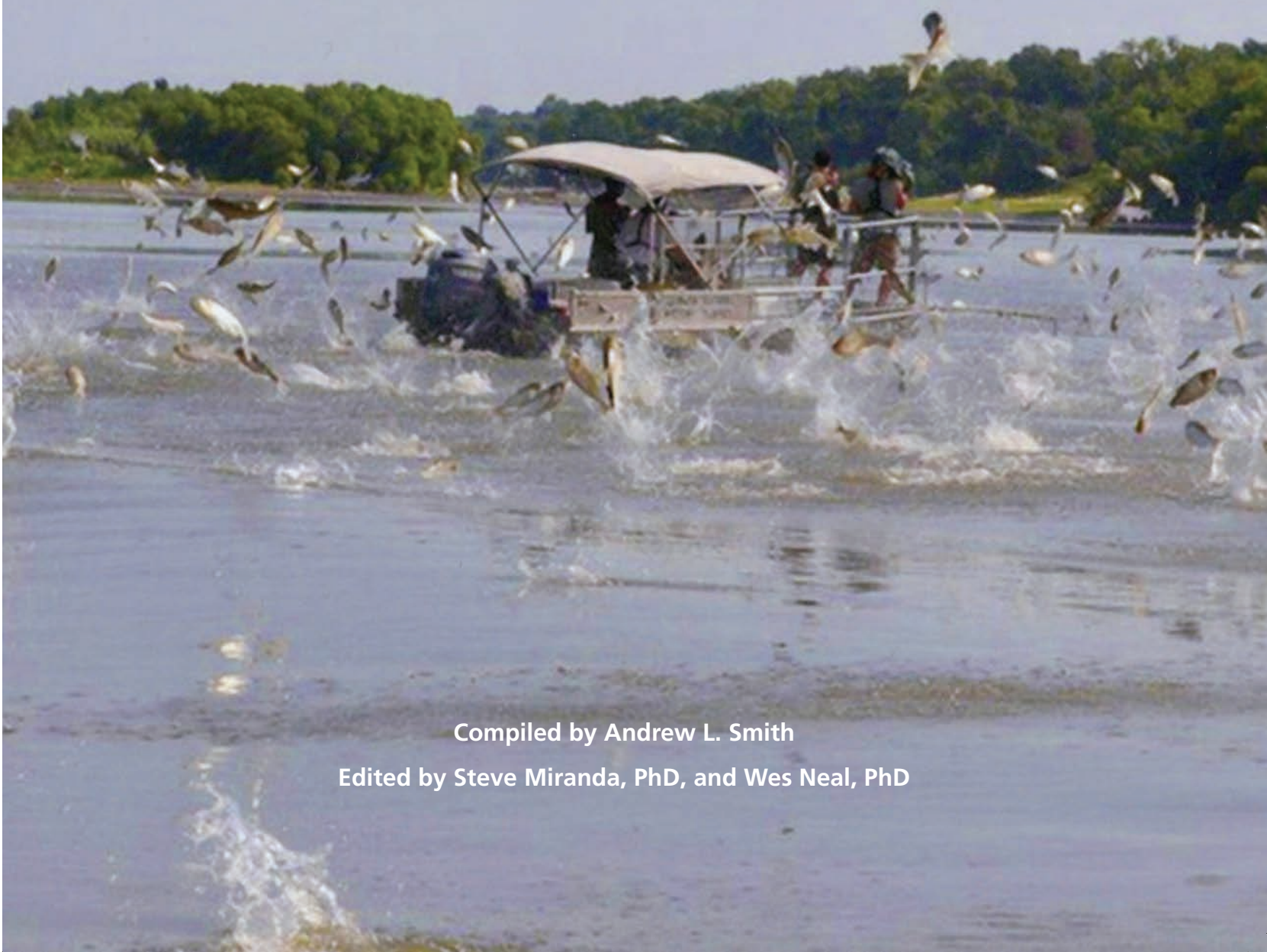
BIGHEADED CARPS

(*Hypophthalmichthys molitrix* and *H. nobilis*)

An Annotated Bibliography on Literature Composed from 1970 to 2014



Compiled by Andrew L. Smith

Edited by Steve Miranda, PhD, and Wes Neal, PhD

Bigheaded Carps

(*Hypophthalmichthys molitrix* and *H. nobilis*): An Annotated Bibliography on Literature Composed from 1970 to 2014

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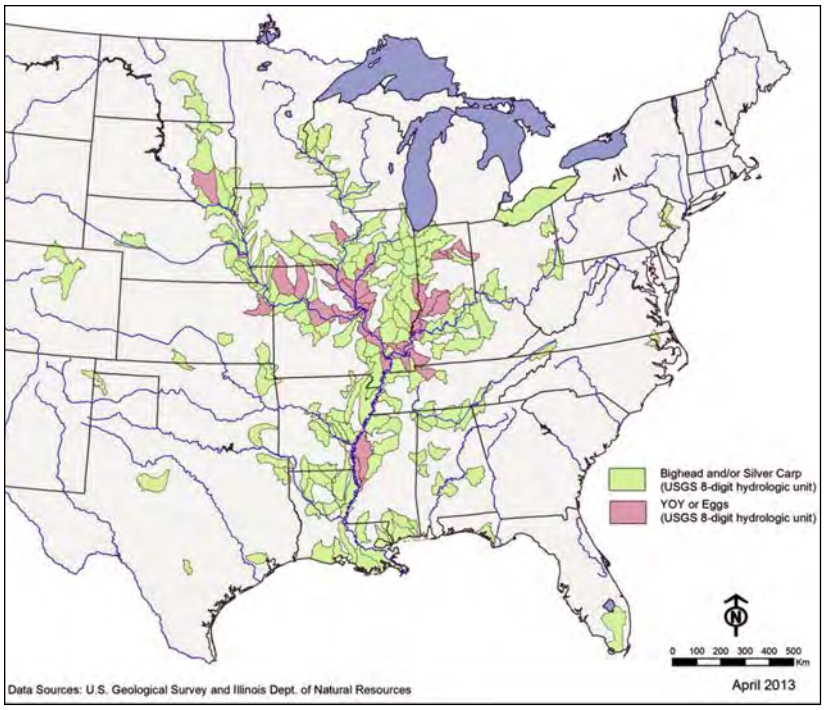
Photo courtesy of Asian Carp Regional Coordinating Committee

Silver carp (top) and bighead carp (bottom)
(Photo courtesy of Asian Carp Regional Coordinating Committee)

Introduction

The family Cyprinidae is the largest family of freshwater fish in existence. This diverse family encompasses some 3,268 species of fish, ranging from goldfish (*Carassius auratus*) to the widely introduced Asian carp (Nelson 2006). Although there are nine species of Asian carp that have been introduced outside of their native range, this annotated bibliography will focus primarily on the genus *Hypophthalmichthys* (the bigheaded carps), with an emphasis on the two species of most concern in the southeastern United States: silver carp (*H.* molitrix) and bighead carp (*H. nobilis*), regarding their invasive progression throughout North America. Asian carp are considered to be among the most important fish worldwide in terms of aquaculture production. They have been continuously used and introduced outside of their native range for centuries in applications such as in the fish food industry and in the biological control of plankton in manmade aquatic facilities (reservoirs, sewage treatment lagoons, and aquaculture ponds) (Kolar et al. 2007). This practice has recently caused an increase in management strategies that protect native fauna and ensure biodiversity, ecosystem integrity and function, and human safety.

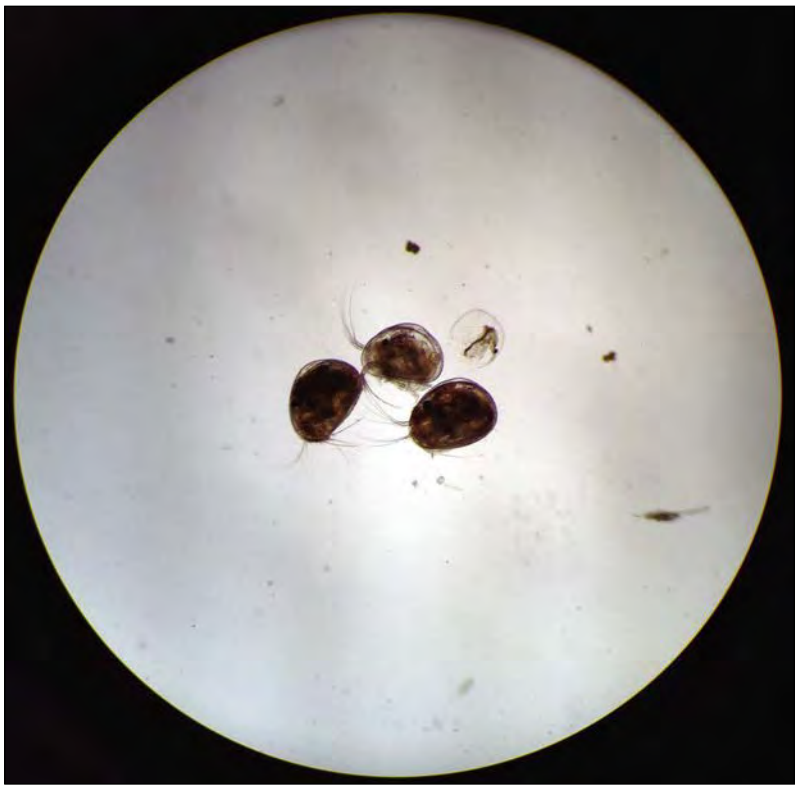
Bighead carp and silver carp are heavy-bodied fish with low-positioned eyes in proximity to their ventral surface. They have scaleless heads. This genus of carp (*Hypophthalmichthys*) has been used in the United States since the early 1970s and has become established in rivers and associated backwaters following its escape from confinement in the 1970s (silver carp) and 1980s (bighead carp). Reproducing populations occur throughout much of the Mississippi River basin; no bigheaded carps have been reported above Gavin's Point Dam, an area of the Missouri River that represents a large northwest section of the Mississippi River basin (Chapman, USGS, personal communication). While some native predatory fish such as blue catfish (*Ictalurus furcatus*) and channel catfish (*Ictalurus punctatus*), as well as some piscivorous birds such as brown pelicans (*Pelecanus occidentalis*), white pelicans (*P. erythrorhynchos*), and great blue herons (*Ardea herodias*), will prey on bigheaded carps, this predation is insufficient to control carp populations. Their evolutionary, natural predators reside in eastern Asia. With no natural predators or other mechanisms of control, these voracious, planktivorous feeders could pose a serious threat to native fauna and their environment, potentially altering ecosystem dynamics and function (Kolar et al. 2007). Their populations appear to be increasing exponentially (Chick and Pegg 2001), and they are aggressively outcompeting and possibly displacing native fish from resources such as quality feeding areas and desirable habitat. Bigheaded carps recruitment is typically strong during years of high water, and the high-water years that occurred in the 1990s were likely important in the subsequent population growth (Chapman, personal communication). As their populations continue to become denser and expand, availability of resources that are essential to native species could become less readily available. If this species reaches carrying capacity, the results could be even worse. However, it should be noted that in some areas of the lower Missouri River, where bighead carp are quite rare (almost certainly due to competition from silver carp), Asian carp have likely approached their carrying capacity as the condition factor of these fish has bottomed



out and growth has become much slower in the presence of intense competition. Duane Chapman of the U.S. Geological Survey reported catching six emaciated bighead carp among hundreds of silver carp in an area about as far upstream as adult Asian carp will go (personal communication). This suggests that the emaciated bighead carp were likely searching for water that had not yet been filtered by the abundant silver carp, and possibly still contained an efficient amount of plankton. However, lower-order streams (i.e., headwaters) are primarily reliant on allochthonous energy inputs, and plankton (both phytoplankton and zooplankton) is not a primary component of the trophic web. Filter-feeding fish are generally absent from lower-order streams because there isn't much to filter. Filter-feeding fish may be coming to these lower-order streams because the plankton supply in higher-order streams has been depleted.

Bighead and silver carp typically feed on primary producers such as phytoplankton and primary consumers, particularly zooplankton (Borutskiy 1973), which are the trophic foundation for most aquatic ecosystems. Aside from competing for these food resources with some of North America's native filter-feeding fish (e.g., American paddlefish [*Polyodon spathula*], bigmouth buffalo [*Ictiobus cyprinellus*], and gizzard shad [*Dorosoma cepedianum*]), their influence on plankton abundance and distribution could have detrimental effects on developing larvae and juveniles of numerous other native fish (Burke et al. 1986). During early development, most fish species depend on plankton as a nonreplaceable resource. Diminishment of this resource could have harmful cascading effects throughout the trophic tiers of these ecosystems. These impacts are likely to manifest in years to come and could have severe ecological, societal, and economic effects as Asian carp populations continue to expand throughout North America's waterways.

Asian carp also have effects on human populations, directly and indirectly. The sounds and vibrations emitted by boats cause these fish to leap from the water, which can cause collisions and serious injuries to boaters. Silver and bigheaded carp are heavy-bodied fish and, in nonnative waters of the United States, are capable of reaching a body mass of about 40 pounds for silver carp and about 100 pounds for bighead carp. Silver and silver x bigheaded carp hybrids (which have the potential to jump and superficially resemble bigheaded carp) pose a direct threat to recreational users. According to reports from the Environmental Protection Agency (EPA), injuries have included cuts, broken bones, concussions, black eyes, and back injuries. While bigheaded carp are typically more languid than silver carp and do not normally jump from



A microscopic view of plankton (by Andrew L. Smith).

the water, silver carp are prone to jumping when stimulated and are capable of leaping 2.5–3 m out of the water. In July 2007, the U.S. Department of the Interior declared all black (*Mylopharyngodon piceus*), silver, and largescale silver carp (*H. harmandii*) to be injurious species under the Lacy Act, prohibiting the further trade of either species. Bigheaded carp have since been included.

Silver carp may pose direct and apparent threats to human safety, but all bigheaded carp can be detrimental to the human population indirectly through ecological impacts. Their populations continue to dramatically increase, allowing them to exploit resources on which native fish and wildlife depend. They have the potential to lower overall production in rivers and reservoirs by reducing planktonic resources and, thereby, outcompeting and possibly displacing desirable species. Crustacean zooplankton abundance has decreased by 50–90 percent (depending on individual study) following establishment of these species. A decrease in abundance and body condition of native fish could result in less successful angling opportunities, which could have negative economic effects by lowering consumer expenditures on recreational activities.

These are the objectives of this bibliography:

1) Provide a brief review of the available literature resources concerning bigheaded carp in North America, with an emphasis on (but not limited to) their invasion in the eastern areas of the country where they pose the greatest threat.

2) Make these resources easily accessible for managers and researchers by consolidating them into a comprehensive and searchable list in an electronic journal via the Mississippi State University Extension Service and Center for Resolving Human-Wildlife Conflicts.

3) Provide outreach, education, and other various resources for stakeholders and the general public to raise awareness concerning Asian carp.

4) Continue to increase capacity in human-wildlife conflict resolution and management.

This publication is not intended to incriminate or place blame on any entity or individual.

This bibliography begins with material that encompasses much of the aspects of Asian carp taxonomy, distribution, life history, and management. Following the synopsis material is taxonomy information such as genetics, morphology, and physiology. Then, it progresses toward the distribution of the species, their natural histories, and the environmental and economic impacts associated with them. The final section focuses on management strategies and techniques that agencies are employing to eradicate and control them.

An American paddlefish (top) and a healthy silver carp (photos courtesy of U.S. Army Corps of Engineers Research and Development Center).

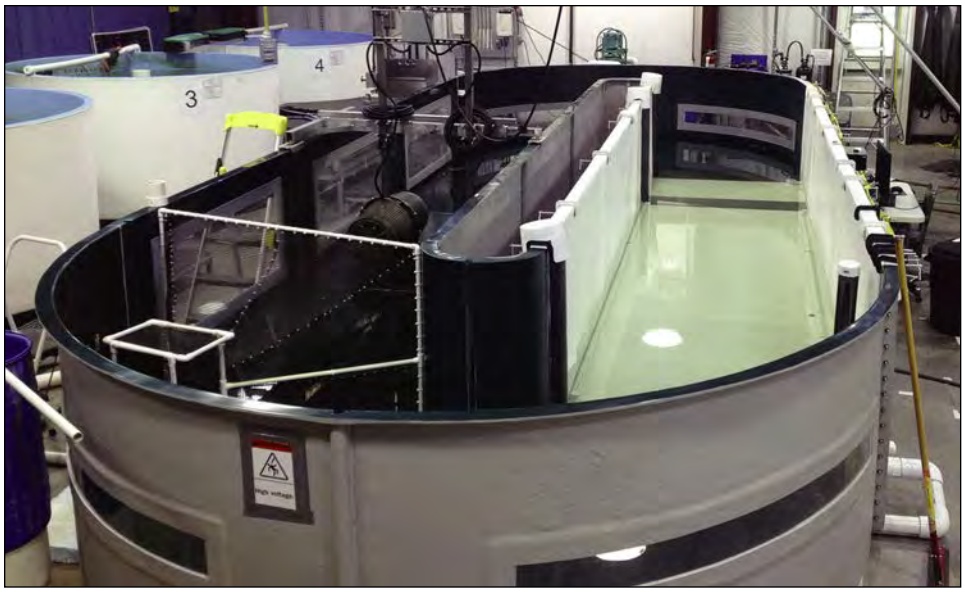
A Note for Using this Bibliography

This bibliography is not intended to replace the original documents but to supplement and guide users in a concise manner. Please consult the original source documents and materials for further understanding. Some publications have been summarized in a concise manner, while others appear in their original form. Many of the publications listed in this bibliography offer a wide variety of information concerning Asian carp and other invasive species and have been placed categorically into sections that are most representative of their contents. All titles have been standardized. Source titles are written as originally published and may include outdated names. All scientific names listed in the appendices and index follow currently accepted taxonomy.

