; the territories of American Samoa, Guam, Puerto Rico, the U.S. Virgin Islands, and the Commonwealth of the Northern Mariana Islands; and U.S. insular possessions, including the Midway Islands, Wake Island, Palmyra Atoll, Howland Island, Johnston Island, Baker Island, Kingman Reef, Jarvis Island, and other U.S. islands, cays, and reefs that are not part of the 50 States.


USGS

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Vision Statement

The vision behind this strategic framework is to enable U.S. Geological Survey researchers to pursue a portfolio of leading-edge, partner-driven science for development, evaluation, and refinement of technologies for preventing the spread of bighead, black, grass, and silver carp to uninvaded waters and for reducing populations or effects of these species where they are present or established.

Introduction

The collective term “invasive carp” includes *Hypophthalmichthys nobilis* (bighead carp), *Mylopharyngodon piceus* (black carp), *Ctenopharyngodon idella* (grass carp), and *H. molitrix* (silver carp). These species were formerly known as “Asian carp,” but for scientific and societal reasons (Kočovský and others, 2018) and following the Presidential Memorandum of January 26, 2021, “Condemning and Combating Racism, Xenophobia, and Intolerance Against Asian Americans and Pacific Islanders in the United States,” the U.S. Geological Survey (USGS) abandoned that term and adopted “invasive carp” when referring to these species collectively. In some scientific publications they are referred to collectively as the four major Chinese carps (Song and others, 2018). Bighead carp and silver carp (together “bigheaded carp”) are filter-feeding planktivores that restructure the food web by their consumption of the foundation of that web, with effects that cascade throughout the ecosystems they invade. Silver carp also jump out of the water when disturbed, which can injure watercraft operators and recreational users and damage their property. Grass carp are unique among freshwater fish in their ability to consume large amounts of aquatic vegetation. This characteristic has resulted in the highly successful use of grass carp as a biocontrol for nuisance vegetation and the broad distribution of grass carp across much of the Nation. Unfortunately, uncontrolled populations of grass carp can result in the decimation of beneficial vegetation that is habitat for native fish and waterfowl and protects shorelines from erosion. Black carp, which have a diet predominately of mollusks (Nico and others, 2005), are used successfully to control nuisance snails in aquaculture. North America has the most diverse assemblage of freshwater mussels in the world (Williams and others, 1993), but most populations are imperiled. Because black carp can reach over 40 kilograms and can consume large adult mussels, they pose an existential threat to imperiled mussel species. All four species of invasive carp have escaped captivity and are reproducing in parts of the Mississippi River Basin (Nico and others, 2005). Grass carp are also reproducing in tributaries to Lake Erie, one of the Laurentian Great Lakes (Embke and others, 2016), and the Colorado River upstream of Lake Powell (Brandenburg and others, 2019).

USGS research on invasive carp in U.S. waterways began in the late 2000s following publication of high-level synopses and risk assessments (Nico and others, 2005; Kolar and others, 2007). Those assessments identified several fundamental knowledge gaps that needed to be filled in support of development of potential control methods. Using discretionary funding, USGS researchers began filling these knowledge gaps, studying embryology, diets, and habitats and assessing hydrodynamic suitability in potential spawning rivers. These early efforts formed the foundation for new areas of research with the ultimate goal of informing management efforts. The results of this research led to Congress allocating funding to further support USGS research, which was initially focused on protecting the Great Lakes from invasion by bighead, black, and silver carp.

In 2017, building on our past work and acknowledging the need for a longer term strategy, the USGS developed its first 5-year strategic plan (for the years 2017–21) for invasive carp research. Within this period, Congress provided additional funding, including focused amounts for research on grass carp in the Great Lakes and Upper Mississippi River Basins and for protection of subbasins of the Mississippi River for all four invasive carp species. The strategic plan laid out specific goals and objectives for several research areas that had definable endpoints or milestones. Among the major accomplishments during 2017 through 2021 were the following:

- development of deterrent technologies (Murchy and others, 2017), mass removal methods (Chapman, 2020), and species-specific delivery methods for piscicides (Poole and others, 2018);
- locating and verifying spawning tributaries and specific spawning areas for grass carp in Lake Erie tributaries (Embke and others, 2018);
- improvements in and novel applications of sampling for environmental deoxyribonucleic acid (eDNA) for detecting species presence and as an indicator of spawning (Erickson and others, 2019);
- development and use of novel mathematical models to assess the potential utility of various control techniques (Erickson and others, 2017);
- understanding upstream passage at bottleneck dams; and
- participation in and leadership of structured decision-making efforts to identify best management alternatives (Post van der Burg and others, 2021).

In 2020 and 2021, we began large-scale evaluations of key deterrent technologies, such as the USGS-developed underwater acoustic deterrent system at Lock and Dam 19 on the Mississippi River near Keokuk, Iowa, and we partnered with the U.S. Fish and Wildlife Service to evaluate a deterrent system that incorporates sound, lights, and a bubble screen at Barkley Lock and Dam near Lake City, Kentucky. We also initiated multiyear evaluations of baits and attractants for grass carp in the Great Lakes. All these research lines were supported and informed by management partner needs.

The years from 2017 to 2021 were also a period of increased coordination among State and Federal management and research partners and interested parties (app. 1) in research and management of bighead, black, grass, and silver carp. Coordinating bodies, such as the Invasive Carp Regional Coordinating Committee, the Great Lakes Fishery Commission, the Mississippi Interstate Cooperative Resource Association (MICRA), and the MICRA subbasin invasive carp partnerships, worked with States to identify broad research needs and priorities, which were communicated by way of priority documents and strategic plans. Annual USGS research efforts within our existing program reflected those priorities.

The USGS views the next 5 years as a transition from the foundation building, tool development, proof-of-concept testing, and initial evaluations that characterized the previous 15 years to a period of implementing and evaluating control tools. With past research (app. 2) providing a foundation of fundamental science and a suite of potential monitoring and control tools and techniques, our emphasis will necessarily shift to research needs as defined by management agencies for evaluating long-term monitoring and control. However, there remain some fundamental biological science needs for research on the less studied black carp and on other native and invasive species that may need to be addressed to inform decisions on newly conceived control tools. The USGS developed this framework to identify ongoing needs for evaluating and further developing technologies in support of management of bighead, black, grass, and silver carp.

This document is a strategic framework that identifies the general areas within which the USGS anticipates research needs. The objective is to enable USGS researchers to pursue a portfolio of leading-edge, partner-driven science supporting the development, evaluation, and refinement of technologies for controlling the spread of bighead, black, grass, and silver carp to (1) protect the Great Lakes and other uninvaded waters from these species and (2) reduce populations where they are present or established to minimize adverse effects. A review of this document by Federal and State agencies verified the need for research on the topical areas identified herein. This framework is not a fixed plan for specific research projects or funding; rather, it identifies broad topics within which the USGS and our partners anticipate research will be needed. This framework also allows for flexibility to meet new research needs identified by the USGS and our partners.

Specific projects pursued under the topic areas will be developed by working directly with the several work groups of the Invasive Carp Regional Coordinating Committee, the Great Lakes Grass Carp Advisory Committee, MICRA subbasin partnerships, and other work groups that may form during 2023–27.

The following sections of this document describe the motivation behind this strategic framework, outline the role of the USGS in researching invasive carp, and present seven broad themes of USGS invasive carp research. Previous USGS research is then summarized, and anticipated research directions during 2023–27 are described. Lastly, the plan for annual evaluation and adjustment of research directions is described.

Document Purpose and Use

This strategic framework was created to ensure that research performed by the USGS is directed toward furthering management-relevant understanding of the effects, detection, control, and containment of invasive carp. Ultimately, all such efforts are intended to provide the maximum benefit to Tribal, State, Provincial, and Federal partners and to United States citizens. This document serves as a guide to prioritizing USGS funding for research on bighead, black, grass, and silver carp and provides a framework for evaluating existing and proposed research by the USGS. This framework is intended to provide for proactive response by the USGS to changing research needs as they are identified. The framework is intended to allow the flexibility to adapt to changing trends, policy, and needs, rather than focusing on short-term, actionable tasks.

This strategic framework is designed to be compatible with the USGS 2020–2030 Science Strategy (USGS, 2021) and the goals of the USGS mission areas and programs. Within this framework, the USGS provides the research support needed to accomplish the goals and priorities expressed in the Department of Interior's Invasive Species Strategic Plan (U.S. Department of the Interior, 2021) and in the "Management and Control Plan for Bighead, Black, Grass, and Silver Carps in the United States" (Conover and others, 2007), which was approved by the multiagency Aquatic Nuisance Species Task Force. This framework supports priorities for the management of invasive carp as expressed in regional plans (for example, Mississippi River Basin Invasive Carp Control Strategy Frameworks, and the "Lake Erie Grass Carp Adaptive Response Strategy—2019–2023" [Lake Erie Committee, 2018]) and State plans (for example, Ohio Department of Natural Resources Division of Wildlife, 2019).

Support of Partner Priorities

USGS efforts support science needs as expressed by State, binational, and regional partners such as the Invasive Carp Regional Coordinating Committee (http://www.invasivecarp.us/), the Great Lakes Fisheries Commission's Council of Lake Committees (http://www.glfc.org/council-of-lake-committees.php), the Great Lakes Grass Carp Advisory Committee, MICRA (http://www.micrarivers.org/), and several State agencies (for example, Ohio Department of Natural Resources Division of Wildlife, 2019). The USGS is a signatory to A Joint Strategic Plan for Management of Great Lakes Fisheries (http://www.glfc.org/joint-strategic-plan-committees.php), which has relevance for USGS research in the Great Lakes. Preventing entry of bighead, black, and silver carp to the Great Lakes is a high priority for Canada (Mandrak and Cudmore, 2004), our binational partner in research and management of the Great Lakes, and informs Canadian efforts toward prevention and management. USGS research also supports efforts of Federal management partners, such as the invasive carp subbasin partnerships (that is, the invasive carp partnerships of the Upper Mississippi River; Lower Mississippi River; Missouri River; Ohio River; Tennessee and Cumberland Rivers; and Arkansas, Red, and White Rivers), the U.S. Army Corps of Engineers, the Tennessee Valley Authority, the National Park Service, and regional aquatic nuisance species panels. The USGS will remain apprised of the priorities of the various agencies, interested parties, basin and subbasin partnerships by attendance of USGS representatives at appropriate subbasin partnership meetings and at professional society conferences, by direct contacts between USGS scientists and managers, and by soliciting partner input at periodic symposia of USGS invasive carp research.

Priorities and goals of these groups may change over time, and the USGS must anticipate and be responsive to those changes without compromising a cohesive long-term strategy and while respecting USGS mandates and priorities. This approach will require USGS researchers to strike a balance among (1) completing existing lines of research on beneficial tools and products already in development or undergoing evaluation of efficacy, (2) leading development of new lines of research, and (3) responding quickly to developing needs and the changing priorities of partner agencies as expressed by interested parties and through basin and subbasin invasive carp partnerships.

Support of Regional Priorities

Priorities and approaches to invasive carp management vary across the United States, and this variation must be considered as part of the overall USGS approach. For example, management efforts in the Mississippi River Basin generally focus on containment and control and are coordinated by the U.S. Fish and Wildlife Service in partnership with MICRA through the multiple subbasin invasive carp partnerships. In contrast, efforts in the Great Lakes Basin generally focus on preventing invasion by bighead, black, and silver carp and reducing the grass carp population and are coordinated by a well-established multijurisdictional fishery management structure. In addition, there are areas of emerging or potential concern, such as the Upper Colorado River Basin (States of Colorado, Utah, and Wyoming), where reproduction of grass carp has been observed (Brandenburg and others, 2019), and the Hudson River (State of New York), where at least one diploid grass carp has been captured (USGS, 2022a). The USGS strives to work within governance structures in the several basins in which our research is conducted while maintaining a broad perspective on the applicability of research to other geographic areas.

Table 1. Annual Federal funding for U.S. Geological Survey research on invasive carp, by fiscal year and funding authority, 2012–22.