British to Metric Unit Conversions

1 inch = 2.54 cm
1 foot = 0.3048 m
1 mile = 1.60934 km
1 acre = .404686 ha

Celsius = ((F-32)/9)*5
Fahrenheit = ((9*C)/5)+32



A team of scientists experiments with electrical field barrier technology in the Environmental Laboratory of U.S. Army Corps of Engineers Research and Development Center in Vicksburg, Mississippi (photo courtesy of U.S. Army Corps of Engineers Research and Development Center).

The Chicago Sanitary and Ship Canal Aquatic Nuisance Species Dispersal Barrier (photo courtesy of Asian Carp Regional Coordinating Committee).

A primary concern of the Asian carps' invasion is the potential risk of these species entering the Great Lakes. This could cost the Great Lakes Fishery — an industry valued at more than $7 billion — millions of dollars in control costs and resources. A diverse team of scientists and agencies has coordinated the construction of electric barriers, which have been strategically placed on the river to prevent (repel) Asian carps from reaching and becoming established in the Great Lakes.

Annotated Bibliography

Broad Synopsis Material

1.) Chapman, D.C., and Hoff, M.H. 2011. Invasive Asian carp in North America. American Fisheries Society. American Fisheries Society Symposium 74.

This book examines the history, biology, and status of Asian carp (grass carp, black carp, bigheaded carp, and silver carp) and reviews current research on control measures; explores the factors influencing recruitment and spread of Asian carp; considers current research on habitat requirements of bigheaded carp; analyzes data on diet overlap and potential competition between carp and native fishes; and examines the use of pheromones as controls for Asian carp.

2.) Hayer, C.A., Breeggemann, J.J., Klumb, R.A., Graeb, B.D.S., Bertrand, K.N. 2014. Population characteristics of bighead and silver carp on the northwestern front of their North American invasion. *Aquatic Invasions* 9(3):289–303.

Bigheaded and silver carp have been introduced worldwide and are invading three prairie stream tributaries to the Missouri River in the United States. The authors have documented spatial and temporal trends in population dynamics (i.e., density, size structure, age, growth, and condition) of Asian carp in the Big Sioux, James, and Vermillion from 2009 to 2012. They also examined the body condition of native planktivores such as gizzard shad, bigmouth buffalo, and emerald shiner using Fulton's K condition factor. Overall, 469 silver carp and eight bigheaded carp were collected using boat electrofishing, and mean catch-per-unit-effort of silver carp increased annually. The three rivers' populations were similar in length frequencies. Silver carp growth was faster initially than in later ages and overall was slower than Middle Mississippi River populations. Silver carp recruitment was erratic, with 2010 year class dominating 91 percent of catches while condition remained similar across rivers, season, and years. South Dakota silver carp populations were predicted from length-weight regression to be lighter than the Gavin's Point reach population of the Missouri River and heavier than those of both the Middle Mississippi River and Illinois River. Additionally, mean catch-per-unit-effort for bigmouth buffalo and emerald shiner decreased over the study period.

3.) Irons, K.S., Sass, G.G., McClelland, M.A., O'hara, T.M. 2011. Bighead carp invasion of the La Grange Reach of the Illinois River: Insights from the Long Term Resource Monitoring Program. *In*: Chapman, D.C. and M.H. Hoff (eds) Invasive Asian Carp in North America. American Fisheries Society Symposium 74:31–50.

Bigheaded carps, including the nonnative bighead carp *Hypophthalmichthys nobilis* and the silver carp *H. molitrix*, have been present in the Illinois River since the mid-1990s. The Long Term Resource Monitoring Program (LTRMP) is part of the U.S. Army Corps of Engineers' Environmental Management Program on the Upper Mississippi River System (UMRS) and has monitored fish communities in La Grange Reach, Illinois River since 1990. LTRMP has collected abundance, age and growth, and maturation and recruitment information for these carp as they have invaded the UMRS. Bigheaded carp have been collected in La Grange Reach by the LTRMP since 1995 and 1998. Since 2000, LTRMP catches of bigheaded carp have increased, and substantial spawning and recruitment has been evident. Length–frequency distribution analyses for both species have provided insight into growth rates, mean sizes at age, and cohort strength. Maturation schedules of bigheaded carp have been variable during the invasion, yet recruitment was positively correlated with Illinois River flow.

4.) Jennings, D.P. 1988. Bighead carp (*Hypophthalmichthys nobilis*): A biological synopsis. U.S. Fish and Wildlife Service. *Biological Report* 88(29) 35 pp.

The bigheaded carp (*Hypophthalmichthys nobilis*) is recognized throughout the world, primarily because of its versatility in aquaculture operations. It is endemic to eastern China and has been introduced worldwide as an important fish food. It also has been used in combination with other species of phytophagous fish to improve water quality and increase fish production, both in culture facilities and natural systems. This report on bigheaded carp summarizes in detail the taxonomy, morphology, distribution, dispersal, and reproductive requirements such as temperature, oxygen, and salinity. It also provides detail on life history stages and traits, nutrition and development, behavior, population structure (demographics, abundance and density, natality and recruitment, mortality, and population dynamics), exploitation for human use, protection and management, and aquaculture practices.

5.) Kolar, C.S., Chapman, D.C., Courtenay Jr., W.R., Housel, C.M., Williams, J.D., Jennings, D.P. 2007. Bigheaded carps: A biological synopsis and environmental risk assessment. American Fisheries Society. Bethesda, Maryland.

This book is a detailed risk assessment and biological synopsis of the bigheaded carp of the genus *Hypophthalmichthys*, which includes the bigheaded, silver, and largescale silver carp. It summarizes the scientific literature describing their biology, ecology, uses, ecological effects, and risks to the environment. Includes information on taxonomy and distinguishing characteristics, hybrids, native and introduced ranges, temperature and salinity tolerances, fecundity, sexual maturity and mating behavior, spawning, early development, feeding habits, growth rate and longevity, response to physical stimuli, associated diseases and parasites, human uses, environmental effects, potential range, and population control measures. Summarizes United States federal and state regulations and assesses the risk posed by these species in the United States.

6.) Moyle, P.B. 1986. Fish introductions into North America: Patterns and ecological impact. Ecology of biological invasions of North America and Hawaii: pp. 27–43.

After the discovery of artificial propagation in France in the 1840s, the idea of enhancing wild fish populations through the introduction of hatchery-reared fish quickly spread to North America and, by the 1870s, private, state, and federal fish hatcheries were common. The most important species reared at this time was the carp, which by 1890 was found throughout North America, thanks to the development of railroads and fish transport cars. Other species were raised as well, however, so that by 1873, a railroad car containing 300,000 fish of 10 species was on its way to California (Sheeley 1917). Such cars usually carried Pacific Coast salmonids back to the eastern seaboard on the return trip. This practice of taxon redistribution (Regier and Applegate 1972) continues to the present time, not only with fish but with other aquatic organisms as well (e.g., Carlton 1974).

Taxonomy — Genetics

7.) Lamer, J.T., Dolan, C.R., Petersen, J.L., Chick, J.H., Epifanio, J.M. 2010. Introgressive hybridization between bigheaded carp and silver carp in the Mississippi and Illinois rivers. *North American Journal of Fisheries Management* 30(6):1452–1461.

Multiple presumptively diagnostic morphological characteristics classify Asian carp as either bigheaded or silver carp. However, hybrids pose a dilemma. Fish exhibiting mixed morphological features in backwaters of the Illinois River near the confluence of the Mississippi River were collected and biopsied for tissue and were analyzed at four diagnostic allozyme loci via starch gel electrophoresis. The comparison revealed a high percentage of hybridization (22.5 percent) from an indiscriminate sample of 120 fish. Moreover, an unexpected percentage (12.5 percent) of individuals identified in the wild as either parental bigheaded or silver carp by gill raker morphology were genetically identified as hybrids. Two levels of hybridization were detected, first-generation hybrids (F1) and post-F1 hybrids, revealing the onset of extensive introgression and the potential for a hybrid swarm. Variation in the amplified COII domain of mitochondrial DNA indicated a strong directional bias of hybrids (88 percent) containing silver carp maternal lineages. Morphologically, F1 hybrids were often identifiable by the presence of twisted gill rakers, but post-F1 hybrids were difficult to identify with any appreciable certainty, creating concern where taxonomic assignment is critical for management and monitoring. Observations in aquaculture have shown reduced jumping behavior, fitness, and condition of fish from post-F1 matings between these species. A hybrid swarm may ultimately decrease invasion success as introgression continues.

8.) Li, S.F., Xu, J.W., Yang, Q. L., Wang, C.H., Chen, Q., Chapman, D.C., Lu, G. 2009. A comparison of complete mitochondrial genomes of silver carp *Hypophthalmichthys molitrix* and bigheaded carp *Hypophthalmichthys nobilis*: Implications for their taxonomic relationship and phylogeny. *Journal of Fish Biology* 74(8):1787–1803

Based upon morphological characteristics, silver carp and bighead carp have been classified into either the same genus (*Hypophthalmichthys*) or two distinct genera. Consequently, the taxonomic relationship of the two species at the generic level remains equivocal. This issue is addressed by sequencing complete mitochondrial genomes of silver and bigheaded carp, comparing their mitogenome organization, structure and sequence similarity, and conducting a comprehensive phylogenetic analysis of cyprinid species. As with other cyprinid fish, the mitogenomes of the two species were structurally conserved, containing 37 genes including 13 protein-coding genes, two ribosomal RNA genes, 22 transfer RNA (tRNAs) genes, and a putative control region (D-loop). Sequence similarity between the two mitogenomes varied in different genes or regions, being highest in the tRNA genes (98.8 percent), lowest in the control region (89.4 percent), and intermediate in the protein-coding genes (94.2 percent). Analyses of the sequence comparison and phylogeny using concatenated protein sequences support the view that the two species belong to the genus *Hypophthalmichthys.*

9.) Li, S.F., Xu, J.W., Yang, Q.L., Wang, C.H., Chapman, D.C., Lu, G. 2011. Significant genetic differentiation between native and introduced silver carp (*Hypophthalmichthys molitrix*) inferred from mtDNA analysis. *Environmental Biology of Fish* 92(4):503–511.

Silver carp is native to China and has been introduced to over 80 countries. The extent of genetic diversity in introduced silver carp and the genetic divergence between introduced and native populations remain largely unknown. In this study, 241 silver carp sampled from three major native rivers and two nonnative rivers (Mississippi River and Danube River) were analyzed using nucleotide sequences of mitochondrial COI gene and D-loop region. A total of 73 haplotypes were observed, with no haplotype found common to all the five populations and eight haplotypes shared by two to four populations. As compared with introduced populations, all native populations possess both higher haplotype diversity and higher nucleotide diversity, presumably a result of the founder effect. Significant genetic differentiation was revealed between native and introduced populations as well as among five sampled populations, suggesting strong selection pressures might have occurred in introduced populations. Collectively, this study not only provides baseline information for sustainable use of silver carp in their native country (China), but also offers first-hand genetic data for the control of silver carp in countries (e.g., the United States) where they are considered invasive.

Taxonomy — Morphology and Physiology

10.) Chapman, D.C., ed. 2006. Early development of four cyprinids native to the Yangtze River, China. U.S. Geological Survey Data Series 239, 51 p.

This document is a translation of a paper and appendices that were originally in Chinese. Due to their importance, they have been edited and translated into English. Chapter 1 (*Notes on the Translation and Use of "A Study of the Early Development of Grass Carp, Black Carp, Silver Carp, and Bigheaded Carp in the Yangtze River, China")* is designed to place that translation into the appropriate context for the benefit of the North American scientist. The editor describes the historical context in which the data were collected while also providing direction on the use of the translation, including a description of the Chinese morphometric conventions, which differ from those used by North American scientists. Lastly, the editors provide information on how the larvae of the subject fish, which are now established in the Mississippi River Basin, may be differentiated from other fish present in the basin. The paper presented in Chapter 2 (*A Study of the Early Development of Grass Carp, Black Carp, Silver Carp, and Bigheaded Carp in the Yangtze River, China*) describes the characteristics of 48 early developmental stages of the four famous domestic fish in the Yangtze River in China. The paper compares the morphological similarities and differences among the four species with about 200 original drawings. The results of this paper were mainly based on continuous observations of the early development of eggs and larvae of the four species collected from the upstream and middle sections of the Yangtze River between 1961 and 1963.

11.) Soin, S.G., and Sukhanova, A.I. 1972. Comparative morphological analysis of the development of the grass carp, the black carp, the silver carp, and the bigheaded carp (Cyprinidae). *Journal of Ichthyology* 12(1):61–71.

An account is given of general and specific structural features in the development of embryos, larvae, and fingerlings of the four selected species of Asian carp that are being extensively acclimatized in Russia. A number of significant differences have been established in their development relating to the size of eggs and embryos, number of myotomes, nature and degree of pigmentation, proportions in development of the keel and scales, and also a number of other characteristics.

Walleser, L.R., Howard, D.R., Sandheinrich, M.B., Gaikowski, M.P., Amberg, J.J. 2014. Confocal microscopy as a useful approach to describe gill rakers of Asian species of carp and native filter-feeding fish of the Upper Mississippi River system. *Journal of Fish Biology* 85(5):1777–1784.

12.) To better understand potential diet overlap among exotic Asian species of carp and native filter-feeding fish of the upper Mississippi River system, microscopy was used to document morphological differences in the gill rakers. Analyzing samples first with light microscopy, the three-dimensional structure of gill rakers in *Hypophthalmichthys molitrix*, *H. nobilis,* and *Dorosoma cepedianum* was more thoroughly described and illustrated than previous work with traditional microscopy techniques. The three-dimensional structure of gill rakers in *Ictiobus cyprinellus* was described and illustrated for the first time.

Distribution — Introduced Waters

13.) Britton, J.R., and Davies, G.D. 2007. First U.K. recording in the wild of the bigheaded carp. *Journal of Fish Biology* 70(4):1280–1282.

Prior to this documentation, there were no reports in the scientific literature of bigheaded carp in the wild in the waters of the United Kingdom. Aside from a single report (unpublished record) that stated some imported fish were being held on a secure aquaculture site, there were no other observations of any bigheaded carp in the wild that had escaped confinement. In September 2005 an angler captured an 11.5 kg fish from a lake in Downham Market, Norfolk, that was initially identified as *H. nobilis*. This prompted further investigation, and surveys were initiated in January 2006 using a 100 m seine. During this survey, five specimens between the lengths of 746 and 796 mm with a mass from 10.1 to 13.5 kg were collected in the lake and removed to a holding facility where their meristic characters were recorded. Evaluation of their gill rays and lengths of the ventral keel allowed conclusion that the species were in fact *H. nobilis* and not *H. molitrix* (silver carp).

14.) Economidis, P.S., Dimitriou, E., Pagoni, R., Michaloudi, E., Natsis, L. 2000. Introduced and translocated fish species in the inland waters of Greece. *Fisheries Management and Ecology* 7(3):239–250.

Over the last seven decades, 23 exotic fish species have been introduced into the inland waters of Greece. Some of these species were deliberately planned due to the species exploitative qualities, both ecologically and economically. These species included rainbow trout, Pacific salmon, grass carp, and silver carp. Some species have become fully acclimatized and have built up important populations. In other cases, the transfers and introductions have had considerable negative impacts, particularly where introduced species have outcompeted native forms.

15.) Freeze, M., and Henderson, S. 1982. Distribution and status of bigheaded carp and silver carp in Arkansas. *North American Journal of Fisheries Management* 2(2):197–200.

Bigheaded carp and silver carp are being utilized at six hatcheries and have been purposely stocked at four research sites in Arkansas. Reports of silver carp in Arkansas public waters in January 1980 prompted this investigation. Commercial fishermen reported catching 166 silver carp at seven different sites, but they did not report catching bigheaded carp. An intensive sampling effort on the Arkansas River by Arkansas Game and Fish Commission personnel was unsuccessful in procuring addition specimens.

16.) Herborg, L.M., Mandrak, N.E., Cudmore, B.C., MacIsaac, H.J. 2007. Comparative distribution and invasion risk of snakehead (Channidae) and Asian carp (Cyprinidae) species in North America. *Canadian Journal of Fisheries and Aquatic Sciences* 64(12):1723–1735.

As nonindigenous species are a major threat to global biodiversity, cost-effective management requires identification of areas at high risk of establishment. Here the authors predict suitable environments of 14 high-profile species of nonindigenous snakehead (Channidae) and Asian carp (Cyprinidae) species in North America based upon ecological niche modeling and compare the driving environmental variables for the two fish groups. Snakehead distributions were correlated with thermal factors, whereas those of Asian carp were related mainly to precipitation. Predicted suitable ranges for these nonindigenous species can be divided into three main areas: Mexico and the southern United States (five species); Mexico and the United States up to ~35°N (three species); and most of Mexico, continuous United States, and southern Canada (six species). For the province of Ontario, the number and location of aquarium stores and live fish markets with predicted areas of suitable environments were combined to identify areas at risk of introduction and establishment. Several watersheds draining into northwestern Lake Ontario were identified as having the highest risk, highlighting the increased predictive value of this approach.

17.) Tucker, J.K., Cronin, F.A., Hrabik, R.A., Petersen, M.D., Herzog, D.P. 1996. The bigheaded carp (*Hypophthalmichthys nobilis*) in the Mississippi River. *Journal of Freshwater Ecology* 11(2):241–243.