[A fiscal year is from October 1 through September 30 and is designated by the calendar year in which it ends. H.R., House of Representatives]

Fiscal year	Annual funding (millions)		Authority
	General	Grass carp	
2012	$2.50	$0.00	H.R. 2055—Consolidated Appropriations Act
2013	$2.50	$0.00	H.R. 933—Consolidated and Further Continuing Appropriations Act
2014	$3.50	$0.00	H.R. 3080—Water Resources Reform and Development Act
2015	$5.50	$0.00	H.R. 83—Consolidated and Further Continuing Appropriations Act
2016	$5.50	$0.00	H.R. 2029—Consolidated Appropriations Act
2017	[1]$5.62	$0.00	H.R. 244—Consolidated Appropriations Act (Public Law 115–31)
2018	$5.62	$0.00	H.R. 1625—Consolidated Appropriations Act
2019	$7.62	[2]$2.00	House Report 116–9—Making Further Continuing Appropriations for the Department of Homeland Security for Fiscal Year 2019, and for Other Purposes
2020	$10.62	$3.00	H.R. 1865—Further Consolidated Appropriations Act (Public Law 116–94)
2021	$10.62	$3.00	H.R. 133—Consolidated Appropriations Act (Public Law 116–260)
2022	$11.00	$3.00	H.R. 2371—Consolidated Appropriations Act (Public Law 117–103)

[1]Congress included $120,000 of nonspecific appropriated funds in the budget for invasive carp research.

[2]Congress provided $1 million in new funding and directed the U.S. Geological Survey to redirect $1M from land and water research activities.

From the U.S. Geological Survey (USGS) Science Strategy (USGS, 2021, p. 2):

"The USGS mission is to monitor, analyze, and predict current and evolving dynamics of complex human and natural Earth system interactions and to deliver actionable intelligence at scales and timeframes relevant to decision makers.

The USGS is committed to an unbiased and impartial scientific understanding of the Earth's systems and to continually evolve as societal needs change while embracing new technologies and capabilities.

Our vision is to

Lead the Nation in 21st-century integrated research, assessments, and prediction of natural resources and processes to meet society's needs."

Funding Authority and Congressional Priorities

The USGS was established by The Organic Act of 1879, as amended. The USGS was tasked with production of science for the benefit of the Nation. Several acts of Congress from 2012 to 2022 (table 1) have resulted in directed funding of $11.0 million annually to the USGS for research in support of management of invasive carp in three broad areas. A total of $6 million is for research toward preventing invasion of the Great Lakes by bighead, black, and silver carp; $2 million is for research within the six named subbasins of the Mississippi River (the Upper Mississippi; Lower Mississippi; Missouri; Ohio; Tennessee and Cumberland; and Arkansas, Red, and White River subbasins); and $3 million is for research to control grass carp in the Upper Mississippi River and the Great Lakes.

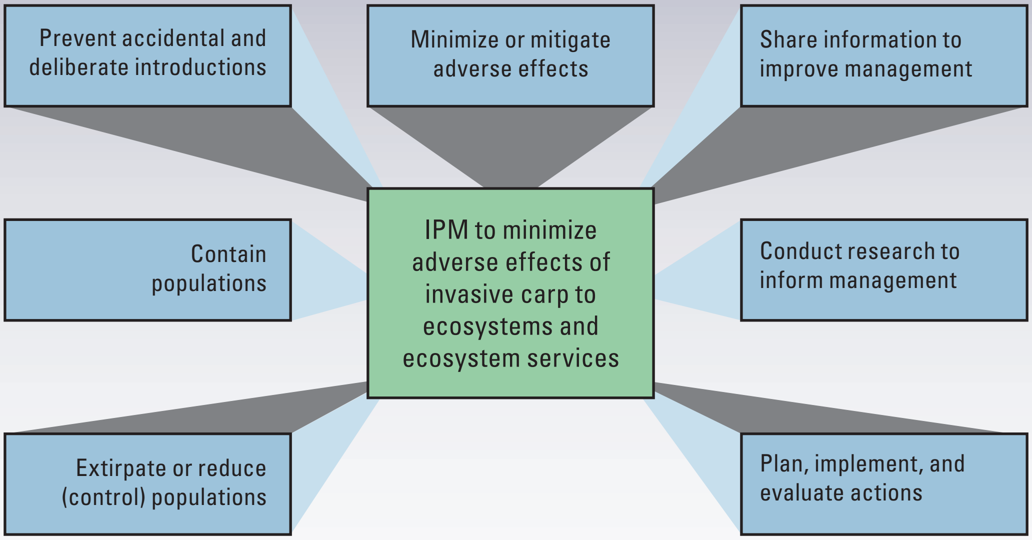


Figure 1. Diagram of integrated pest management (IPM) within the U.S. Department of the Interior, as it applies to invasive carp.

Roles, Responsibilities, and Commitments of the U.S. Geological Survey for Invasive Carp Science

USGS research produces actionable intelligence and tools for managers and decision makers to employ in the control of bighead, black, grass, and silver carp populations. The USGS investigates how multiple control tools may be integrated to reach management goals, under the principle of integrated pest management (fig. 1). A key focus is applied research with specific goals of assisting managerial objectives identified by partners. At times, research efforts are directed toward basic biological understanding of invasive carp because that understanding is a prerequisite for effective, efficient, and safe application of control tools. A basic biological understanding is also sometimes necessary before new techniques can be hypothesized or envisioned. Basic research results are also often applicable to risk assessments and to structured decision making, resulting in improved products. Because the basic research on biology of invasive carp is at the foundation of all empirical analyses, this information provided by the USGS is used by other interested parties for their own scientific, management, and educational outreach purposes. All USGS invasive carp research, whether basic or applied, is performed with the ultimate goal of improving the ability of managers to control invasive carp or ameliorate their undesirable effects.

The USGS provides technical support to partners and the public. This includes dissemination of technology developed by the USGS, as well as making existing scientific knowledge more accessible. This support is provided through workshops, symposia, and the direct availability of individual USGS scientist expertise to partners. Our science products are published in the peer-reviewed literature, including USGS publications, presented at scientific and management meetings, and announced through fact sheets and other forms of outreach. USGS scientists respond to requests from the public media to provide unbiased information on invasive carp. On request, the USGS provides information to the public, to public media, or to partner agencies on how to prevent inadvertent introductions of invasive carp into new areas. News releases are developed to provide information on USGS products and findings that are relevant to the public. We provide graphics and information for partners to use in their own outreach efforts. We provide information on USGS invasive carp science to the public via web pages, such as the Nonindigenous Aquatic Species database (https://nas.er.usgs.gov/) or pages maintained by individual USGS science centers, and we provide information to be posted online by partners such as the Invasive Carp Regional Coordinating Committee or State, Tribal, or Federal partners.

USGS research and technical support on invasive carp has overlap with, supports, and is supported by multiple USGS mission areas and programs. Although most research is funded by the Ecosystems Mission Area (https://www.usgs.gov/mission-areas/ecosystems/about-ecosystems-mission-area) and the Biological Threats and Invasive Species Research Program (https://www.usgs.gov/mission-areas/ecosystems/biological-threats-and-invasive-species-research-program), links to other mission areas (https://www.usgs.gov/science/mission-areas) will enhance USGS products and help them fulfill the Nation's information needs. Links to the Species Management Research Program (https://www.usgs.gov/mission-areas/ecosystems/species-management-research-program) are particularly strong because invasive carp have adversely affected fisheries wherever they invade. Climate change may affect where invasive carp can invade, and the carp invasion, by means of the substantial changes they cause in food webs, is relevant to the Environmental Health Program (https://www.usgs.gov/programs/environmental-health-program) because the invasion affects environmental contaminant cycling and fate. The reproductive success of invasive carp is closely tied to hydrologic conditions; thus the Water Resources Mission Area (https://www.usgs.gov/mission-areas/water-resources) is involved in invasive carp science to support deterrent technologies, control strategies, and risk assessments that depend on water quality and hydrodynamics. Furthermore, the USGS streamgage network can support real-time fish telemetry and be used in forecasting invasive carp spawning conditions.

USGS Fundamental Science Practices policy requires that all information and data generated by or funded by the USGS that are used in the development of information products be released to the public, including partner agencies and unallied researchers (Fundamental Science Practices Advisory Committee, 2011). This requirement provides a high degree of accountability and allows for the maximum benefit to the Nation by ensuring that USGS data can be reliably used by researchers inside or outside of the USGS to generate new understanding beyond the original intent of the research.

USGS invasive carp science (USGS, 2022b) is focused on benefitting the American people, and dissemination of that science to those who can benefit is of preeminent importance. Projects typically conclude with interpretation and dissemination of results through data releases, presentations, peer-reviewed publications, and workshops, often with outreach to fishery managers, other interested parties, and Congress.

Themes of U.S. Geological Survey Invasive Carp Science

The Seven Themes of U.S. Geological Survey Invasive Carp Science

- Deterrents
- Genetic control methods
- Baits and attractants
- Pesticides
- Removal, herding, and aggregating methods
- Decision support and modeling
- Early detection and surveillance

USGS invasive carp research has several foci, which as a suite have the ultimate goal of providing tools to improve early detection of, rapid response to, and containment and control of invasive carp populations. Here we briefly outline these foci and address challenges that inform our research in these areas.

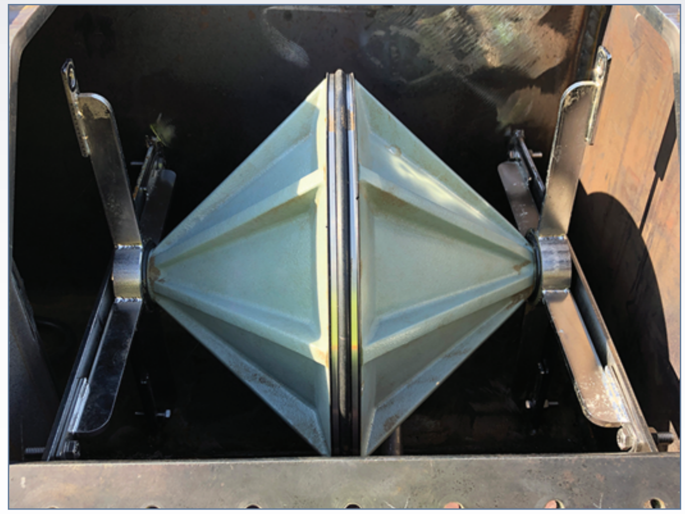
The stages of carp invasion in North America differ by species of carp and by region. Different stages of invasion and different environmental scenarios require different responses. For example, bigheaded carp are not thought to be present in the Great Lakes Basin; barriers to their invasion are thus highly desired and appropriate, as are efforts in early detection. In areas where carp are more abundant, efforts for control, containment, or amelioration of undesirable effects might be more appropriate. Although the USGS does not make decisions as to what types of control should be deployed for any given resource, the USGS provides tools for managers that are applicable to any stage or scenario of invasion and assists with selection and integration of tools. Our research on invasive carp will be aligned with the goals in the national plan (Conover and others, 2007) and those of regional partners, interested parties, and the subbasin partnerships.

Invasive carp might have direct effects on the Department of the Interior's trust resources (U.S. Department of the Interior, 2022), such as the black carp's threat to endangered mollusks, but they are also environmental engineers that change habitat (for example, removal of vegetation, or increased turbidity due to grass carp foraging) and disrupt food webs (for example, restructuring of the planktonic community by bigheaded carp). Invasive carp may alter environmental energy or trophic pathways, sequester nutritive compounds such as Omega-3 fatty acids, cause changes in biodiversity and species assemblages, and affect the physical environment by altering substrates or aquatic vegetation. Our research includes risk assessments and directed studies designed to deepen understanding of the likely effects of invasive carp.

USGS scientists must be cognizant of the potential for undesirable environmental effects of management activities and quantify those effects where possible to inform management decisions on the deployment of new or existing control methods. Invasive carp management activities can occasionally have undesirable short-term effects on native species, such as bycatch of native species during research on removal methods or impeding native fish movements at deterrent research sites. USGS scientists must also be aware of the potential for undesirable effects of their research activities and avoid unintended harm to the resources they intend to protect or to other users of the resource.