In this publication, the authors report collections of the bigheaded carp in the Mississippi River in Missouri and Illinois between 1991 and 1994. A total of 48 specimens were collected, ranging from 18 to 790 mm total length. Young-of-the-year fish were caught in 1992 and 1994, which suggests that the species is able to reproduce in the Mississippi River and may become established.

18.) Kelly, A.M., Engle, C.R., Armstrong, M.L., Freeze, M., Mitchell, A.J., Chapman, D.C., Hoff, M.H. 2011. History of introductions and governmental involvement in promoting the use of grass, silver, and bighead carp. *In*: Chapman, D.C., and Hoff, M.H. (eds) Invasive Asian Carps in North America. *American* Fisheries Society Symposium 74:163–174.

This paper traces the chronology associated with importations of Asian carps to North America and discusses the most likely pathways of their introduction to the wild. Beginning with the first importation of an Asian carp species (grass carp) in 1963, via U.S. Fish and Wildlife Service, and ending in the 1980s where the research and stockings of silver and bigheaded carp were conducted by at least six state and federal agencies and three universities in seven states. The authors determine that the public-sector agencies, which were successful in encouraging development and use of Asian carp, are the likeliest pathways for the earliest escapes of grass carp, silver carp, and bigheaded carp.

19.) Kocovsky, P.M., Chapman, D.C., McKeena, J.E. 2012. Thermal and hydrologic suitability of Lake Erie and its major tributaries for spawning of Asian carps. *Journal of Great Lakes Research* 38(1):159–166.

Asian carps have expanded throughout the Mississippi River basin and threaten to invade Lakes Michigan and Erie. Although adult bigheaded and grass carp have been captured in Lake Erie, self-sustaining populations are not likely to exist. Here the authors examine thermal conditions within Lake Erie to determine if Asian carps would mature, and to estimate time of year when fish would reach spawning conditions. The authors also examined the suitability (thermal and hydrologic conditions) for spawning of Asian carps in the largest tributaries to western and central Lake Erie. The Maumee, Sandusky, and Grand Rivers were predicted to be the most likely to support spawning of Asian carps. The Black, Huron, Portage, and Vermilion Rivers were predicted to be less suitable. The evidence suggests that the largest western and central tributaries in Lake Erie are thermally and hydrologically suitable to support spawning.

20.) Koehn, J.D. 2004. Carp (*Cyprinus carpio*) as a powerful invader in Australian waterways. *Freshwater Biology* 49(7):882–894.

The invasion of carp (*Cyprinus carpio L.*) in Australia illustrates how quickly an introduced fish species can spread and dominate fish communities. This species has become the most abundant large freshwater fish in southeast Australia, now distributed over 1 million km^2. In addition to its invasiveness, the degradation of aquatic environments in southeast Australia has given them a relative advantage over native species. Derivation of relative measures of 13 species-specific attributes allowed a quantitative comparison between carp and abundant native fish species across five major Australian drainage divisions. In four of six geographical regions analyzed, the authors observed that carp differ clearly from native species in their behavior, resource use, and population dynamics. The authors used climate matching to predict future range expansion of carp in Australia. The results suggest that all of Australia's surface waters are climatically suitable for carp. Given their historical spread, dispersal mechanisms and ecological requirements, the expansion of carp across the remainder of Australia is to be expected.

21.) Laird, C.A., and Page, L.M. 1996. Nonnative fish inhabiting the streams and lakes of Illinois. *Illinois Natural History Survey Bulletin* 35(1):1–51.

At the turn of the century, only one nonnative species of fish, the common carp, was established in Illinois. By 1996 the number of fish introductions was totaling 22 species. Because several of these fish have only recently become introduced or are expanding their range in Illinois, they are not familiar to most residents of the state. The authors include keys and descriptions that are intended to assist in the identification and monitoring of the impacts of these 22 species. Also included for each species is a brief summary of its ecological and life history characteristics and a discussion of its Illinois distribution.

22.) Lohmeyer, A.M., and Garvey, J.E. 2008. Placing the North American invasion of Asian carp in a spatially explicit context. *Biological Invasions* 11(4):905–916.

The bigheaded (*Hypothalmichthys nobilis*) and silver carp (*H. molitrix*) have invaded much of the Mississippi River. It is unclear how reproduction in northern impounded (closed) pools of the Upper Mississippi River System (UMRS) compares to unimpounded (open) southern reaches. During spring through summer 2005 and 2006 and once in spring 2007, the authors quantified larval and juvenile production in the pooled and open UMRS. They then simulated population dynamics in pools as a function of apparent reproductive success. Larvae occurred during about 2 weeks each spring. Peak density and apparent spawn duration were greater in the open reach. Larval production peaked when discharge was high plus rising and water temperatures reached 18°C. Most juveniles (>97 percent) occurred in the open reach. Low flow during drought years in the pools may limit reproductive success. The simulation demonstrated that, by treating dams as barriers to invasion from the lower open river (i.e., a source), climatic conditions may interact with flow in pools to limit populations by creating an isolated sink.

23.) Nico, L.G., and Fuller, P.L. 1999. Spatial and temporal patterns of nonindigenous fish introductions in the United States. *Fisheries* 24(1):6–27.

In 1978 biologists in Gainesville, Florida, began compiling records on the distribution and status of nonindigenous fish known in the U.S. inland waters. The database, now in electronic format, contains approximately 17,000 records representing more than 500 nonindigenous fish taxa. Using this database the authors are able to more thoroughly analyze patterns of introduction and the spread of nonindigenous fish within the United States. This paper introduces the authors' database and provides an overview of temporal and spatial patterns of nonindigenous fish distributions in the U.S. inland waters.

24.) O'Connell, M.T., O'Connell, A.U., Barko, V.A. 2011. Occurrence and predicted dispersal of bigheaded carp in the Mississippi River System: development of a heuristic tool. *In*: Chapman, D.C., and Hoff, M.H. (eds), Invasive Asian Carps in North America. American Fisheries Society Symposium 74:51–71.

Bigheaded carp have become established in the Mississippi River System (MRS) and pose a serious threat to native fish and aquatic ecosystems throughout North America. Determining their dispersal dynamics is an essential management tool for controlling their

expansion. To better understand how they have spread through the MRS, the authors developed a simple diffusion model to be used as a heuristic tool to generate insights regarding dispersion patterns. The authors first collected occurrence data from fish museums and government agencies spanning more than 30 years of sampling in the MRS and nearby rivers. These were then combined into a geographic information system database and used to create yearly occurrence maps for this species. They then developed a diffusion model for bigheaded carp using information on their movement and reproduction. The resulting model can be used to track the dispersal of hypothetical carp populations from different points of introduction within the MRS. With this model, they generated and compared four possible dispersal scenarios for bigheaded carp based on likely points of introduction to determine which type of introduction pattern (single introduction versus multiple introductions) best matches actual occurrence data. The results suggest expanding bigheaded carp populations in the MRS began from multiple origins rather than a single introduction. The results also suggest that bigheaded carp are possibly more widely dispersed than current occurrence data indicates and that the species is likely extending its range "under the radar" of standardized sampling. Finally, the authors used these dispersal scenarios to predict potential high carp density hot spots that could develop over the next 20 years in the MRS and should be targeted for control management.

25.) Rasmussen, J.L. 2002. The Cal-Sag and Chicago Sanitary and Ship Canal: A perspective on the spread and control of selected aquatic nuisance fish species. U.S. Fish and Wildlife Service, 4469 – 48th Avenue Court, Rock Island, IL 61201. 26pp.

This report summarizes the historical conditions and species communities that were present during pre and post-anthropogenic manipulation of watersheds such as Lake Michigan and the Illinois River. The author briefly describes the purpose and construction of the Cal-Sag Chicago Sanitary and Ship Canal and the resulting environmental impacts that it has had, with an emphasis on invasive species. Included is a detailed description of the invasive species process, the current invasions in The Great Lakes and Mississippi River Basin, the invasive fish species of most concern facilitated by the Cal-Sag and Chicago Sanitary and Ship Canal. The author also summarizes the potential impacts of invasion as well as prioritizes which invasions are of the most importance and demand urgent action. In conclusion, the author provides alternative management suggestions for stopping the transfer of aquatic nuisance species between The Great Lakes and Mississippi River Basin ecosystems.

26.) Thomas, R.G., Jenkins, J.A., David, J. 2011. Occurrence and distribution of Asian carps in Louisiana. *In*: Chapman, D.C., and Hoff, M.H. (eds), Invasive Asian Carps of North America. American Fisheries Society Symposium 74:239–250.

In the 1970s, commercial fishers reported sightings of grass carp in large rivers and associated backwaters of Louisiana; the first specimen in Louisiana Department of Wildlife and Fisheries' fishery independent sampling was recorded in 1976. Beginning in the early 1980s, commercial fishers noted increasing populations of bigheaded carp and silver carp (collectively recognized as bigheaded carp). Populations of bigheaded carps appear to be increasing at a much slower rate than in the Midwest, possibly due to limited suitability of and access to backwater habitat for juvenile fish. In 2002, harvester reports of sporadic captures of "different-looking" grass carp indicated the possible presence of black carp. Because both normal diploid and triploid (in which triploidy has been induced to cause sterility) black carp have been stocked in the Mississippi basin, determination of the ploidy (number of chromosome sets) of these fish is important. Since 2002, postmortem ploidy determinations using cells from eyeballs removed from six wild black carp captured in Louisiana showed each to be a normal diploid, indicative of breeding capability and potential reproducing populations. Although reported commercial landings of grass and bighead carp have been as high as 34,830 kg/year, limited market demand in past years resulted in many captures being discarded. A protocol for obtaining samples for easily determining ploidy is reported here. Accurate data on Asian carp distributions and their reproductive potential provides information to fisheries researchers that will be constructive in documenting the spread of these invasive species and in the assessment of risk to habitats.

Distribution — Expansion

27.) Aitkin, J.K., Lohr, S., Heimowitz, P., Hill, M. 2008. Columbia River Basin Asian carps risk evaluation. U.S. Fish and Wildlife Service.

The West has been invaded by a number of aquatic invasive species: however, a new possible invader to the Pacific Northwest is a group of nonindigenous cyprinid fish known as the Asian or Chinese carps. These species have recently been addressed by the National Aquatic Nuisance Species Task Force via the "Management and Control Plan for Bigheaded, Black, Grass, and Silver Carps in the United States." Although that plan addresses national management, it does not focus heavily on the Pacific Northwest. This report is a cursory evaluation of environmental conditions and pathways of introduction to evaluate the potential for Asian carp arrival and subsequent survival and reproduction in the Columbia River basin. The authors focus on the lower Columbia River and conclude that habitat characteristics, water temperatures, discharge, and water velocity appear conducive for survival and reproduction of Asian carps. They also provide recommendations on future research (water hardness conditions and the effects on embryonic development) as well as recommending further education for stakeholders and the general public.

28.) Broennimann, O., Treier, U.A., Muller-Scharer, H., Thuiller, W., Peterson, A.T., Guisan, A. 2007. Evidence of climatic niche shift during biological invasion. *Ecology Letters* 10(8):701–709.

In this paper the authors use niche-based modeling to test the assumption that invasive species conserve their climatic niche in the invaded ranges by analyzing the climatic niche spaces of spotted knapweed in western North America and Europe. They show with robust cross-continental data that a shift of the observed climatic niche occurred between native and nonnative ranges, providing the first empirical evidence that an invasive species can occupy climatically distinct niche spaces following its introduction into a new area. The models fail to predict a current invaded distribution but correctly predict areas of introduction.

29.) Chen, P., Wiley, E.O., McNyset, K.M. 2006. Ecological niche modeling as a predictive tool: Silver and bighead carp in North America. *Biological Invasions* 9(1):43–51.

In this study the authors use the Genetic Algorithm for Rule-set Prediction (GARP) to model the niches of these two carps in their native ranges using hydrologic and general environmental parameters in concert with native distributional data. The results accurately predicted native occurrence data withheld from the modeling process.

The authors then projected the niche models onto the North American landscape. Native niche range models significantly predicted known occurrence data from North American introductions. Further, the models suggest that both species have the potential of spreading throughout the eastern U.S. and selected areas of the West Coast.

30.) Cudmore, B.C., Mandrak, N.E., Dettmers, J.M., Chapman, D.C., Kolar, C.S. 2012. Binational ecological risk assessment of bigheaded carps (*Hypophthalmichthys spp.*) for the Great Lakes Basin. DFO Can. Sci. Advis. Sec. Res. Doc. 2011/114. vi + 57 p.

A binational ecological risk assessment was conducted to provide scientifically defensible advice for managers and decision-makers in Canada and the United States. This risk assessment looked at the likelihood of arrival, survival, establishment, and spread of bigheaded carps to obtain an overall probability of introduction. Results of the risk assessment show that there is enough food and habitat for bigheaded carp survival in the Great Lakes, especially in Lake Erie and productive embayments in the other lakes. Analyses of tributaries around the Canadian Great Lakes and the American waters of Lake Erie indicate that there are many suitable tributaries for bigheaded carp spawning. To avoid the trajectory of the invasion process and prevent or minimize anticipated consequences, it is important to continue to focus efforts on reducing the probability of introduction of these species at either the arrival, survival, establishment, or spread stage (depending on location).

31.) DeVaney, S.C., McNyset, K.M., Williams, J.B., Peterson, A.T., Wiley, E.O. 2009. A tale of four "carp": Invasion potential and ecological niche modeling. *PLoS ONE* 4(5): e5451. doi:10.1371/journal.pone.0005451.

Predictive methods can be essential in the management and control of invasive species, by helping to determine which areas are of most concern. In this study the authors assessed the geographic potential of four Eurasian cyprinid fish (common carp, tench, grass carp, and black carp) as invaders in North America via ecological niche modeling (ENM). These carp represent four stages of invasion of the continent (a long-established invader with a wide distribution, a long-established invader whose distribution is expanding, and a newly introduced potential invader that is not yet established), and as such illustrate the progressive reduction of distributional disequilibrium over the history of species' invasions. Ecological niche modeling was used to estimate the potential distributional area for each species in North America using models based on native range and distribution data. Models were evaluated using independent validation data on native and invaded areas. Omission error was calculated for the independent validation data for each species and all native range tests were highly successful. Results showed that model omission was high for introduced tench populations; however, the model correctly identified some areas where the species has been successful. Distributional predictions for black carp show that large portions of eastern North America are at risk. ENMs predicted potential range of carp species accurately even in regions where the species have not been present until recently. ENM can forecast species' potential geographic ranges with reasonable precision and within the short screening time required by proposed U.S. invasive species legislation.

32.) Fuller, P.L. 2003. Freshwater aquatic vertebrate introductions in the United States: Patterns and pathways. Ruiz, G.M., and Carlton, J.T. (eds.), pages 123–151 *in* Invasive Species: Vectors and Management Strategies.

While the translocation of species has occurred for millennia and has many societal benefits, it also often has unforeseen impacts in native ecosystems. Today, there are very few freshwater ecosystems that have not been altered by introductions. In this chapter, the author examines patterns in time and space of freshwater vertebrate introductions (excluding birds) in the continental United States and the Hawaiian Islands. Furthermore, there is discussion whether the likelihood of a successful invasion can be correlated to pathways, making some recommendations about pathways of freshwater introductions and ways they can be managed to reduce numbers of aquatic introductions. This chapter primarily focuses on fish.

33.) Hayer, C.A., Graeb, B.D.S, Bertrand, K.N. 2014. Adult, juvenile, and young-of-year bigheaded, *Hypophthalmichthys nobilis* (Richardson, 1845), and silver carp, *H. molitrix* (Valenciennes, 1844), range expansion on the northwestern front of the invasion in North America. *BioInvasions Records* 3(4):283–289.

Asian carp (bigheaded and silver carp) were collected with boat electrofishing over 4 years in the three South Dakota tributaries to the Missouri River at the beginning of their invasion into this region. This paper documents their annual movement upstream into these tributaries and identifies differences in distribution by age-0, juvenile, and adults. By the end of the study in 2012, Asian carp dispersion was slowed or halted in these tributaries due to artificial and natural barriers. These records represent the northern most records of Asian carps in North America (46.931042, -98.708975).

34.) Jerde, C.L., Chadderton, W.L., Mahon, A.R. Renshaw, M.A., Corush, J., Budny, M.L., Mysorekar, S., Lodge, D.M. 2013. Detection of Asian carp DNA as part of a Great Lakes basin-wide surveillance program. *Canadian Journal of Fisheries and Aquatic Sciences* 70(4):522–526.

In this study the authors used environmental DNA (eDNA) sampling for the early detection of bigheaded and silver carp, which are in the early stages of invasion of the Great Lakes. Since 2009, 2,822 samples have been collected from the Great Lakes basin to delimit the extent of Asian carp incursions. Samples collected in the Chicago Area Waterway System and in the western basin of Lake Erie indicate the presence of Asian carp DNA in the Great Lakes. These positive eDNA detections are within 6 and 4 km from where bigheaded carp were recovered in Lake Calumet, near Lake Michigan (2010), and from Sandusky Bay, Lake Erie (2000), respectively.

35.) Jerde, C.L., Mahon, A.R., Chadderton, W.L. Lodge, D.M. 2011. "Sight-unseen" detection of rare aquatic species using environmental DNA. *Conservation Letters* 4(2):150–157.

Early detection of an incipient invasion by a harmful species increases the feasibility of rapid responses to eradicate the species or contain its spread. Here the authors demonstrate the efficacy of environmental DNA (eDNA) as a detection tool in freshwater environments. Specifically, the authors delimit the invasion fronts of two species of Asian carps in Chicago, Illinois, area canals and waterways. Quantitative comparisons with traditional fisheries surveillance tools illustrate the greater sensitivity of eDNA and reveal that the risk of invasion to the Laurentian Great Lakes is imminent.

36.) Rahel, F.J. and Olden, J.D. 2008. Assessing the effects of climate change on aquatic invasive species. *Conservation Biology* 22(3):521–533.

Here the authors present a conceptual framework and empirical review of the interactive effects of climate change and invasive species in freshwater ecosystems. The changes in climate will alter the pathways by which nonnative species enter aquatic systems. Climate change will influence the likelihood of new species becoming established by eliminating cold temperatures or winter hypoxia that currently prevent survival and by increasing the construction of reservoirs that serve as hotspots for invasive species. It may also modify the ecological impacts of invasive species by enhancing their competitive and predatory effects on native species and by increasing the virulence to some diseases. The findings in this study highlight the complex interactions between climate change and invasive species that will influence how aquatic ecosystems and their biota will respond to novel environmental conditions.

Natural History — Dispersal and Habitat

37.) Calkins, H.A., Tripp, S.J., Garvey, J.E. 2012. Linking silver carp habitat selection to flow and phytoplankton in the Mississippi River. *Biological Invasions* 14(5):949–958.

To quantify habitat selection relative to river flow and potential phytoplankton food, 77 adult silver carp were implanted with ultrasonic transmitters during spring 2008 through spring 2009 in adjacent upstream dammed and downstream undammed reaches (48 km total) of the Mississippi River. Sixty-seven percent of the fish were located. Selection of major river habitat features (dammed vs. undammed, backwaters, channel border, wing dikes, island side channels, and the main channel) was quantified. Flow rates and chlorophyll a concentration were compared between silver carp locations and random sites. Foregut chlorophyll a concentrations plus presence of macrozooplankton and detritus of 240 non-tagged silver carp were quantified. About 30 percent of silver carp moved upstream into the dammed reach, where average flow was slower and chlorophyll a concentration was higher. Silver carp selected wing dike areas of moderate flow and elevated chlorophyll a relative to random sites. No silver carp occurred in areas where flow was absent. Wing dikes were preferred while the main channel was avoided. Chlorophyll a concentrations in guts were positively related to temperature and were unrelated to flow or river chlorophyll a concentration. Macrozooplankton and detritus were rare in guts. Silver carp seek areas of low flow and successfully forage across a range of temperatures, flows, and chlorophyll a concentrations that occur in rivers and large lakes.

38.) DeGrandchamp, K.L., Garvey, J.E., Colombo, R.E. 2008. Movement and habitat selection by invasive Asian carps in a large river. *Transactions of the American Fisheries Society* 137(1):45–56.

In this study the authors evaluated the habitat use and movements of 50 adult bigheaded carp and 50 silver carp by means of ultrasonic telemetry during spring-summer 2004 and 2005 to gain insight into the conditions that facilitate their establishment, persistence, and dispersal in the lower Illinois River. The relative availability of four microhabitat categories (main channel, island side channel, channel border, and connected backwater) was quantified to determine selection; discriminant function analysis was used to evaluate changes in physical characteristics within each category. A flood pulse occurred in spring through early summer in 2004 but not 2005. Movement rates (km/week) of both species were positively correlated with flow but not with temperature. Including data from stationary receivers greatly increased estimates of daily movement. During low summer flow, both species typically selected channel borders and avoided the main channel and backwaters. Both species rarely occupied depths over 4 m, regardless of abiotic conditions. Flood pulse appears to trigger dispersal, while habitat use is only specific during low summer flow. These results suggest that movement prevention efforts (e.g., dispersal barriers) will require particular vigilance during late-winter or spring flooding, and controlled removal (e.g. harvest) should be directed toward selected habitats during summer.

39.) Garcia, T., Jackson, P.R., Murphy, E.A., Valocchi, A.J., Garcia, M.H. 2013. Development of a fluvial egg drift simulator to evaluate the transport and dispersion of Asian carp eggs in rivers. *Ecological Modeling* 263:211–222.

In this study the authors use FluEgg (Fluvial Egg Drift Simulator), a three-dimensional Lagrangian model capable of evaluating the influence of flow velocity, shear dispersion, and turbulent diffusion on the transport and dispersal patterns of Asian carp eggs. The results of this research support the identification of critical hydrodynamic conditions required to maintain eggs in suspension, assist in the evaluation of suitable spawning rivers for Asian carp populations, and facilitate the development of prevention, control, and management strategies for Asian carp species in aquatic ecosystems.

40.) Hoover, J.J., Southern, L.W., Katzenmeyer, A.W., Hahn, N.M. 2012. Swimming performance of bigheaded carp and silver carp: Methodology, metrics, and management applications. ANSRP Technical Notes Collection. ERDC/TN ANSRP-12-3. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

This study summarizes laboratory swim studies of two species of Asian carp, 36–334 mm total length, and suggests ways that swimming performance data can be used to contain these invasive species. Following their introduction in the Lower Mississippi River in the 1980s, both species have dispersed upriver toward the Great Lakes and laterally into floodplain wetlands and tributaries. Predicting rates and likelihood of carp dispersal and containing populations with hydraulic barriers (or other types of barriers) are options for managers, but quantitative data are required on the swimming performance of carp.

41.) Liss, S.A., Sass, G.G., Suski, C.D. 2013. Spatial and temporal influence on the physiological condition of invasive silver carp. *Conservation Physiology* 1(1):1–13.

Here the authors quantified nutritional and stress parameters (alkaline phosphate, cholesterol, protein, triglycerides, cortisol, and glucose) in invasive silver carp inhabiting four large rivers throughout three distinct time periods in the Midwestern United States. The analysis of the physiological condition of wild-caught silver carp across broad spatial and temporal scales is essential because stress and nutritional parameters can link individuals to their habitats and vary among populations across environments. During each time period, the authors collected blood samples from individual silver carp in the Illinois River and portions of the Mississippi, Ohio, and Wabash rivers in Illinois. Tests were conducted for relationships between silver carp nutrition and stress in three categories (across rivers, reaches within rivers, and time periods). Principle component analyses separated physiological parameters into a stress com-

ponent and two nutritional components representative of short-term feeding and body energy reserves. Akaike's information criterion suggested that time period had the greatest influence on stress. Stress levels were consistent in all four rivers and declined across time periods. Akaike's information criterion also suggested that interactions of time period and river had the greatest influence on short-term feeding and body energy reserves. There was no specific pattern across time periods within each river or across rivers. These results provide a better understanding of nutritional and stress conditions in silver carp across a broad landscape and temporal scale, with implications for managing and predicting the spread of this species.

42.) Lohmeyer, A.M. 2008. Larval Asian carp in the Upper and Middle Mississippi River: An index of establishment and dispersal potential. Thesis. Southern Illinois University.

To determine whether bigheaded and silver carp are able to successfully reproduce in navigation pools of the Upper Mississippi River (UMR) relative to the unimpounded lower reaches, the author compared the reproductive output of Asian carp between the pooled UMR and unpooled Middle Mississippi River (MMR) by quantifying larval densities and inferring survival to the juvenile stage. During May through August 2005 and 2006, larvae were sampled from the MMR and UMR Pools 26, 24, 22, and 20. Juveniles were sampled by seining in backwater sites in each of the UMR pools and in the MMR from July through September of 2005 and 2006. A total of 582 larval samples was collected with larval Asian carp occurring in only 25 samples. Peak density was greater in the MMR than in Pool 26, and spawn duration was longer in the MMR than in Pool 26. Larval production occurred with high or rising discharge after water temperatures reached 18°C. Sites that contained high densities of larval Asian carp also contained juveniles. No juveniles occurred in Pools 24, 22, or 20. The author concludes that current water level management in the UMR may limit larval production of Asian carp and subsequent recruitment to the juvenile stage during dry years.

43.) Peters, L.M., Pegg, M.A., Reinhardt, U.G. 2006. Movements of adult radio-tagged bigheaded carp in the Illinois River. *Transactions of the American Fisheries Society* 135(5): 1205–1212.

In this study, to better understand the rate of expansion in bigheaded carp, the authors used radiotelemetry to document movements of bigheaded carp within the LaGrange Reach of the Illinois River, Illinois. They surgically implanted transmitters into 42 adults in June 2003 and May–July 2004. Successful relocation of individuals decreased over time and ended in August of both years. They analyzed 132 observations from 23 adults and found a mean (±SE) movement rate of 1.70 ± 0.74 km/d. The highest movement rate was 14.33 km/d. The maximum distance traveled by an individual was 163 km upstream in 35 days, and the top 10 percent of movements as observed by boat were between 26.5 and 56.5 km within 3–10 days. 43 percent of fish died or dropped transmitters for unknown reasons, but handling, environmental conditions, or both may have contributed to the loss. This study was the first to document the movement rates and patterns of bigheaded carp within the United States and shows that adults are capable of moving considerable distances in a short time.

44.) Phelps, Q.E., Tripp, S.J., Herzog, D.P, Garvey, J.E. 2014. Temporary connectivity: The relative benefits of large river floodplain inundation in the Lower Mississippi River. *Restoration Ecology* 23: 53–56.

The New Madrid Floodway at the confluence of the Mississippi and Ohio Rivers was opened during the historic flooding of 2011, providing a unique opportunity to evaluate the influence of floodplain inundation on fish species diversity, relative abundance, and growth. The authors sampled the floodplain and the adjacent river at three stratified random locations with replication biweekly from commencement of inundation (late May) through early October. Their results showed that species diversity, relative abundance, and growth were higher in the floodplain than in the main channel, supporting previous studies that suggested floodplain inundation may be important for riverine fishes.

45.) Schrank, S.J., Braaten, P.J., Guy, C.S. 2001. Spatiotemporal variation in density of larval bigheaded carp in the lower Missouri River. *Transactions of the American Fisheries Society* 130(5): 809–814.

The objectives of this study were to examine the temporal and spatial variation in the density of bigheaded carp larvae and to estimate their spawning date in the lower Missouri River. The authors sampled larval fish once per week at four sites between White Cloud, Kansas, and Lexington, Missouri, from May through July 1997 and 1998. Density of larval bigheaded carp varied spatially and temporally. Density was greatest at the most downstream site (Lexington, Missouri) and lowest at the most upstream site (White Cloud, Kansas) in 1997. Bigheaded carp spawning occurred in three distinct periods (June 16–19, 1997; June 23–26, 1998; and July 3, 1998). Spawning in both years occurred in conjunction with an increase in discharge after water temperatures had stabilized above 22°C. These data suggest a link between water temperature and discharge as spawning cues and successful hatching criteria for bigheaded carp in the lower Missouri River.

46.) Varble, K.A., Hoover, J.J., George, S.G., Murphy, C.E., Killgore, K.J. 2007. Floodplain wetlands as nurseries for silver carp, *Hypophthalmichthys molitrix;* a conceptual model for use in managing local populations. ANSRP Technical Notes Collection (ERDC/TN ANSRP-07-4). Vicksburg, MS: U.S. Army Engineer Research and Development Center.

This study summarizes recent observations of silver carp in small wetlands of the Lower Mississippi River and suggests management actions for their control based on wetland hydrology and pattern of fish movements. The authors used hydrographs from 2003 and 2006 to determine periods of connectivity in a floodplain reach of the lower Mississippi River near Eagle Lake, north of Vicksburg, MS. Fish were collected via electrofishing and seine, then combined, to determine species composition and relative abundance of silver carp. Demographics of silver carp were studied by monthly sampling of the population. Jumping fish were enumerated by four observers, and counts were made from the downstream berm to the upstream berm, a distance of 3.8 km, as the boat traveled at a speed of 11 km/hr (previously determined to be the speed at which silver carp are stimulated to jump). Specimens that landed in the boat were measured and dissected to determine gender and reproductive state. The left pectoral fin ray was excised for age and growth determination. Paddlefish were also measured, weighed, and evaluated for robustness or condition to determine if any competition was present between paddlefish and silver carp. More than 20 species of fish were collected and were dominated taxonomically (7 species)

and numerically (nearly 50 percent) by sunfishes. Some planktivores were present but none were abundant: gizzard shad (9.5 percent), threadfin shad (1.5 percent), bigmouth buffalo (5.1 percent), and paddlefish (2.4 percent). Paddlefish were not robust. However, other population parameters appeared less variable. Overall, results showed that during most dates, females were slightly more abundant, larger, heavier, and more robust than males. None of the paddlefish collected in Forest Home Chute appeared robust, and, when compared with paddlefish collected from the Mississippi Delta, all were conspicuously underweight. The authors also sampled Pools 1–3 with results showing that silver carp were present in all three but were the only abundant fish in Pool 1. This study suggest that in the lower Mississippi River, nurseries may occur in main channel and oxbow habitats, but significant nurseries occur on the wetland floodplain and, in some cases, are remote from main channel spawning areas, possibly due to temperature requirements of young fish. Results also suggest that silver carp could be maturing at a faster rate and possibly are able to reproduce outside of the presumed spawning season in the United States (April to June). The large volume of plankton found in the fish indicates that shifts in plankton availability are inevitable. The authors believe that the reduction of plankton via silver carp may help explain the low numbers of shad present and the poor condition of paddlefish, implying some competition is occurring. In discussion, the authors go on to explain the requirements of silver carp for spawning and recruitment and provide a model based on their data with suggestions on how it may be used to prevent local recruitment. They also discuss the use of control structures and other management strategies (such as restoration-based measures) to reduce the likelihood of recruitment.

47.) Wilson, M.R. 2012. Habitat preference, dispersal, and population trends of three species of invasive Asian carps in tributaries of the La Grange reach of the Illinois River. Aquatic Nuisance Species Research Program. Final Report (ERDC/EL CR-12-2) U.S. Army Engineer Research and Development Center.

During the summer of 2009, a drainage-wide survey of the La Grange Reach of the Illinois River was conducted to determine the extent to which silver carp and bigheaded carp were utilizing first- through fourth-order streams in this system. Field sampling of 36 sites in 2009 produced a total of five grass carp and no other Asian carp specimens, indicating temporary nonresident utilization of small streams. Field data were combined with records from the Illinois Natural History Survey Fish Collection, Illinois Department of Natural Resources survey data, and the Long Term Resource Monitoring Program. Statistical analyses were performed to test for correlation of population trends between the Illinois River mainstem and its associated tributaries. Results revealed a positive relationship between annual mainstem and tributary population trends for grass carp and silver carp, as well as continually increasing population size for all three species in both mainstem and tributary populations.

Natural History — Reproduction

48.) Chapman, D.C., and Deters, J.E. 2009. Effect of water hardness and dissolved-solid concentration on hatching success and egg size in bigheaded carp. *Transactions of the American Fisheries Society* 138(6):1226–1231.

To evaluate whether soft water may cause the bursting of Asian carp eggs and possibly be a factor used to limit the spread of the species, the authors exposed fertilized eggs of bigheaded carp to waters with a wide range of hardness and dissolved-solid concentrations. Hatching rate and egg size were not significantly affected by different water qualities. These results suggest that caution should be used when treating hardness and dissolved-solid concentrations as limiting factors in management decisions.

49.) Coulter, A.A., Keller, D., Amberg, J.J., Bailey E.J., Goforth, R.R. 2013. Phenotypic plasticity in the spawning traits of bigheaded carp (*Hypophthalmichthys spp.*) in novel ecosystems. *Freshwater Biology* 58(5):1029–1037.

Due to the assumption that high phenotypic plasticity contributes to the invasive success of bigheaded carp in novel ecosystems, the authors collected drifting eggs from a Midwestern U.S. river from June to September 2011 and from April to June 2012 to investigate the spawning traits of bigheaded carp in novel ecosystems. Unlike reports from the native range, the presence of drifting eggs was not related to changes in hydrological regime or mean daily water temperature. Finding drifting eggs throughout the summer and as late as September 1, 2011, indicates that bigheaded carp are capable of protracted spawning. The authors also detected bigheaded carp eggs in a river reach where the channel is *c.* 30 m wide with a catchment area of 4,579 km^2, the smallest stream in which spawning has yet been documented. These findings provide direct evidence that bigheaded carp exhibit plastic spawning traits in novel ecosystems that may facilitate invasion and establishment in a wider range of river conditions than previously thought.

50.) DeGrandchamp, K.L., Garvey, J.E., Csoboth, L.A. 2007. Linking adult reproduction and larval density of invasive carp in a large river. *Transactions of the American Fisheries Society* 136(5):1327–1334.

In this study the authors quantified mean density of Asian carp larvae, mean monthly gonadosomatic index (GSI) of adult males and females, and number of eggs within mature females in the lower Illinois River during 2004 and 2005. During 2004, Asian carp larvae were found during 32 percent of sampling weeks; mean GSI and fecundity were relatively low for adults, probably reflecting partially spawned individuals and perhaps low reproductive investment. During the drought of 2005, larval stages were present during only one (5 percent) of the sampling weeks, where mean GSI and fecundity of adults were higher through summer. Females resorbed their eggs instead of spawning during this year. These results suggest that spawning conditions during low water periods may be unsuitable for Asian carps, inhibiting adult spawning and yielding few larvae. Spawning conditions during 2004 were better but still yielded low densities of larvae relative to native fish. Their data shows that reproduction in the lower Illinois River is linked to river flow and its impact on adult spawning decisions, but conditions for strong year-class production (i.e., high larval densities) may be rarer than previously expected.

51.) Deters, J.E., Chapman, D.C., McElroy, B. 2013. Location and timing of Asian carp spawning in the Lower Missouri River. *Environmental Biology of Fish* 96(5):617–629.