Deterrents

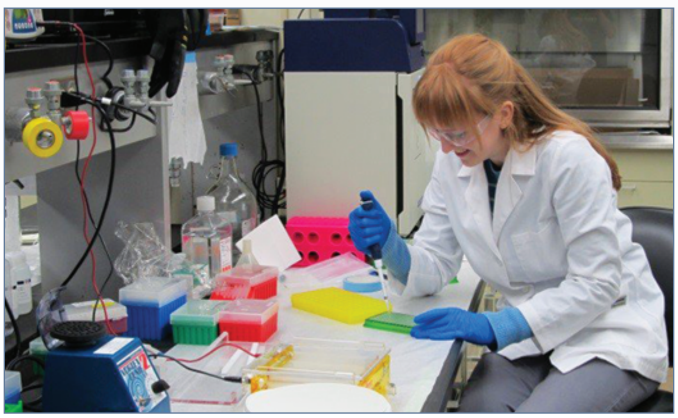
One factor that likely contributes significantly to the invasiveness of invasive carp is their mobility (Vallazza and others, 2020; Coulter and others, 2022). They are highly mobile within large floodplain river systems and are able to find conditions to meet or optimize their life history requirements, including reproduction, foraging, and shelter. The USGS, in collaboration with partners, is developing or testing behavioral deterrents that limit movement, particularly longitudinal movement, through bottleneck dams (for example, Lock and Dam 19 near Keokuk, Iowa, on the Upper Mississippi River) or other important intrasystem and intersystem corridors (for example, spawning tributaries or shipping canals). Promising deterrents that the USGS continues to develop and test include carbon dioxide, underwater acoustic deterrents, and oblique bubble curtains (Cupp and others, 2021). We and our partners are also studying the movement and behavior of invasive carp at system- and location-specific scales (for example, at Barkley Lock and Dam on the Cumberland River near Lake City, Kentucky) to inform decisions concerning the development and testing of deterrents.



Genetic Control Methods

Approaches and technologies that manipulate or exploit genetics and its processes have the potential to effectively target low-abundance populations and be truly species-specific without nontarget effects. These technologies are now commonly used in agriculture to control pests (for example, see Rato and others, 2021), and new techniques are regularly identified and developed. The USGS has expertise in genetics and genomics that can be exploited to develop genetic tools for control of invasive carp.

USGS researchers have begun research into development of genetic tools and into techniques for applying potential tools and assessing their safety and effectiveness. The USGS has begun sequencing the transcriptome of bighead, black, grass, and silver carp. This information can be used by USGS scientists and partners to develop and evaluate ribonucleic acid interference (RNAi) for silver carp, bighead carp, grass carp, and black carp. We use modeling to evaluate the potential of these technologies to identify which have promise for practical applications in controlling invasive carp and are modeling physiological pathways and identifying unique genetic sequences so natural processes can be exploited. Our research supports assessing the efficacy and registration of these technologies for use in natural resource management.



As new technologies and approaches are developed, the USGS will evaluate their practicality and utility. We acknowledge that there can be public concern regarding the risks associated with new technologies. The USGS has participated in workshops (for example, Genetic Control of Invasive Species; Minnesota Department of Natural Resources, June 11, 2019) to help identify appropriate public outreach on the benefits and risks of genetic controls and to remain cognizant of the degree of public support for these activities. Public support and established regulatory pathways will be among the criteria used for determination of project direction (Erickson and others, 2017).

Baits and Attractants

The USGS is evaluating the use of chemical and food attractants for aggregating bigheaded carp in support of removal efforts. Previous studies have tested the effectiveness of an algal attractant composed of *Spirulina* and *Chlorella* in controlled laboratory and pond studies (Claus and Sorensen, 2017), and field applications are ongoing. The USGS is focused on testing the effectiveness of an algal attractant for concentration of bigheaded carp in the field. The USGS conducted field tests at several sites on the Missouri River, in backwaters of the Illinois River, and at Mallard Lake near St. Louis, Missouri, using either manual application or automated feeding platforms. The USGS is also testing the use of amino acids to enhance the feeding response of invasive carp. In collaboration with State partner agencies, the USGS continues evaluating the use of the algal stimulus to enhance capture rates of bigheaded carp when using passive capture gears such as trap nets.

Another goal for this research is to identify habitat types where baits and attractants are most effective. In addition, the USGS is developing attractants and baits to aid in species-selective delivery of a control chemical. The USGS plans to focus on screening other potential attractants for all species of invasive carp by using electro-olfactogram assays (Claus and Sorensen, 2017; Sorensen and others, 2019). Attractants that elicit a physioelectrical response will be further tested to evaluate the species' behavioral response to the stimulus. If a strong behavioral response is observed, field tests will be conducted to determine whether the stimulus can effectively concentrate carp for more efficient removal. These methods and techniques will be shared with interested management agencies so that invasive carp can be harvested more efficiently according to each State's action plan for removal.

Pesticides

In collaboration with partners, the USGS is identifying and testing new chemicals and delivery mechanisms that target invasive carp while minimizing effects on native organisms. We plan to continue developing and refining quantitative structure activity relationships to prioritize toxicity screening with cellular assays. The USGS and its partners have developed cell lines for the four invasive carp as well as several native species. We are committed to expanding these cell lines to improve the efficiency of screening potential chemical controls. The USGS and partners continue to evaluate the metabolic and toxicological responses to exposure to different classes of chemicals in invasive carp and native aquatic organisms. Additionally, delivery technologies like microencapsulation have been developed and used to selectively deliver a control chemical to invasive carp in laboratory and field studies. The USGS and partners will continue to develop and refine these technologies so they can be incorporated into integrated pest management strategies by Tribal, State, and Federal natural resource agencies. Registration of new chemical controls is vital for use by resource agencies. The USGS works directly with the U.S. Environmental Protection Agency to ensure data requirements for pesticide registration are complete. We successfully obtained a section-3 registration from the U.S. Environmental Protection Agency for carbon dioxide as a fishery chemical under the name Carbon Dioxide-Carp (https://www.usgs.gov/centers/upper-midwest-environmental-sciences-center/science/registration-carbon-dioxide-carp) and intend to maintain that registration.

Removal, Herding, and Aggregating Methods

Removal is currently the primary method used by resource managers to address existing populations of invasive carp, and removal efforts have focused on the highly abundant bigheaded carp. Increases in bigheaded carp removal can be achieved by increasing efficiency of removal gears, by understanding and taking advantage of natural or preexisting aggregations of carp, or by removing artificially aggregated carp. The USGS will continue to conduct research to develop these methods and to evaluate their efficacy. Bigheaded carp have a limited affiliation to a specific home range and under some conditions move long distances and form large aggregations, which offers opportunities to exploit those aggregations. We will continue to advance understanding of natural aggregations using acoustic methods of locating fish, and studying their relations to habitat variables, such as water temperature, velocity, and food availability. Invasive carp may be artificially aggregated by either driving or attracting the fish to a location where large numbers of fish are harvested efficiently. Driving of fish uses stimuli that are avoided by the carp, such as sounds or electricity (Ridgway and others, 2021), and may include barriers that limit the directions that fleeing fish may choose, as in the Modified Unified Method (Chapman, 2020). Food attractants for carp have to date been the most successful attractive stimuli (Cupp and others, 2021), but pheromone attractants may also be useful. We will continue to investigate and evaluate potential attractants.