In this study the authors sampled for silver, bigheaded, and grass carp eggs in 12 sites on the Lower Missouri River and in six tributaries from May through July 2005 and May through June 2006 to examine the spatial and temporal dynamics of spawning activity. Eggs were categorized into thirty developmental stages. The authors estimated spawning times and locations based on developmental stage, temperature dependent rate of development, and water velocity. Spawning rate was higher in the daytime between 5 a.m. and 9 p.m. than at night. Spawning was not limited to a few sites, as has been reported for the Yangtze River (the natal habitat of the species), but more eggs were spawned in areas of high sinuosity. A sediment transport model was employed to estimate vertical egg concentration profiles and total egg fluxes during spawning periods on the Missouri River. Identification of substantial spawning activity within tributaries or at tributary confluences was not examined in this study.

52.) Duan, X., Liu, S., Huang, M., Qiu, S., Li, Z., Wang, K., Chen, D. 2009. Changes in abundance of larvae of the four domestic Chinese carps in the middle reach of the Yangtze River, China, before and after closing of the Three Gorges Dam. *Environmental Biology of Fish* 86:12–22.

A systematic study on the dynamics of the abundance of larvae of four domestic Chinese carps was performed from 1997 to 2005 in the middle reach of the Yangtze River. The authors calculated the relative abundance of fry drifting through the middle reach in the breeding seasons from early May to late June every year. Several environmental parameters related to the dynamics of larval abundance were also examined simultaneously. Their results clearly show that the construction of the Three Gorges Dam between the upper and middle reaches of the Yangtze River has had a drastic negative influence on the abundance of fish larvae, causing their numbers to decrease every year from 1997 to 2005.

53.) Jiang, W., Liu, H.Z., Duan, Z.H., Cao, W.X. 2010. Seasonal variation in drifting eggs and larvae in the upper Yangtze, China. *Zoological Science* 27(5): 402–409.

In this March 5–July 25, 2008, study ichthyoplankton drifting into the Three Gorges Reservoir from the upper reaches of the Yangtze River were sampled daily to investigate the species composition, abundance, and seasonal variation in early-stage fish in the area. Twenty-eight species were identified by analyzing fish eggs and larvae, and 14.16 billion individuals were estimated drifting through the sampling section during the investigation. Six peaks of drift density were identified during the sampling period, and a significant correlation was found between drift density and water discharge. The dominant species were different in each drift peak, indicating different spawning times for the major species. The total amount of four major Chinese carps that drifted through the sampling section was estimated at 0.88 billion, indicating an increase in the population sizes of these species in the upper reaches of the Yangtze River after construction of the Three Gorges dam. The authors suggest that these reaches have become the largest spawning area for the four major Chinese carps in the Yangtze River and provide important spawning sites for many species of fish.

54.) Murphy, E.A., and Jackson, P.R. 2013. Hydraulic and water-quality data collection for the investigation of Great Lakes tributaries for Asian carp spawning and egg-transport suitability. U.S Geological Survey Scientific Investigations Report 2013–5106, 30 p. http://pubs.usgs.gov/sir/2013/5106/.

Two Lake Michigan tributaries (the Milwaukee and St. Joseph Rivers) and two Lake Erie tributaries (the Maumee and Sandusky Rivers) were investigated to determine if these tributaries possess the hydraulic and water-quality characteristics required by Asian carps to allow successful spawning. Non-standard data-processing techniques, combined with detailed laboratory analysis of Asian carp egg characteristics, allowed an assessment of the transport capabilities of each of the four tributaries. Results suggested that all four tributaries exhibited potential settling zones for Asian carp eggs both within the estuaries and river mouths and within the lower 100 km of the river. Dams played a leading role in defining these settling zones, with the exception of dams on the Sandusky River. The impoundments created by many of the larger dams on these rivers acted to sufficiently decelerate the flows and allowed the shear velocity to drop below the settling velocity for Asian carp eggs, which would allow the eggs to fall out of suspension and settle on the bottom where it is thought the eggs would perish. The Milwaukee River exhibited only a short settling zone upstream of the Grafton Dam, whereas the St. Joseph and Maumee Rivers both had extensive settling zones behind major dams. These longer settling zones are likely to capture more eggs than shorter settling reaches. All four rivers exhibited settling zones at their river mouths, with the Lake Erie tributaries having much larger settling zones extending more than 10 km up the tributaries. While hydraulic data from all four rivers indicated settling of eggs is possible in some locations, all four rivers also exhibited sufficient temperatures, water-quality characteristics, turbulence, and transport times outside of settling zones for successful suspension and development of Asian carp eggs to the hatching stage before the threat of settlement. These observed data indicate that these four Great Lakes tributaries have sufficient hydraulic and water-quality characteristics to support successful spawning and recruitment of Asian carp. The data indicate that with the right temperature and flow conditions, river reaches as short as 25 km may allow Asian carp eggs sufficient time to develop to hatching. Additionally, examining the relation between critical shear velocity and mean velocity, egg settling appears to take place at mean velocities in the range of 15–25 centimeters per second, a much lower value than is generally cited in the literature. A first-order estimate of minimum transport velocity for Asian carp eggs in a river can be obtained by using mean flow depth and river substrate data; curves were constructed to show this relation. These finding would expand the number of possible tributaries suitable for Asian carp spawning.

55.) Papoulias, D.M., Chapman, D.C., Tillitt, D.E. 2006. Reproductive condition and occurrence of intersex in bigheaded carp and silver carp in the Missouri River. *Hydrobiologia* 571(1):355–360.

This paper discusses the reproductive biology of bigheaded and silver carp. The authors present evidence that indicates that bigheaded and silver carp in the Missouri River have a protracted spawning period that extends from early spring through fall and shows that some individual bigheaded and silver carp are spawning multiple times during reproductive season. Despite the successful maturation and reproduction of these two species, observations of intersex, atresia, and sterility were reported. The authors express that the reproductive abnormalities that were observed in this study should be considered when evaluating the environmental condition of the Missouri River relative to supporting a healthy fish fauna.

56.) Rach, J.J., Sass, G.G., Luoma, J.A., Gaikowski, M.P. 2010. Effects of water hardness on size and hatching success of silver carp eggs. *North American Journal of Fisheries Management* 30(1):230–237.

In this study the authors tested the effect of water hardness on silver carp egg enlargement and hatching success. Groups of newly fertilized eggs were placed in water at one of five nominal water hardness levels for 1 hour to harden. Egg groups were then placed in separate incubation vessels housed in two recirculation systems that were supplied with either soft or hard water to evaluate hatching success. Eggs that were initially placed in 50 mg/L water to harden were larger and had a greater probability of hatch than eggs hardened in other water hardness levels. Unlike the effect of water hardness during egg hardening, the water hardness during incubation appeared to have no effect on egg hatching success. This research suggests that water hardness may not be a limiting factor in the reproduction, recruitment, and range expansion of silver carp in North America.

Natural History – Growth, Feeding, & Survival

57.) Bitterlich, G., and Gnaiger, E. 1984. Phytoplanktivorous or omnivorous fish? Digestibility of zooplankton by silvercarp, *Hypophthalmichthys molitrix* (Val.). *Aquaculture* 40(3):261–263.

The authors examined the decomposition of small zooplankton, rotatoria and nauplii, to determine the selectivity of the filter-feeding silver carp via in-vitro incubation, in the fish's gut fluid. Results showed that all three species of plankton decomposed rapidly during incubation while algae remained unchanged. The gut content analysis erroneously suggests a phytoplanktivorous strategy, whereas omnivorous feeding may actually be required for maintaining positive energy balance in these stomachless fish.

58.) Chapman, D.C. (ed). 2006. Early development of four cyprinids native to the Yangtze River, China. U.S. Geological Survey Data Series 239, 51 p.

The paper presented in chapter 2, *A Study of the Early Development of Grass Carp, Black Carp, Silver Carp, and Bigheaded Carp in the Yangtze River, China*, describes the characteristics of 48 early developmental stages of the four famous domestic fish in the Yangtze River in China. The paper compares the morphological similarities and differences among the four species with about 200 original drawings. The results of this paper were mainly based on continuous observations of the early development of eggs and larvae of the four species collected from the upstream and middle sections of the Yangtze River between 1961 and 1963.

59.) Chapman, D.C., and George, A.E. 2011. Developmental rate and behavior of early life stages of bigheaded and silver carp. Scientific Investigations Report 2011–5076. U.S. Department of the Interior, U.S. Geological Society.

In this study bigheaded carp and silver carp were cultured to the one-chamber gas bladder stage under two different temperature treatments. The authors provide a photographic guide for bigheaded and silver carp embryonic and larval development, while also including notes about egg morphology and larval swimming behavior. Preliminary information on developmental time and hourly thermal units for each stage is also provided. Both carp species developed faster under warmer conditions. Developmental stages and behaviors are generally consistent with earlier research with the exception that strong vertical swimming immediately after hatching was documented in this report.

60.) Cooke, S.L., and Hill, W.R. 2010. Can filter-feeding Asian carp invade the Laurentian Great Lakes? A bioenergetics modeling exercise. *Freshwater Biology* 55(10)-2138–2152.

In this exercise the authors developed bioenergetics models, using parameters from Asian carp and other fish species, to explore the possibility that planktonic food resources are insufficient to support the growth of silver carp and bigheaded carp in the Great Lakes. The models estimated basic metabolic requirements of silver and bigheaded carp under various body sizes, swimming speeds, and reproductive stages. These requirements were then related to planktonic food resources and environmental temperatures to predict when and where silver and bigheaded carp may survive in the Great Lakes, and how far they may travel. The authors found that full-sized bigheaded carp require 61.0 kJ d^{-1} just to maintain their body mass at 20°C. Silver carp energy requirements were slightly higher. When applied to various habitats in the Great Lakes, their results suggest that silver and bigheaded carp will be unable to colonize most open-water regions because of limited plankton availability. However, in some circumstances, carp metabolism at lower temperatures may be low enough to permit positive growth even at very low rations. The results from this modeling simulation also suggest when and where Asian carp could become established in the Great Lakes.

61.) Cremer, M.C., and Smitherman, R.O. 1980. Food habits and growth of silver and bigheaded carp in cages and ponds. *Aquaculture* 20(1):57–64.

In order to investigate the food habits of silver and bigheaded carp, the authors conducted an analysis of the intestinal contents. Their results showed that silver carp consumed primarily phytoplankton, while bigheaded carp consumed large quantities of zooplankton and detritus in addition to phytoplankton. The size of particles filtered by bigheaded carp was larger than that filtered by silver carp. Artificial feed was readily consumed by bigheaded carp but not by silver carp. The authors indicated that no growth difference occurred for silver carp in fertilized ponds and ponds receiving artificial feed. However, their results did show that growth of bigheaded carp increased substantially with the addition of artificial feed. Their data also showed that silver carp grew more rapidly in cages than bigheaded carp.

62.) Dong, S., and Li, D. 1994. Comparative studies on the feeding selectivity of silver carp *Hypophthalmichthys molitrix* and bigheaded carp *Aristichthys nobilis. Journal of Fish Biology* 44(4):621–626.

In this study the authors showed that silver carp and bigheaded carp exhibited size-selection for food particles in aquarium experiments, but did not select their preferred species of plankton actively when they were distributed evenly in the water. This experiment also showed that these carp possess the capacity of selection for feeding areas. The removal rates of silver carp for smaller plankton were higher than those bigheaded carp. The removal rates of bigger plankton by bigheaded carp were higher than those of silver carp, but for plankton about 70 μm dia. the rates by these two species were almost equal.

63.) Esmaeili, H.R., and Johal, M.H. 2003. Age, growth, and fisheries of silver carp *Hypophthalmichthys molitrix* (Val., 1844) in Gobindsagar Reservoir, India. American Fisheries Society Syposium 38:127–138.

This paper discusses the importance and history of silver carp in the Middle East and provides a brief overview of the historical fish composition in the Gobindsagar Reservoir (native and introduced fauna), one of the largest and deepest reservoirs in India. The authors discuss the positive and negative impacts of the introduction of silver carp on the environment, economy, and native fish communities. They recognize that the overall composition has been significantly altered by its introduction, increasing from nil to 80.97 percent during the past two decades. The authors collected silver carp between 235 and 1,000 mm monthly from August 1998 to May 2000 using gill nets. They took measurements and calculations of total length, fork length, and standard length as well as recording the sex of each individual to determine length-weight relationships and to explore the functions of age and growth, and potential fisheries for silver carp. For age and growth studies, scales were removed and examined. A theoretical harvestable size was determined using statistical analysis by plotting and evaluating the crossing points of the following curves: length increment in percentage of length of the first growth season and length (by age-class) in percentage of the final growth season. Results showed that the average calculated weight showed an increasing trend with increase in age while, in contrast, the values of specific rate of weight increase decreased with the increase in age (except in age-class 8). They determined that the harvestable size of this fish is at the end of age-class 3 and onto age class 5. The authors conclude that while silver carp have done well in Gobindsagar, the effects on the native fauna have been negative, with the presence of competition for resources between the carp and the native fish being apparent. They also recognize that the grazing of copepod nauplii by silver carp disturbs Copepoda life history and thus causes poor performance of native fishes. The authors determine from their observations that temperature has great impact on growth rate and maturity of this fish. They also go on to discuss the phenomena of growth compensation in the Gobindsagar Reservoir and other Indian populations of silver carp.

64.) Garcia, L.M.B, Garcia, C.M.H., Pineda, A.F.S., Gammad, E.A., Canta, J., Simon, S.P.D., Hilomen-Garcia, G.V., Gonzal, A.C., Santiago, C.B. 1999. Survival and growth of bigheaded carp fry exposed to low salinities. *Aquaculture International* 7(4):241–250.

In this study bigheaded carp fry of various ages (11, 18, and 35 days post-hatch) were exposed to the low salinities. Practical indices of salinity tolerance assessed the effect of 96 h direct exposure to low salinities (0–16 percent). Mean and median survival times of fry decreased as salinity of rearing medium increased. Younger fry were less able to tolerate exposure to these salinities than their older cohorts. Median lethal salinity after 96 h revealed higher tolerance among 35-day-old fry (7.6 percent) than 11- (2.3 percent) and 18-day-old fry (6.0 percent), demonstrating that survival in saline water depends on age at initial exposure. Mean body weight of 18-day-old fry reared in 0 and 2 percent for 3 and 4 weeks was higher than for those reared in 4 and 6 percent for the same period. Growth over these periods was inversely related with the range of salinities tested. These results demonstrate that, despite their known stenohalinity, bigheaded carp fry possess some degree of osmoregulatory capability, allowing them to survive and grow in lakes that periodically are subjected to saltwater inflow.

65.) George, A.E., and Chapman, D.C. 2013. Aspects of embryonic and larval development in bighead carp *Hypophthalmichthys nobilis* and silver carp *Hypophthalmichthys molitrix*. PLoS ONE 8(8): e73829 doi:10.371/journal.pone.0073829.

In this study, the embryonic and larval development rates, size, and behaviors of bigheaded carp were tracked at two temperature treatments, one "cold" and one "warm." Developmental rates were computed using previously described stages of development and the cumulative thermal unit method. Both species have similar thermal requirements, with a minimum developmental temperature for embryonic stages of 12.1°C for silver carp and 12.9°C for bighead carp, and 13.3°C for silver carp larval stages and 13.4°C for bigheaded carp larval stages. Egg size differed among species and temperature treatments, as egg size was larger in bigheaded carp and "warm" temperature treatments. The larvae started robust upward vertical swimming immediately after hatching, interspersed with intervals of sinking. Vertical swimming tubes were used to measure water column distribution and ascent and descent rates of vertically swimming fish. Water column distribution and ascent and descent rates changed with ontogeny. Water column distribution also showed some diel periodicity. Developmental rates, size, and behaviors contribute to the drift distance needed to fulfill the early life history requirements of bigheaded carps and can be used in conjunction with transport information to assess invasibility of a river.

66.) Gu, B., Schell, D.M., Huang, X., Yie, F. 1996. Stable isotope evidence for dietary overlap between two planktivorous fish in aquaculture ponds. *Canadian Journal of Fisheries and Aquatic Sciences* 53(12):2814–2818.

Here the authors report stable carbon and nitrogen isotope values from five polyculture ponds in Zhanjiang, China, to determine carbon sources and trophic interactions between the two species. Their results indicated that fish growth was supported by phytoplankton production. Progressive increases in δ^{15}N from phytoplankton, zooplankton, to fish were indicated. Mean muscle δ^{15}N values of bighead were 0.4 to 2.3 percent higher than those for silver carp. These isotopic differences were less than the 3–4 percent expected from feeding on two adjacent trophic levels and suggested that there were various degrees of dietary overlap between the two species among the fish ponds. They estimated that, on the basis of an isotope model, silver carp and bighead carp obtained from 23 to 87 percent, with an average of 60 percent, of their food from the same trophic level.

67.) Jirasek, J., Hampl, A., Sirotek, D. 1981. Growth morphology of the filtering apparatus of silver carp (*Hypophthalmichthys molitrix*): I. Gross anatomy state. *Aquaculture* 26(1):41–48.

In planimetric studies on the filtering and respiratory parts of individual gill arches of the right-hand-side gill apparatus of 30 silver carps aged 1, 2, and 3 years, it was found that the area of the respiratory part increased from the first to the fourth gill arch in all age categories, and the area of the filtering part increased from the first to the third arch. The total area of the filtering part of the right-hand-side filtering apparatus was 390, 1,440, and 2,130 mm^2 in 1-, 2-, and 3-year-old silver carps. In 2- and 3-year-old fish, the increase corresponded to 264.5 and 439.2 percent, respectively. In the second year, the growth rate of the filtering part is 10 percent higher than that of the respiratory part. In the third year, the relative growth of the filtering part decreased while that of the respiratory part markedly increased. According to the authors' observations, the thick lamellae occur in those sites where the lamella is in contact

with the system of longitudinal trabeculae supporting the filtering apparatus from the lateral side. In contrast to a previous study that showed the ratio between the area of the filtering and respiratory parts of gill arches was 1.3:1 (and did not change with age), they found that in 2- and 3-year-old fish, the ratio between filtering and respiratory parts was 2:1 (in the first 2 years of life) and 3:2, respectively.

68.) Nuevo, M., Sheehan, R.J., Wills, P.S. 2004. Age and growth of the bigheaded carp *Hypophthalmichthys nobilis* (RICHARDSON 1845) in the middle Mississippi River. *Archiv für Hydrobiologie* 160(2):215–230.

An age and growth study was conducted on the bigheaded carp *Hypophthalmichthys nobilis* population from the middle Mississippi River (MMR) using pectoral fin ray cross-sections. Bigheaded carp (N = 92) were collected from the MMR and from Pool 26 (N = 40) during 1998 and spring of 1999. Length-frequency distributions were dominated by the 800–900 mm length class in both the MMR and Pool 26. Age classes 1–6 were represented in the MMR sample, and only ages 4–6 in the Pool 26 sample. Age 4 (1994 year class) was dominant in 1998 in the MMR. The mean condition factor (K) was 1.03 for all bigheaded carp collected, and ranged from 0.58 to 2.04. Condition factor was significantly higher for Pool 26 than for the MMR (ANOVA; $p \leq 0.0001$) but not significantly different between sexes (ANOVA; $p = 0.60$). Condition factor peaked in May and decreased sharply during June and July of 1998. An unconstrained von Bertalanffy growth equation was obtained. Growth was fast in both the MMR and Pool 26, but no significant differences in relative or absolute growth were found between the two populations. Bigheaded carp is much more abundant in the MMR than reported in the literature or commercial fisheries harvest reports. Recruitment of bigheaded carp from the MMR was not consistent, but fast growth (reaching 1 kg by age 2) and high abundance suggest that a commercial fishery for bigheaded carp could be sustained in the MMR.

69.) Omarov, M.O. 1970. The daily food consumption of silver carp *Hypophthalmichthys molitrix* (Val.). *Journal of Ichthyology* 10(3):425–426.

The objectives of this study were to determine the quantitative aspect of the nutrition of silver carp, daily food consumption, and daily feeding patterns. This experiment showed that silver carps feed most during daylight hours and far less at night. They feed most intensively between 4 and 8 a.m., when they consume 23.3 percent of their daily food consumption. Minimum feeding, 8.1 percent of the daily food consumption, is observed between 20 and 24 hours. They consume 25.1 percent of the daily food intake during the hours of darkness and 84.9 percent during the daylight hours. The daily food consumption was 17.2 percent of the weight of fish in the second year of life. It was found that, during the second year of life, food consumption was greater than in the fingerling stages. The authors consider that keeping the fish in a container during the experiment may have had adverse effects on the feeding conditions of the silver carps and concluded that the actual food consumption will be even greater.

70.) Phelps, Q.E., and Willis, D.W. 2013. Development of an Asian carp size structure index and application through demonstration. *North American Journal of Fisheries Management* 33(2):338–343.

In this study the authors used data from national and international published reports or manuscripts to develop standard length categories for four species of Asian carp. Due to the similarities in maximum reported size for bigheaded carp and grass carp, the authors propose the following standardized length categories for those two species: stock = 30 cm, quality = 54 cm, preferred = 68 cm, memorable = 89 cm, and trophy = 111 cm. Proposed black carp length categories are stock = 40 cm, quality = 72 cm, preferred = 90 cm, memorable = 118 cm, and trophy = 148 cm. Finally, they propose the following length categories for silver carp: stock = 25 cm, quality = 45 cm, preferred = 56 cm, memorable = 74 cm, and trophy = 93 cm. Existing data collected in the Illinois and Mississippi Rivers from 2003 to 2011 was used to evaluate silver carp proportional size distribution (PSD). Incremental PSD provided a temporal index of silver carp size structure in the Illinois River, and strong cohorts could be followed through the incremental PSD values over time. Traditional PSD provided a quantifiable, comparative index of silver carp size structure among two locations in the Mississippi River and one location in the Illinois River.

71.) Schrank, S.J., and Guy, C.S. 2002. Age, growth, and gonadal characteristics of adult bigheaded carp, *Hypophthalmichthys nobilis*, in the lower Mississippi River. *Environmental Biology of Fish* 64(4):443–450.

The objectives of this study were to assess age, growth, and gonadal characteristics of bigheaded carp in the Missouri River. Adult bigheaded carp in the authors' sample varied from age 3 to age 7, and length varied from 475 to 1050 mm. There was a large variation in length at age and, overall, bigheaded carp exhibited fast growth. The sample was dominated by bigheaded carp from the 1994 class. There was no difference in gonad development (i.e., gonadal somatic index [GSI], egg diameter) between winter and spring samples. Length of male bigheaded carp and GSI were not significantly correlated; however, females exhibited a positive linear relationship between length and GSI. In each ovary, egg diameter frequencies exhibited a bimodal distribution, indicating protracted spawning. Mean fecundity was 226,213, with a maximum fecundity of 769,964. Bigheaded carp in the Missouri River have similar life history characteristics to Asian and European populations.

72.) Smith, D.W. 1989. The feeding selectivity of silver carp, *Hypophthalmichthys molitrix* Val. *Journal of Fish Biology* 34(6):819–828.

In this study the effects of particle size, fish size, and temperature on the filtration rate of silver carp were determined. When feeding at 20°C on zooplankton and spherical particles (yeast, micronic beads, and pollen), 32-g silver carp filter particles larger than 70 µm at a maximum rate of 18.251 h^{-1}. For particles smaller than 70 µm, filtration rates (FR) decrease with decreasing particle size until there is no measured filtration for particles smaller than 10 µm. FR rise as fish size, particle size, and temperature increase. FR per unit biomass, however, fall as fish size increases. The results of these trials are consistent with the hypothesis that particle selection by silver carp is a mechanical, passive function of gill raker morphology.

73.) Spataru, P., and Gophen, M. 1985. Feeding behavior of silver carp *Hypophthalmichthys molitrix* Val. and its impact on the food web in Lake Kinneret, Israel. *Hydrobiologia* 120(1):53–61.

The authors sampled gut contents of silver carp from September to January and found they contained predominately zooplankton. Indices of electivity for zooplankton were positive from September to December and negative during January to August; results were vice versa for phytoplankton. They recognize that the accumulation of silver carp has likely contributed to the recent intensification of predation pressure of planktivorous fish on zooplankton in Lake Kinneret. They also acknowledge that silver carp compete with commercially valuable native fish species by feeding on the same zooplankton resources during summer and fall. Additionally, the grazing population of microcrustaceans is reduced at the time it is needed to prevent microalgae blooms. The authors conclude that market demands for silver carp are low, catchability of this fish is poor, and it can be cultured efficiently in ponds. They recommend the stocking of silver carp in Lake Kinneret should cease.

74.) Wanner, G.A., and Klumb, R.A. 2009. Length-weight relationships for three Asian carp species in the Missouri River. *Journal of Freshwater Ecology* 24(3):489–495.

The objectives of this study were to describe the length-weight relationships (condition) of Asian carp from 2003 to 2007 in the Missouri River downstream of Gavin's Point Dam, South Dakota, to St. Louis. All total, 388 bigheaded, 75 silver, and 111 grass carp were measured and weighed. Short bigheaded weighed significantly less in the upper Missouri River from Gavin's Point Dam to the Platte River compared to fish of the lower Missouri River from the Grand River to the Mississippi River. Conversely, long bigheaded carp in the upper Missouri River attained greater weights than fish of similar length downstream. Though not significant, condition similarly varied between the upper and lower Missouri River for silver carp and grass carp.

75.) Williamson, C.J., and Garvey, J.E. 2005. Growth, fecundity, and diets of newly established silver carp in the middle Mississippi River. *Transactions of the American Fisheries Society* 134(6):1423–1430.

During 2003, the authors determined the population status and potential impact of silver carp in the middle Mississippi River (MMR). They quantified growth, age structure, fecundity, and diets of silver carp sampled with trammel nets and AC electrofishing in main-channel areas. Mean length at age in the MMR exceeded that of populations in Asia by as much as 26 percent. Individuals were typically more than 1 year old and 230 mm total length, suggesting that small, young fish were absent. Individuals in this population matured earlier (age 2) than in the species' native range. Regardless of phytoplankton variation (using chlorophyll a as a surrogate) and zooplankton concentration at MMR sites, phytoplankton was consistently most abundant in diets. Silver carp are finding suitable resources within the MMR, allowing individuals to grow rapidly during early life, persist as adults, and successfully disperse upstream.

76.) Zhou, Q., Xie, P., Xu, J.W., Ke, Z., Guo, L. 2009. Growth and food availability of silver and bighead carp: Evidence from stable isotope and gut content analysis. *Aquaculture Research* 40(14):1616–1625.

A 2-year investigation of growth and food availability of silver and bigheaded carp was carried out using stable isotope and gut content analysis in a large pen in Meiliang Bay of Lake Taihu, China. Both silver and bigheaded carp exhibited significantly higher δ13C in 2005 than in 2004, which can probably be attributed to two factors: (a) the difference between isotopic compositions at the base of the pelagic food web and (b) the difference between the compositions of prey items and stable isotopes. The significantly positive correlations between body length, body weight, and stable isotope ratios indicated that isotopic changes in silver and bigheaded carp resulted from the accumulation of biomass concomitant with rapid growth. Because of the drastic decrease in zooplankton in the diet in 2005, silver and bigheaded carp grew faster in 2004 than in 2005. Bigheaded carp showed a lower trophic level than silver carp in 2005 as indicated by stable nitrogen isotope ratios, which was possibly explained by the interspecific difference between the prey species and the food quality of silver and bigheaded carp.

Natural History – Mortality and Diseases

77.) Bejerano, Y., Sarig, S., Horne, M.T., Roberts, R.J. 1979. Mass mortalities in silver carp *Hypophthalmichthys molitrix* (Valenciennes) associated with bacterial infection from handling. *Journal of Fish Diseases* 2(1):49–56.

The authors examined the mass mortalities in silver carp that were related to infections of handling lesions with *Proteus rettgeri*, a gram negative bacterium normally found in the gut of poultry. Poultry feces are used extensively to fertilize carp ponds, and experimental infections showed that the condition could be reproduced by scarification and exposure to the micro-organism or by its inoculation. However, the authors concluded that it is unlikely to be the only cause of such mortalities since any one of a wide variety of other gram-negative microorganisms could be expected to produce similar losses if presented with the opportunity.

78. Hoole, D., Bucke, D., Burgess, P., Wellby, I. 2008. Diseases of carp and other Cyprinid fishes. Wiley Online Library.

The contents of this book are presented in a digestible format that will help with the understanding of diseases associated with Cyprinid fishes. It considers both infectious diseases that are transmissible between fish and noninfectious diseases that include nutritional disorders and tumors.

79.) Wilcox, J. 2013. Parasites of invasive carp and native fish in the Wabash River. Thesis. Eastern Illinois University, Charleston, Illinois.

Parasites and pathogens are theorized to play an important role in determining the outcome of invasions by nonnative species, both as potential mediators of the population growth of invasive species and as invasive species themselves. This study examines and compares the abundance and species richness of digestive tract helminthes in native and nonnative fish of the lower Wabash River. The target species of this study are silver carp, common carp, gizzard shad, freshwater drum, quillback carpsucker, and river shiner. All were dissected to search for invasive parasites, evaluate the

potential for the invasive carp to be experiencing enemy release, and assess the impact of these invasive fish on the population dynamics of the overall community of fish parasites. An additional 29 silver carp from the Illinois River were also dissected, as part of a further search for parasites. No intestinal parasites were found in the 82 silver carp that were dissected, although several enteric helminthes were found in gizzard shad. Common carp were found to be infected with a single species of nematode, although at relatively low prevalence, intensity, and abundance. Both species of carp had lower rates of parasitism than reported from regions in which they have been established longer. Overall, the results are consistent with enemy release in silver carp, at both the geographic and community levels. The results for common carp were more ambiguous but did not rule out the potential for enemy release.

Environmental Effects – Plankton Communities

80.) Cooke, S.L., Hill, W.R., Meyer, K.P. 2009. Feeding at different plankton densities alters invasive bigheaded carp (*Hypophthalmichthys nobilis*) growth and zooplankton species composition. *Hydrobiologia* 625(1):185–193.

The purpose of this study was to determine how different plankton densities affect bigheaded carp biomass and how bigheaded carp affect zooplankton species composition. The authors conducted a 37-day indoor mesocosm experiment with high and low plankton treatments in the presence and absence of juvenile bigheaded carp. Carp lost weight in the low plankton treatment and gained weight in the high plankton treatment, suggesting that food availability may be a limiting factor to bigheaded carp growth in regions of low plankton densities. In the presence of carp, zooplankton shifted from Daphnia to copepod dominance, while in the absence of carp, Daphnia remained dominant. Chydorids and ostracods increased in the presence of carp, but only in the low plankton treatment, suggesting that the impact of bigheaded carp on zooplankton species composition may vary with zooplankton density. Chlorophyll was higher in the absence of carp than in the presence. Chlorophyll and zooplankton densities in many Great Lakes ecosystems are substantially lower than the low treatment conditions, so results suggest that Asian carp establishment in these regions may be unlikely.

81.) Domaizon, I., and Devaux, J. 1999. Experimental study of the impacts of silver carp on plankton communities of eutrophic Villerest reservoir (France). *Aquatic Ecology* 33(2):193–204.

In this experiment the authors examined the impact of five silver carp biomass levels on plankton communities and water quality of eutrophic Villerest reservoir (France) using outdoor mesocosms. The presence of silver carp led to changes in zooplankton and phytoplankton assemblages. High fish biomass strongly reduced cladoceran abundance (through predation). Silver carp inefficiently grazed down particles < 20 µm. More importantly, however, the suppression of herbivorous cladocerans resulted in the increase of small algae, which were relieved from grazing and benefit from high nutrient concentrations. In contrast, in mesocosms without fish, the dominance of cladocerans (mainly Daphnia) controlled small algae and probably also larger algae (colonial chlorophytes, cyanobacteria). Thus, the Secchi disc transparency increased markedly. Through cascade effects, the modification of grazer communities led to changes in the utilization patterns of the added nutrients by phytoplankton communities. In high fish biomass treatments, nutrients were more efficiently accumulated into particulate fractions compared with no-fish and low-fish biomass treatments that were characterized by higher dissolved nutrient concentrations. Zooplankton was an essential source of food for silver carp. The productivity of zooplankton sustained a moderate silver carp biomass. In the presence of the highest fish biomass, the productivity of zooplankton was not large enough, and silver carps fed on additional phytoplankton. Although mesocosms with high fish biomass were characterized by a slight cyanobacteria development compared with other fish mesocosms, silver carp was not effective in reducing cyanobacteria dominance.

82.) Fukushima, M., Takamura, N., Sun, L., Nakagawa, M., Matsushige, K., Xie, P. 1999. Changes in the plankton community following introduction of filter-feeding planktivorous fish. *Freshwater Biology* 42(4):719–735.

Enclosure experiments in a shallow eutrophic lake, in which a biomass gradient of silver carp was created, and subsequent community changes in both zooplankton and phytoplankton were examined. During a summer experiment, a bloom of Anabaena flos-aquae developed solely in an enclosure without silver carp. Concurrent with or slightly preceding the Anabaena bloom, the number of rotifer species and their abundance increased from seven to 12 species after the bloom in this fish-free enclosure. Protozoans and bacteria were generally insensitive to the gradient of silver carp biomass. During an autumn experiment, on the other hand, large herbivorous crustaceans were more efficient than silver carp in suppressing the algae, partly because the lower water temperature (≈ 24 °C) inhibited active feeding of this warm-water fish and also formation of algal colonies. Heterotrophic nanoflagellate and bacterial densities were also influenced negatively by the crustaceans. Correspondence analysis was applied to the weekly community data of zooplankton and phytoplankton. A major effect detected in the zooplankton community was the presence/absence of silver carp rather than the biomass of silver carp. The major effect detected in the phytoplankton community before the Anabaena bloom was the fish biomass, but this shifted to the presence/absence of the fish after the bloom.

83.) Guangjie, Z., Xuemin, Z., Yonghong, B., Zhengyu, H. 2011. Effects of silver carp (*Hypophthalmichthys molitrix*) on spring phytoplankton community structure of Three Gorges Reservoir (China): Results from an enclosure experiment. *Journal of Limnology* 70(1):26–32.

In this study, an enclosure experiment was conducted to assess the impact of silver carp on the plankton community structure and water quality of the Three Gorges Reservoir from April 2 to May 2, 2008. The field experiment was performed in six enclosures. Stocking silver carp into enclosures caused a dramatic change in the aquatic ecosystem. For example, pH, transparency, dissolved oxygen, and phosphate were reduced, while chlorophyll a concentration and turbidity increased dramatically. Furthermore, during the enclosure experiment, some zooplankton such as rotifer and copepoda were significantly reduced, and some phytoplankton and protozoa were significantly increased by silver carp. The predation by silver carp might have increased phytoplankton biomass through reducing the densities of some zooplankton, which directly fed on phytoplankton. It was concluded that silver carp was not suitable for clearing spring phytoplankton (<20 µm) blooms in the Three Gorges Reservoir at the present time.

84.) Lu, M., Xie, P., Tang, H., Shao, Z., Xie, L. 2002. Experimental study of trophic cascade effect on silver carp (*Hypophthalmichthys molitrixon*) in a subtropical lake, Lake Donghu: On plankton community and underlying mechanisms of changes of crustacean community. *Hydrobiologia* 487(1):19–31.