Decision Support and Modeling

Managers often need to make decisions under conditions of uncertain science, incomplete data, diverse interested parties with competing interests, and difficult tradeoffs including prioritization of effort and funding. Structured decision making (SDM) and risk assessments provide tools for defensible and transparent decisions that factor in the priorities of interested parties. The USGS facilitates SDM workshops, provides expertise in the decision-making and risk assessment processes, and often provides experts that can assist in providing up-to-date science on relevant and requisite subject matter for use in SDM workshops. Representatives of management agencies and other interested parties frequently participate in these risk assessments and SDM workshops. Tools developed during SDM workshops are heuristic models or mathematical models that are populated by existing or hypothetical data or by existing expert opinions. The goal of SDM workshops and risk assessments is to provide tools for defensible and transparent decisions that factor in the priorities of interested parties. An SDM workshop might include scenario planning and modeling that consider multiple, sometimes simultaneous, methods of response in an integrated approach to biothreats posed by invasive carp. The USGS will continue to lead SDM workshops and provide subject-matter expertise for SDM processes.

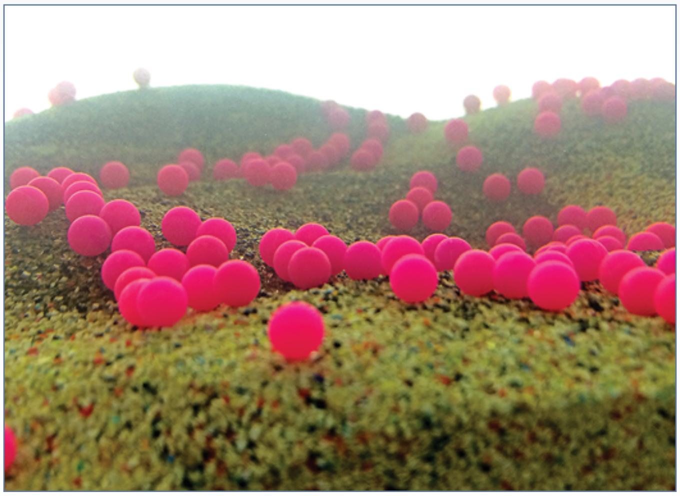
Early Detection and Surveillance

Managers require knowledge of where invasive carp have invaded, and early detection of carp arrival may provide managers with the opportunity to take quick action to prevent establishment. Similarly, knowledge of other status variables, such as where invasive carp are reproducing or established, is necessary to inform management decisions. The USGS will continue to develop new tools and improve the utility of available surveillance and early detection tools, such as eDNA and integration of eDNA detection into streamgage networks using automated sampling and analysis equipment. Many tools can be used for early detection or surveillance and monitoring, including capture techniques specific to low densities of fish, hydroacoustics, and eDNA.

U.S. Geological Survey Invasive Carp Science Strategy

Where We Have Been—Past Science Consolidation and Synthesis

Before bighead, black, grass, and silver carp were imported to the United States, they were already among the most studied freshwater species because of their importance in aquaculture. However, almost all the available information was relevant to aquaculture, not the biology or effects of wild fish. Substantial research on the effects of grass carp introductions to North America began in the 1970s (Michewicz and others, 1972; Stanley and others, 1978), but little scientific literature existed on the biology or potential effects of wild bigheaded carp or black carp in North America until USGS risk assessments in the 2000s (Nico and others, 2005; Kolar and others, 2007). Risk assessments by the USGS indicated substantial cause for concern. As carp populations and ranges expanded, research followed to better understand the life cycle and ecology of wild invasive carp (Chapman and Deters, 2009; Chapman and George, 2011). Those efforts were followed by research focused on control, including diverse but potentially integrated research directions. A recent synthesis by Cupp and others (2021) provides an overview of USGS research on promising tools, including models, for controlling invasive carp.



The USGS responds to emerging topics on invasive carp as they are identified by management agencies (Post van der Burg and others, 2021) but also identifies important new topics of concern and new potential techniques relevant to risk assessment, detection, population assessment, or control that have the potential to substantially change understanding or revolutionize aspects of carp management. For example, USGS researchers played a key role in identification of grass carp recruitment in the Lake Erie Basin (Chapman and others, 2013; Embke and others, 2016), which ultimately resulted in broad collaborative research and management of grass carp in the Great Lakes. Development of egg and larval drift models (Garcia and others, 2013) and applications (Embke and others, 2018) used to predict where invasive carp can reproduce effectively or where spawning events occur were initiated by the USGS and have found application in management across the invaded range. The USGS will continue to direct scientific expertise and available funding to projects that have the potential to provide new pathways for invasive carp control. Although every such investment may not be successful, paradigm-shifting tools cannot be developed without investment in new ideas.

Where We Are Going—U.S. Geological Survey Science Foci for the Next 5 Years

USGS research efforts for the 5 years beginning in 2023 will be multifaceted for maximum benefit to the U.S. public and to respond to partner needs. There is a need to increase effort in high-risk areas, especially connections between basins, such as the Tennessee-Tombigbee Waterway (Mississippi), where the range and effects of invasive carp might rapidly increase. There is also a need to better understand and exploit recruitment limitations in impounded parts of major rivers, where the carp invasion has been slow but still progresses. To address those needs, the USGS will engage with partners to identify areas where efforts can be increased to address greater needs and where efforts can be decreased because research is mature or has become routine, or where returns on research effort are low. While there is a need to remain open toward new or yet unidentified directions, the following important areas of ongoing research and extension of that research are anticipated to encompass most upcoming USGS invasive carp science. These areas of research fall within the general seven themes of USGS carp research previously described, and some may cross over multiple themes. For example, management strategy evaluation can apply to any of the elements related to control of carp populations that are instituted by managers. Scientific research projects will have a definitive lifetime from inception to completion. Research projects will cease, and funding will end, when the research objectives have been achieved and the outcome of the research has been disseminated. Technology or tool development projects cease when the tool is tested, validated, and disseminated to management agencies. Inevitably, research may find some initially promising tools to be impractical, and funding will be diverted to other more promising avenues of research.

- *Early detection and surveillance*.—There are critical needs for invasive carp research focused on early detection of carp invasion and on carp reproductive success in new areas. The USGS will continue to inform managers of invasive carp expansions (for example, as documented by Larson and others, 2017) and provide new tools for early detection and rapid response (for example, Hayer and others, 2020). Monitoring invasive carp abundance and short-term movements and concentrations with hydroacoustics can inform removal and the evaluation of management actions; monitoring has become and will remain important as part of integrated management of invasive carp. Improvement and validation of hydroacoustic methods will thus be an important research area.

- *Deterrents*.—Deterrents are key tools for reducing the risk of new invasions and expansions of existing populations. The USGS has led efforts to develop sound-based and carbon dioxide deterrents and will continue to pursue development of new technologies. We will rigorously research the effectiveness of deterrents at preventing movements of bighead, black, grass, and silver carp while assessing negative effects on movements of native species. Research on the movements and behavior of invasive carp at key population bottlenecks, such as navigation locks, canals, and tributaries, will be conducted to inform decisions on the development and application of deterrents.
- *Removal*.—Removal and physical barriers have emerged as primary tools for management of existing populations of invasive carp. Long-term management of carp through removal or deterrent maintenance is within the mandate of management agencies but not that of the USGS. Development of tools to improve removal efforts, reduce bycatch, or improve deterrent efficiency are within the scope of USGS research and are important over the next 5 years. The USGS may also participate in evaluation of the success of removal or barriers through demographic research or other methods.
- *Early life history*.—Over the previous 10 years, USGS research has provided greater understanding of the early life history of bigheaded carp and grass carp. That knowledge has been important in assessing where carp could reproduce and recruit, and thus in determining what environments are most at risk. Further research on early life history might be needed in new areas, such as the subbasins of the Mississippi River where our research has been limited, and potentially

elsewhere in the United States if congressional funding mandates permit (for example, the Colorado River, Hudson River, or Mobile River). Knowledge of invasive carp early life history is a prerequisite for devising control methods that interfere with those early life requirements. There is also a need for early life history information on black carp so that it might be brought up to the level of understanding of bighead, grass, and silver carp. The USGS may perform additional research on specific aspects of early life for the purpose of better devising control tactics.

- *Control tools*.—The USGS identifies and develops other tools for control of invasive carp. These may include waterborne or foodborne toxins that provide selective control of carp, attractants that concentrate carp for removal, sex alteration, genetic controls such as RNAi, beginning work towards gene drives, or yet unidentified tactics that could possibly reduce carp populations substantially. Control and containment tools or other invasive carp management strategies may have unanticipated adverse or possibly favorable effects on nontarget resources. If necessary, the USGS may initiate research to identify or quantify important side effects of invasive carp management strategies. Effective control tools developed by the USGS or others might require substantial research or monitoring to comply with regulatory statutes. Although USGS researchers might engage in development of new controls that are unfamiliar to managers, they will prioritize their research to avoid spending research resources on technologies that managers would not use. The USGS will pursue technology transfer when new tools are ready for management application.

- *Management strategy evaluation*.—Managers require an understanding of the kinds and extent of effects of management actions to inform resource allocation and to determine suitable targets for invasive carp abundance or biomass where control is undertaken. The USGS may work to better understand the effects of the carp invasion on native environments, including but not limited to effects on fisheries or the mechanisms for those effects. For example, recent publications (such as Chick and others, 2020) have shown deleterious effects of silver carp on native fishes. Bigheaded carp and grass carp cause environmental changes that affect food webs and water quality. Changes in water quality might affect resources in complex ways, including increased risk of harmful algal blooms or hypoxia in the Gulf of Mexico. Black carp prey directly on highly endangered native unionid mussels. USGS research may include evaluating management scenarios in the context of changing climate, as appropriate. As the U.S. Government's independent biology science agency, the USGS must be at the forefront of science that identifies the effects of carp invasion and potential mitigation strategies.

- *Decision support and data management*.—The USGS may guide or participate in SDM processes, population modeling, or other fisheries modeling to inform management actions such as removal or deterrent placement. Typically, this facilitation would occur when a need is identified by managers or interested parties who would be involved in the SDM process. Modeling to inform management can be data intensive, and partners may collect and source necessary data. Shared databases that include quality assurance, standardization, and archival features are broadly recognized at regional and national levels as being useful and necessary to maximize the efficiency and effectiveness of invasive carp management. These needs are already being addressed by the USGS and partners at regional levels (for example, by the FishTracks telemetry database; https://www.usgs.gov/centers/upper-midwest-environmental-sciences-center/science/database-and-web-application-invasive?msclkid=9b15c633b05211ec9af897e854c4a184) and can be used as building blocks for other regional approaches or a national approach to data management, should such an approach be directed by managers.

- *Training and technology transfer*.—After technologies have been developed adequately for dissemination to management agencies, the USGS provides training in use of those tools with the intent that they become primarily performed by management agencies. Tools might be used, for example, in sampling for early life history stages, identification of eggs and determination of egg developmental stages, the use of population and drift models, the use of eDNA for early detection, and aspects of mass harvest techniques. Such tools may be used by the USGS to further new research goals, and the USGS may perform research to further improve disseminated methods, but the USGS does not serve as a contractor to perform developed and disseminated management or monitoring methods.

Evaluating Research Under This Framework and Renewal

The USGS Invasive Carp Working Group, which is composed of principal investigators from across the USGS who design and conduct research in collaboration with agency partners, will meet annually to review performance under this framework and to ensure alignment with congressional funding mandates, guidance from the Program Council for the Biological Threats and Invasive Species Research Program, and partner needs. The Program Council is an advisory group composed of invasive species and disease experts from within the USGS and other U.S. Department of the Interior agencies that advises the Biological Threats and Invasive Species Research Program coordinator on setting program priorities. Existing or long-term research and potential new research are evaluated annually by the Invasive Carp Working Group to ensure a balance between full completion of beneficial projects and new initiatives. Updates on USGS research will be provided to partners through periodic symposia to disseminate USGS research results and apprise attendees on USGS research directions and progress. We will also communicate research results and progress through professional conferences, peer-reviewed literature, meetings of the Invasive Carp Regional Coordinating Committee and its work groups, the Great Lakes Grass Carp Advisory Committee, MICRA subbasin partnerships, and other similar groups. Input solicited and received from those groups will be used to prioritize research directions and ensure that USGS research remains aligned with agency partner priorities.

We will begin the process of developing a new strategic framework on invasive carp research for 2028–32 during the second fiscal quarter of 2027.