An enclosure experiment was carried out to test trophic cascade effect of filter-feeding fish on the ecosystem, growth of crustacean zooplankton, and possible mechanism of changes of crustacean community structure. Four fish biomass levels were set as follows: 0, 116, 176 and 316 g m^{-2}, and lake water (containing ca. 190 g m^{-2} of filter-feeding fishes) was comparatively monitored. Nutrient levels were high in all treatments during the experiment. Lowest algal biomass were measured in fishless treatment. Algal biomass decreased during days 21–56 as a function of fish biomass in treatments of low (LF), medium (MF), and high (HF) fish biomass. Crustacean biomass decreased with increasing fish biomass. Small-bodied cladocerans, *Moina micrura, Diaphanosoma brachyurum,* and *Scapholeberis kingii* survived when fish biomass was high, while large-bodied cladocerans *Daphnia spp*. and the cyclopoids *Theromcyclops taihokuensis*, *T. brevifuratus*, *Mescyclops notius,* and *Cyclops vicinus* were abundant only in MF enclosures. Evasive calanoid *Sinodiaptomus sarsi* was significantly enhanced in LF but decreased significantly with further increase of fish biomass. Demographic data indicated that *M. micrura* was well developed in all treatments. This study indicates that algal biomass might be controlled by silver carp biomass in eutrophic environments. Changes of crustacean community are probably affected by the age of the first generation of species. Species with short generation time were dominant, and species with long generation time survived less with high fish biomass. Evasive calanoids hardly developed in treatments with high fish biomass because of the (bottle neck) effect of nauplii. Species abundance was positively related to fish predation avoidance. Other than direct predation, zooplankton might also be suppressed by filter-feeding fish via competition.

85.) Ma, H., Cui, F., Liu, Z., Fan, Z., He, W., Yin, P. 2010. Effect of filter-feeding fish silver carp on phytoplankton species and size distribution in surface water: A field study in water works. *Journal of Environmental Science* 22(2):161–167.

In this study silver carp were introduced into a pre-sedimentation pond to control excessive phytoplankton in raw water to investigate its effectiveness on phytoplankton control and its effect on the phytoplankton community. The results showed that *Microcystis* could be effectively removed by silver carp stocked in the pre-sedimentation pond and, simultaneously, the concentration of single-cell phytoplankton increased obviously. The difference in phytoplankton species and single-cell phytoplankton size between in the water and in the gut of silver carp indicated that phytoplankton smaller than 5 μm, such as *Chamydomonas* and *Platymonas*, could not be filtered by silver carp; phytoplankton between 5 and 20 μm could be partly filtered; and large phytoplankton, mainly colony-forming *Microcystis,* could be filtered almost completely. These filter-feeding characteristics directly caused the phytoplankton size distribution biased toward miniaturization. Therefore, this biological treatment using silver carp could be applied only to deal with groups of *Microcystis*-dominated eutrophic water and is not appropriate in water bodies where single-cell micro phytoplankton are dominant.

86.) Pongruktham, O., Ochs, C., Hoover, J.J. 2010. Observations of silver carp (*Hypophthalmichthys molitrix*) planktivory in a floodplain lake of the lower Mississippi River basin. *Journal of Freshwater Ecology* 25(1):85–93.

To assess the impacts of silver carp on connected backwater lakes and wetlands, which serve as critical sites for feeding and growth for many native fish species due to their high primary production, the authors examined the composition of plankton samples and of alimentary tract (gut) contents collected from an oxbow lake in Mississippi, Forest Home Chute. In the water-column, the most common types of phytoplankton were euglenoid algae, cyanobacteria, and diatoms. The vast majority of zooplankton was rotifers with densities sometimes exceeding 7,000 organisms per liter. Very high concentrations of phytoplankton in the gut, relative to in the water-column, indicate substantial consumption of phytoplankton. In October 2006, euglenoid phytoplankters were a much greater, and cyanobacteria a much lesser, proportion of prey in the fish gut compared to their proportions in the water-column. In December, however, there was no evidence of selective consumption by the silver carp population. Some of the phytoplankters observed in the lowest portion of the gut, including pinnate diatoms and euglenoid algae, were motile, indicating they had survived transit through the 5- to 7-m long gut tract. There was no evidence of rotifer survival of gut passage. By its high consumption of plankton, possible selective planktivory, and differential digestion of consumed phytoplankton and zooplankton, the silver carp may be altering the food web structure of these important connected lakes.

87.) Radke, R.J., and Kahl, U. 2002. Effects of a filter-feeding fish [silver carp, *Hypophthalmichthys molitrix* (Val.)] on phyto- and zooplankton in a mesotrophic reservoir: Results from an enclosure experiment. *Freshwater Biology* 47(12):2337–2344.

In this study the authors conducted an enclosure experiment to test how a moderate biomass of silver carp affects phytoplankton and crustacean zooplankton in a mesotrophic temperate reservoir. Phytoplankton biomass <30 μm and particulate organic carbon (POC) <30 μm were significantly higher in enclosures with silver carp than in enclosures without fish, whereas Secchi depth was lower. Total copepod biomass declined strongly in both treatments during the experiment, but it was significantly higher in fish-free enclosures. Daphnid biomass was also consistently higher in enclosures without fish, although this effect was not significant. However, the presence of fish led to a fast and significant decrease in the size at maturity of *Daphnia galeata Sars*. Thus, the moderate biomass of silver carp had a stronger negative effect on cladoceran zooplankton than on phytoplankton. Based on these results and those of previous studies, the authors conclude that silver carp should be used for biomanipulation only if the primary aim is to reduce nuisance blooms of large phytoplankton species (e.g., cyanobacteria) that cannot be effectively controlled by large herbivorous zooplankton.

88.) Shao, Z., Xie, P., Zhuge, Y. 2001. Long-term changes in planktonic rotifers in a subtropical Chinese lake dominated by filter-feeding fishes. *Freshwater Biology* 46(7):973–986.

The long-term changes (1956–1998) in density and species composition of planktonic rotifers were studied at two sampling stations (I, II) of Lake Donghu, a shallow eutrophic Chinese Lake densely stocked with filter-feeding fishes. Annual average densities of rotifers increased with an increase in fish yield and eutrophication, while species number decreased from 82 in 1962–63 to 62 in 1994–98. During 1962–98, some species such as *Anuraeopsis fissa*, *Polyarthra spp*. (including *P. dolichoptera* & *P. vulgaris*), *Tri-*

chocerca pusilla, and *Synchaeta oblonga* increased their percentage in abundance remarkably, while the proportion of *Keratella cochlearis* decreased at two relatively eutrophic stations from 19 to 4.2 percent at Station I and from 30 to 3.2 percent at Station II. Small rotifers were less vulnerable to fish predation than large-sized cladocerans. Decreases in cladocerans coincided with increases in rotifers, suggesting that the indirect effect of fish predation on cladocerans might have partly contributed to the population development of rotifers in Lake Donghu during recent decades. The authors also conducted surveys (1994–98) of seasonal dynamics of rotifers at four sampling stations (I–IV) that have varied in trophic status after fragmentation of the lake in the 1960s. A total of 75 species were identified at the four stations. Both densities and biomass of rotifers were considerably higher in the two more eutrophic stations than in the two less eutrophic stations. This indicates that the population increase of rotifers at Stations I and II during recent decades might be partly attributed to eutrophication of the lake water.

89.) Wu, L., Xie, P., Dai, M., Wang, J. 1997. Effects of silver carp density on zooplankton and water quality: Implications for eutrophic lakes in China. *Journal of Freshwater Ecology* 12(3):437–444.

In this study the authors examined the responses of zooplankton community, water transparency, chlorophyll a, and nutrients to manipulation of density of silver carp in a one-way factorial experiment using enclosures placed in Donghu located in Wuhan, P. R. China. Enclosures were treated with four silver carp densities. Total zooplankton abundance (excluding nauplii and rotifers except for *Asplanchna sp*.) and the mean size of dominant cladoceran species were significantly greater in enclosures with 0 and 81 fish densities than those in enclosures with 225 and 485 fish densities. Water transparency also improved significantly when silver carp densities were 0 or 81 g/m^2. The authors did not find any significant effects of silver carp density on chlorophyll a, total phosphorus, or total nitrogen concentrations.

Environmental Effects – Fish Communities

90.) Arthur, R.I., Lorenzen, K., Homekingkeo, P., Sidavong, K., Sengvilaikham, B., Garaway, C.J. 2010. Assessing impacts of introduced aquaculture species on native fish communities: Nile tilapia and major carps in SE Asian freshwaters. *Aquaculture* 299(1):81–88.

To quantify the impact of tilapia and carp stocking on native fish communities in freshwater wetlands of the Mekong region, the authors conducted observational and experimental impact-control studies replicated at the wetland level, at a total of 46 sites in Lao PDR. The studies were designed as paired comparisons of wetlands where the nonnative species, Nile tilapia and bigheaded carp, were stocked in substantial numbers with similar wetlands where the species were absent. Stocking of these nonnative species was associated with significant increases in total fish biomass, by 180 percent in the observational study and by 49 percent in the experiment. Native fish biomass was not affected by stocking of the nonnative species. No significant impacts on native fish species richness, diversity indices, species composition, or feeding guild composition were detected, except for moderately negative effects on Simpson diversity and equitability in the observational study. In the experiment, no effect had a point estimate exceeding − 14 percent, or a 95 percent confidence limit exceeding − 35 percent of the non-impacted value. Use of these nonnative tilapia and carp species in fisheries enhancement in mainland SE Asia supported substantial increases in harvestable biomass while having only mild impacts on native fish communities.

91.) Dettmers, J.M., Gurtreuter, S., Wahl, D.H., Soluk, D.A. 2001. Patterns in abundance of fish in main channels of the upper Mississippi River system. *Canadian Journal of Fisheries and Aquatic Sciences* 58(5):933–942.

In this study the authors used a bottom trawl to estimate spatial and temporal patterns in abundance in the navigation channels of Pool 26 of the Mississippi River and the lower Illinois River. Total biomass density averaged 21 and 29 kg· ha^{-1} in the navigation channels of Pool 26 and the lower Illinois River, respectively. The authors identified spatial and temporal patterns in catches of key species using a generalized linear model based on the negative binomial distribution. Some species, including shovelnose sturgeon, are persistent residents of the main channel. Multiple-season residents, including freshwater drum, rely heavily on the main channel during most of the year but leave it briefly. The authors go on to recommend revision of the prevailing notion that main channels of large temperate rivers serve mainly as corridors for movement among other habitat types.

92.) Hayer, C.A. 2014. Fish assemblage structure, trophic ecology, and potential effects of invading Asian carps in three Missouri River tributaries, South Dakota. Dissertation. South Dakota State University.

This author found that, historically, assemblage structure of eastern South Dakota tributaries to the Missouri River (i.e., James, Vermillion, Big Sioux Rivers) was persistent and displayed signs of biotic resistance. Silver carp population abundance increased each year of sampling (e.g., 2009–12), comprising 45 percent of catches in 2012; however, bigheaded carp did not follow this same pattern, as catches remained minimal during this period. Additionally, the population of silver carp displayed erratic recruitment in that 91 percent of catches were dominated by the 2010 class. Distribution into eastern South Dakota tributaries was stopped by three substantial dams, preventing further natural spread. Isotope analysis and diet analysis revealed that silver carp and gizzard shad overlapped trophically, and the isotopic trophic niche of emerald shiner, which is usually pelagic, potentially moved to more benthic habitats and food sources as a result of silver carp presence. There were no perceived effects of silver carp on bigmouth buffalo, however. With continued population increases of silver carp, the potential for competition for plankton resources becomes greater, and trophic impacts may become more pronounced, especially for gizzard shad and emerald shiner.

93.) Holland, L.E. 1986. Distribution of early life history stages of fish in selected pools of the Upper Mississippi River. *Hydrobiologia* 136(1):121–130.

Little is known about the use of nursery areas by fish in the Upper Mississippi River. Of the nearly 130 species identified in the adult ichthyofauna, only a few are represented proportionally in the available data on early life stages because study designs have not included consideration of the early stages, collection gears have not adequately sampled the young, and eggs and larvae of some species are difficult to sample by conventional approaches. For the species collected, information is available on seasonal variations in total densities, composition, and catch among different habitat types.

However, the data are most accurate for species with buoyant early life stages, such as freshwater drum and gizzard shad. Eggs and larvae of freshwater drum dominate collections made in the main channel, whereas other larval fish are usually most abundant in backwater habitats. The species found there usually deposit eggs on the substrate or on vegetation. Habitat preferences (as indicated by relative abundance) often shift as development proceeds and physical and behavioral changes occur in the larvae. Only limited information is available on the distribution of larvae within habitats, but it is clear that variations within habitats are significant.

94.) Irons, K.S., Sass, G.G., McClelland, M.A., Stafford, J.D. 2007. Reduced condition factor of two native fish species coincident with invasion of non-native Asian carps in the Illinois River, U.S.A. Is this evidence for competition and reduced fitness? *Journal of Fish Biology* 71(sD):258–273.

Due to the evidence of dietary overlap among bigheaded and silver carps with gizzard shad and bigmouth buffalo, total length and mass data from c. 5,000 fish were used to test for changes in body condition of gizzard shad and bigmouth buffalo post-Asian carp establishment, as well as to investigate potential competitive interactions and changes in fitness. Analyses revealed significant declines in body condition of gizzard shad (-7 percent) and bigmouth buffalo (-5 percent) following the Asian carps invasion from 2000 to 2006. Segmented regression analyses showed no significant change in the rate of decline in gizzard shad condition after 2000, whereas the rate of decline in bigmouth buffalo condition increased significantly after 2000. Statistically significant differences in gizzard shad condition after Asian carps establishment (2000–06) was observed, whereas condition of bigmouth buffalo was significantly lower in all years following Asian carp's establishment as compared to 2000. Declines in gizzard shad and bigmouth buffalo condition were significantly correlated with increased commercial harvest of Asian carps and poorly correlated with other abiotic and biotic factors (e.g., temperature, chlorophyll a, and discharge) that may influence fish body condition. These results may suggest that Asian carps are influencing native planktivore body condition, and future research should focus on determining whether food is limited in the Illinois River for native planktivores and other fish species.

95.) Koel, T.M. 2004. Spatial variation in fish species richness of the upper Mississippi River system. *Transactions of the American Fisheries Society* 133(4):984–1003.

The objectives of this study were to describe patterns of fish species richness, evenness, and diversity among representative habitats and river reaches and to examine the relationship between fish species richness and habitat diversity. Each year (1994–99), fish communities of main-channel borders (MCB), side channel borders (SCB), and contiguous backwater shorelines (BWS) were sampled. A total of 0.65 million fish were collected, representing 106 species from the upper Mississippi River. Within pools, species richness based on rarefaction differed significantly among habitats and was highest in BWS and lowest in MCB. At the reach scale, Pools 4, 8, and 13 consistently had the highest species richness; Pool 26, the open-river reach, and the La Grange Reach were significantly lower. Species evenness and diversity indices showed similar trends. The relationship between native fish species richness and habitat diversity was highly significant.

96.) Pegg, M.A., Chick, J.H., Pracheil, B.M. 2009. Potential effects of invasive species on paddlefish. American Fisheries Society Symposium 66:000–000.

This paper discusses potential negative interactions between invasive species and paddlefish, where the outcome is reduced abundance, fitness, growth, or extirpation. These negative interactions can come from direct competition for resources, vectors for the spread of disease or parasites, and subtle effects such as altering the flow of energy within and among other trophic levels. The authors recognize that the most prominent invasive threat to paddlefish may be from fellow filter-feeders bigheaded and silver carp because they consume similar food resources, possibly displace other pelagic species, and can also change the plankton community to one that cannot be as efficiently used by paddlefish. They also acknowledge that these two carp species have had a negative influence on native fish communities in other parts of the world and have been shown to negatively interact with juvenile paddlefish in North America. They conclude with discussion on response plans, which implement movement barriers for removal of invasive species and may also have ramifications for paddlefish in that they restrict movement patterns or reduce abundances as bycatch through harvest schemes.

97.) Sampson, S.J., Chick, J.H., Pegg, M.A. 2009. Diet overlap among two Asian carp and three native fish in backwater lakes on the Illinois and Mississippi Rivers. *Biological Invasions* 11(3):483–496.

In this study the authors examined diet overlap and electivity of Asian carp and three native filter-feeding fishes, bigmouth buffalo, gizzard shad, and paddlefish, in backwater lakes of the Illinois and Mississippi Rivers. Rotifers, *Keratella spp*., *Brachionus spp*., and *Trichocerca spp*., were the most common prey items consumed by Asian carp and gizzard shad, whereas crustacean zooplankton were the preferred prey of paddlefish. Bigmouth buffalo diet was broad, including both rotifers and crustacean zooplankton. Dietary overlap with Asian carp was greatest for gizzard shad followed by bigmouth buffalo, while little overlap was found for paddlefish. Diet similarity based on taxonomy correlated strongly with diet similarity based on size, suggesting filtration efficiency influenced the overlap patterns observed. Although rotifers were the most common prey item consumed by both bigheaded and silver carp, the authors found a negative relation between silver carp CPUE and cladoceran density. The competitive effect of Asian carp on native fish may be forestalled because of the high productivity of Illinois and Mississippi River habitats, yet the potential for negative consequences of Asian carp in less productive ecosystems, including Lake Michigan, should not be underestimated.

98.) Schrank, S.J., Guy, C.S., Fairchild, J.F. 2003. Competitive interactions between age-0 bigheaded carp and paddlefish. *Transactions of the American Fisheries Society* 132(6):1222–1228.