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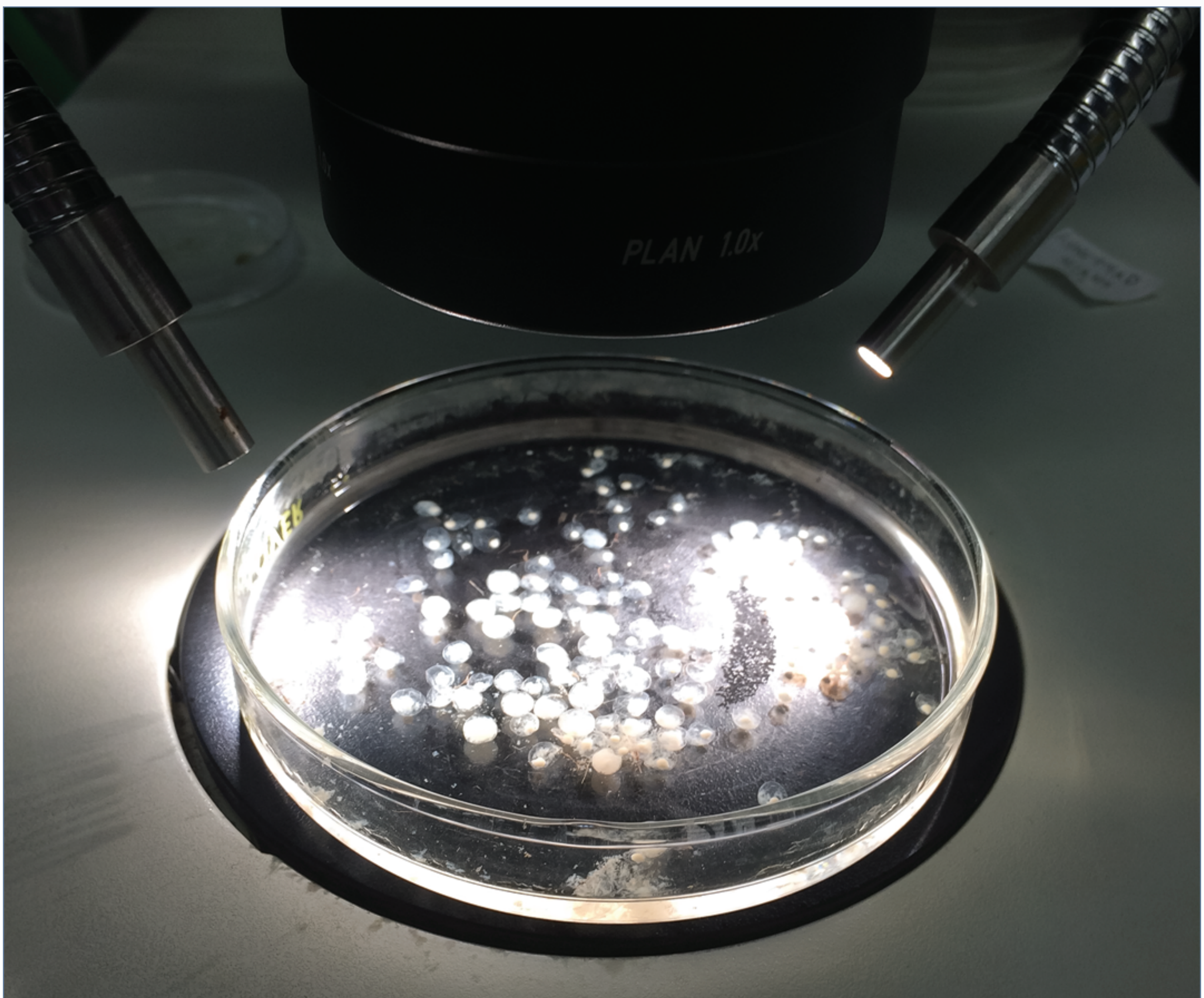
Appendix 1. Key U.S.-Based Organizations, Committees, and Groups Supporting Invasive Carp Research

- Invasive Carp Regional Coordinating Committee: http://invasivecarp.us
- Great Lakes Fishery Commission: http://glfc.org
  - Great Lakes Grass Carp Advisory Committee (of the Great Lakes Fishery Commission)
- Mississippi Interstate Cooperative Resource Association: http://www.micrarivers.org/



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Photographs

All photographs by the U.S. Geological Survey (USGS) except where indicated.

p. iv Removal of silver carp and bighead carp, Creve Coeur Lake, Maryland Heights, Missouri.

p. vi A grass carp about to be released in the Mississippi River after being implanted with an acoustic transmitter to allow tracking of its movements.

p. 2 Black carp and mussels.

p. 4 A USGS scientist collects telemetry from Truman Reservoir.

p. 7 (three photographs) Preparation of speakers and installation of the acoustic deterrent system at Lock 19 on the Mississippi River.

p. 8 (top) Analyzing DNA samples.

p. 8 (bottom) USGS scientists field test invasive carp baits and attractants on the Sandusky River.

p. 9 (top) Supply tanks of liquid carbon dioxide.

p. 9 (bottom) Field trial of a U.S. Geological Survey-developed carbon dioxide deterrent in a backwater of the Illinois River.

p. 10 (top) Removal of invasive carp during USGS-led mass removal research. Photograph by the Missouri Department of Conservation.

p. 10 (bottom) A seine full of invasive carp captured during USGS-led mass removal research. Photograph by the Missouri Department of Conservation.

p. 11 (top) Field sampling for grass carp eggs on the Sandusky River, a tributary to Lake Erie. Photograph by Nicole King.

p. 11 (bottom) Sampling for grass carp on the Sandusky River. Photograph by the Ohio Department of Natural Resources, Division of Wildlife.

p. 12 Synthetic surrogate water-hardened silver carp eggs on a bed of sediment.

p. 12 (bottom) A school of silver carp. Photograph by the U.S. Army Corps of Engineers.

p. 13 Grass carp egg samples.

p. 14 Silver carp jumping.

p. 15 USGS biologist deploying an ichthyoplankton net while sampling for eggs and larvae of invasive grass carp in a tributary to the Great Lakes.

p. 20 (top) USGS scientist holds a black carp captured from the Mississippi River.

p. 20 (bottom) Grass carp eggs being examined for developmental stage.

Inside back cover Juvenile bighead carp.

For more information about this report, contact:
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