The objectives of this study were to experimentally test for competitive interactions between age-0 bigheaded carp and age-0 paddlefish. Differences among water chemistry variables, invertebrate densities, and relative growth of fish were assessed in mesocosms. Water chemistry variables were similar among treatments throughout the experiment and only exhibited a temporal effect. Zooplankton density declined in mesocosms after fish were introduced. In general, zooplankton densities did not differ among treatments but did differ from the control. The relative growth of paddlefish was negative in the paddlefish and paddlefish–bigheaded carp treatments. The relative growth of bigheaded carp was negative in the bigheaded carp treatment but positive in the paddlefish–bigheaded

carp treatment. Age-0 paddlefish exhibited the greatest decrease in relative growth in mesocosms with bigheaded carp. Bigheaded carp exhibited the greatest increase in relative growth in mesocosms with paddlefish. Their data suggest that bigheaded carp have the potential to negatively affect the growth of paddlefish when food resources are limited.

99.) Yallaly, K.L., Seibert, J.R., Phelps, Q.E. 2014. Synergy between silver carp egestion and benthic fishes. *Environmental Biology of Fish* 98(2):511–516.

In this study the authors investigate if an alternative feedback loop exists between Asian carps and native fishes. They postulate that silver carp consuming small planktonic particles with low assimilation efficiency can egest larger, nutrient-rich fecal pellets consumable by other fauna, which may have otherwise been unavailable. To evaluate this feedback loop, they extracted fecal pellets from the hindgut of silver carp. Fecal pellets were fed to age-0 channel catfish and blue catfish (i.e., < 130 mm) in a controlled laboratory setting. Both species of catfish consumed the fecal pellets and subsequently survived and increased in body mass over the 20-day trial period. Their results suggest that a potential alternative feedback loop may exist between silver carp and members of the benthic community and therefore provide a pathway by which nutrients are translocated between habitats (strata). The authors suggest that undigested plankton consumed by silver carp can be converted into nutrient packed pellets and may provide an additional food source to benthic organisms such as age-0 channel catfish and age-0 blue catfish.

Environmental Effects – Fish Communities (Buffalofish)

100.) McComish, T.S. 1967. Food habits of bigmouth and smallmouth buffalo in Lewis and Clark Lake and the Missouri River. *Transactions of the American Fisheries Society* 96(1):70–74.

Although definitive information on the food habits of bigmouth buffalo is available, none has been reported from a main-stem Missouri River reservoir. The smallmouth buffalo reports mentioned represent observations and not detailed microscopic examination. This paper includes the microscopic qualitative and quantitative examination of the food of 386 bigmouth and 277 smallmouth buffalo and includes information on young-of-the-year, subadult, and adult stages.

101.) Minckley, W.L., Johnson, J.E., Rinne, J.N., Willoughby, S.E. 1970. Foods of buffalofishes, genus *Ictiobus*, in central Arizona reservoirs. *Transactions of the American Fisheries Society* 99(2):333–342.

Intestinal tracts of 541 buffalofish (428 bigmouth, 57 black, and 56 small-mouth) caught in 1966–69 in central Arizona reservoirs were analyzed. The authors found that bigmouth buffalo from Roosevelt and Apache Lakes fed mostly on planktonic algae and crustaceans, with indications of a near-bottom-feeding habit. Black and smallmouth buffalo fed on benthic macro-invertebrates, with mollusks being the most important group utilized by both species.

Environmental Effects – Fish Communities (Gizzard Shad)

102.) DeVries, D.R., and Stein, R.A. 1992. Complex interactions between fish and zooplankton: Quantifying the role of an open-water planktivore. *Canadian Journal of Fisheries and Aquatic Sciences* 49(6):1216–1227.

In an enclosure/exclosure experiment, young-of-year gizzard shad at lake densities significantly reduced density of crustacean zooplankton and rotifers within 2 weeks. In addition, phytoplankton that were edible to zooplankton were reduced in enclosures, likely due to a combination of direct herbivory by gizzard shad and reduced nutrient availability due to uptake by the growing gizzard shad. Gizzard shad not only directly influenced zooplankton via predation, but they also indirectly affected zooplankton by reducing phytoplankton abundance. Because larval bluegill migrated to the limnetic zone during or shortly after the zooplankton decline, food available to these zooplanktivorous larvae, as well as their ultimate recruitment, was reduced with gizzard shad. Through direct (i.e., predation) and indirect (i.e., influencing algal abundance) pathways, gizzard shad can drive zooplankton to extinction, thereby reducing recruitment of other fish and controlling community composition.

103.) Drenner, R.W., Mummert, J.R., deNoyelles Jr., F., Kettle, D. 1984. Selective particle ingestion by a filter-feeding fish and its impact on phytoplankton community structure. *Limnology and Oceanography* 29(5):941–948.

The ingestion rates of filter-feeding gizzard shad for different sizes of suspended particles were measured using mixtures of microspheres and zooplankton. Ingestion rate increases as a function of particle size, leveling off at 60 µm. The particle-size-dependent ingestion rates were consistent with a model of filtering efficiency based on the cumulative frequency of interraker distances of gizzard shad gill rakers. Comparison of ponds containing gizzard shad with control ponds without fish showed that gizzard shad suppressed *Ceratium*, the only phytoplankton species large enough to be ingested at a maximum rate. Gizzard shad did not have a significant effect on populations of *Synedra*, *Peridinium*, *Navicula*, *Kirchneriella*, *Cyclotella*, and *Chlamydomonas*. Populations of *Ankistrodesmus*, *Cryptomonas*, *Cosmarium*, *Rhodomonas*, and algae and bacteria from 2–4 µm were enhanced by gizzard shad.

Environmental Effects – Fish Communities (American Paddlefish)

104.) Hoxmeier, R.H.J., and DeVries, D.R. 1997. Habitat use, diet, and population structure of adult and juvenile paddlefish in the lower Alabama River. *Transactions of the American Fisheries Society* 126(2):288–301.

In this study the authors quantified habitat use, diet, and population characteristics of paddlefish in the lower Alabama River in an effort to determine whether juveniles and adults differ in their seasonal use of three types of habitats (oxbow lakes, backwater areas, and channel areas) and to identify differences in population characteristics between fish from the Alabama River and those from other drainage systems. Both juveniles and adults used backwater and channel areas. Paddlefish used backwater areas primarily during summer and fall and channel habitats during winter and spring. Juvenile paddlefish that were present in backwater areas migrated with prespawn adults, whereas juveniles in the oxbow habitat did not. Juvenile pad-

dlefish used oxbow lakes as nursery areas, remaining there until sexual maturity. Paddlefish in the lower Alabama River had shorter life spans than those previously studied farther north, suggesting a latitudinal gradient in fish survival. Although fecundity rates were higher, in part compensating for their shorter life span, growth rates were lower than observed elsewhere. Slow growth may result from inhabiting areas where water is warmer than optimal for feeding. The authors recognize that part of the apparent difference in growth rates may be due to problems in aging paddlefish in previous studies. They found that paddlefish primarily consumed copepods and cladocerans when available; however, ephemeropteran nymphs were consumed heavily in the channel habitat during winter and spring.

105.) Jennings, C.A., and Zigler, S.J. 2000. Ecology and biology of paddlefish in North America: Historical perspectives, management approaches, and research priorities. *Reviews in Fish Biology and Fisheries* 10(2):167–181.

This paper summarizes the ecology and biology of the paddlefish, giving detailed information on its taxonomy, morphology, current and historical distribution, life history stages, reproduction, feeding, and habitat usage. The authors provide information on management approaches and give recommendations for future research by prioritizing the most critical aspects of its life history (early developmental stages, population dynamics, etc.) and reasons for its decline (i.e., pollution, siltation, overharvest, fragmentation, etc.)

Environmental Effects – Potential Effects

106.) Delong, M.D. 2010. Food webs and the Upper Mississippi River: Contributions to our understanding of ecosystem function in large rivers. *Hydrobiologia* 640(1):89–101.

Studies on the Upper Mississippi River, particularly over the last 15 years, have contributed to our understanding of trophic processes in large rivers. The framework established by earlier population-specific studies, however, cannot be overlooked. Examination of the feeding habits of fish ranging from planktivores to piscivores gave the first indication that trophic processes were influenced by the spatial complexity and annual hydrological patterns of river-floodplain ecosystems. Experimental studies, which have often been considered impossible or impractical in large rivers, demonstrated the potential for biotic controls of system dynamics through predator–prey and competitive interactions. Such studies have been particularly helpful in understanding the potential impact of nonnative species, including zebra mussels and Asian carp, to biodiversity and secondary production. Our understanding of riverine ecosystem function expanded greatly as food web studies began the application of a new tool—natural stable isotopes. Studies employing stable isotopes illustrated how food webs in a number of large rivers throughout the world are supported by the autochthonous production of microalgae. This study, coupled with other studies testing the prevailing models of riverine ecosystem function, has given a better understanding of the nature of river ecosystem functions.

107.) Kolar, C.S., and Lodge, D.M. 2002. Ecological predictions and risk assessment for alien fish in North America. *Science* 298(5596):1233–1236.

Methods of risk assessment for alien species, especially for nonagricultural systems, are largely qualitative. Using a generalizable risk assessment approach and statistical models of fish introductions into the Great Lakes, the authors developed a quantitative approach to target prevention efforts on species most likely to cause damage. Models correctly categorized established, quickly spreading, and nuisance fish with 87 to 94 percent accuracy. The authors then identified fish that pose a high risk to the Great Lakes if introduced from unintentional (ballast water) or intentional pathways (sport, pet, bait, and aquaculture industries).

108.) Rogowski, D.L., Soucek, D.J., Levengood, J.M., Johnson, S.R., Chick, J.H., Dettmers, J.M., Pegg, M.A., Epifanio, J.M. 2009. Contaminant concentrations in Asian carps, invasive species in the Mississippi and Illinois Rivers. *Environmental Monitoring and Assessment* 157(1–4):211–222.

In this study the authors investigated differences in concentrations of selected elements in two invasive carp species as a function of sampling site, fish species, length, and trophic differences using stable isotopes (δ^{15}N, δ^{13}C). Fish were collected from three different sites: the Illinois River near Havana, Illinois, and two sites in the Mississippi River—upstream and downstream of the Illinois River confluence. Five bigheaded carp and five silver carp from each site were collected for muscle tissue analyses. Freshwater mussels previously collected in the same areas were used as an isotopic baseline to standardize fish results among sites. Total fish length, trophic position, and corrected ^{13}C were significantly related to concentrations of metals in muscle. Fish length explained the most variation in metal concentrations, with most of that variation related to mercury levels. This result was not unexpected because larger fish are older, giving them a higher probability of exposure and accumulation of contaminants. There was a significant difference in stable isotope profiles between the two species. Bigheaded carp occupied a higher trophic position and had higher levels of corrected ^{13}C than silver carp. Additionally, bigheaded carp had significantly lower concentrations of arsenic and selenium than silver carp. Stable isotope ratios of nitrogen in Asian carp were at levels that are more commonly associated with higher-level predators, or from organisms in areas containing high loads of wastewater effluent.

109.) Simberloff, D., and Stiling, P. 1996. Risk of species introduced for biological control. *Biological Conservation* 78(1):185–192.

Numerous biological control introductions have adversely affected non-target native species. Although many of these problems occurred in the early days of biological control, some are recent. Because of how little monitoring is done on species, communities, and ecosystems that might be affected by biological control agents, it is quite possible that known problems are the tip of an iceberg. Regulations for officially sanctioned releases for biological control are insufficient, and there are also freelance unregulated releases undertaken by private citizens. Cost-benefit analyses for conservation issues, including those associated with biological control, are exceedingly difficult because it is hard to assign values to the loss of species or ecosystem functions. Risk assessment for biological control is difficult because of how hard it is to predict community- and ecosystem-wide impacts of introduced species and because introduced species disperse and evolve. Nevertheless, cost-benefit analyses and risk assessments for biological control introductions would have the salubrious effect of forcing consideration of myriad factors that now often receive cursory attention and of broadening public understanding of the issues. This paper breaks down the risks of introducing species for biological control and shows what repercussions and outcomes have potential to affect our ecosystems and economy.

Economic Effects – Adverse and Positive Effects

110.) Perrings, C., Williamson, M.H., Dalmazzone, S. 2000. The economics of biological invasions. Land use and water resources research. Edward Elgar Publishing.

Biological invasions are an economic problem. Invasions are typically the intended or unintended consequence of economic activity. They impose real costs on society, and the risk of invasion depends on human behavior. Effective control of invasions depends on using the right economic instruments and developing the right institutions. The problem has two special features. The first is that the risks of invasions may be very low, but the potential costs are high. Since they are not reflected in market prices, they are typically ignored. The second is that the control of potentially invasive species is a public good of the "weakest link" variety. Both features indicate a precautionary approach. The author offers recommendations both nationally and globally to assist in the prevention and control of invasive species, as well as providing insight into the development of institutions tasked specifically with dealing with them.

111.) Pimentel, D. 2005. Aquatic nuisance species in the New York State Canal and Hudson River systems and the Great Lakes Basin: An economic and environmental assessment. *Environmental Management* 35(5):692–702.

This paper offers information on the economic consequences associated with aquatic invasive and nuisance species in the United States. A total of 154 aquatic alien species have invaded the New York State Canal and Hudson River systems, and a total of 162 aquatic species have invaded the Great Lakes Basin. Some of these invasive species are causing significant damage and control costs in both aquatic ecosystems. In the New York State Canal and Hudson River systems, the nonindigenous species cause an estimated $500 million in economic losses each year. The economic and environmental situation in the Great Lakes Basin is far more serious, with losses estimated to be about $5.7 billion per year. Commercial and sport fishing suffer the most from the biological invasions, with about $400 million in losses reported for the New York State Canal and Hudson River systems and $4.5 billion in losses reported for the Great Lakes Basin.

112.) Engle, C.R., and Brown, D. 1999. Growth, yield, dressout, and net returns of bigheaded carp *Hypophthalmichthys nobilis* stocked at three densities in fertilized earthen ponds. *Journal of the World Aquaculture Society* 30(3):371–379.

Here, three studies were conducted in 0.10-ha earthen ponds to evaluate the effect of bigheaded carp stocking density on growth, yield, dressout yield, and net returns. Initially, bigheaded carp (average weight of 0.36 kg) were stocked at rates of 500, 320, or 130 fish/ha with three replicates of each treatment. Stocking rates for 2-year-old fish (average weight of 2.45 kg) were reduced to 320, 220, or 130 fish/ha in the second year. Net yields of bigheaded carp stocked at 500 fish/ha (963 kg/ha) were significantly higher than net yields at the 320 fish/ha density (771 kg/ha), and these were significantly greater than net yields at 130 fish/ha (369 kg/ha) in the first growing season. Net yields in the second growing season were not significantly different among densities. There were no significant differences among treatments in yearly growth, which ranged from 11 to 17 g/d in the first and from 6 to 13 g/d in the second growing season. Dressout percentages for whole-dressed, steak, shank fillet, and shank fillets with white meat only did not differ with stocking density. Enterprise and partial budget analysis indicated that monoculture of bigheaded carp in fertilized ponds is profitable only in the short run at average livehaul market prices, because revenues exceeded variable but not fixed costs. The authors found that the negative net returns, when all costs were accounted for, indicated that it is not profitable to construct ponds solely for monoculture of bigheaded carp.

113.) Freeman, D.W. 1996. Bigheaded carps: Assessment of two potential canned products. Proceedings Tropical and Subtropical Seafood Sciences and Technology Society of the Americas, W.S. Otwell (ed.), p. 263–272, Florida Sea Grant Program, SGR 115, Gainesville, Florida.

This study explores the potential for using bigheaded carp as a food resource. Six hundred bigheaded carp were harvested and processed into hybrid-type canned products (having properties that fall between those of a totally boneless product such as tuna and those of a fully boned product such as salmon). The author discusses in detail the process of preparation of the fish for human consumption and concludes with the results and feasibility of using this fish for a canned food product. It was found that while the method of precook significantly affected consumer acceptance of the product (panelists consistently preferred steam-cooked carp over oven-cooked), the overall acceptability was extremely good for both canned carp products.

114.) Freeman, D.W. 1999. Comparison of moist and dry cooking on sensory quality, consumer acceptance, and marketability of canned bigheaded carp. *Journal of Aquatic Food Product Technology* 8(1):33–44.

Canned bigheaded carp has shown potential as a freshwater fish product. A consumer panel of 90 individuals evaluated canned products made from bigheaded carp loins that had been cooked in either steam or a convection oven. The consumers were not told the identity of the fish under consideration. Acceptability was estimated by use of hedonic scales for sensory attributes, open-ended questions about how the products compared to similar canned fish products, and the "just-right" scale for attribute direction for change. Willingness to pay compared to similar products also was determined for each product. Both carp products were light in color and contained less than 1 percent crude lipids. Acceptability of both products was good, with the steam-cooked carp products being slightly more preferred in most categories. For the sensory attribute "overall liking," 54 percent of panelists rated the steam-cooked product as either "like very much" or "like moderately." Likewise, over 60 percent of panelists indicated that either carp product was better than or equal to canned tuna and that they would be willing to pay as much for either product as tuna.

115.) Malaypally, S.P., Liceaga, A.M., Kim, K.H., Ferruzzi, M., San Martin, F., Goforth, R.R. 2014. Influence of molecular weight on intracellular antioxidant activity of invasive silver carp (*Hypophthalmichthys molitrix*) protein hydrolysates. *Journal of Functional Foods* 1–9.

Protein hydrolysates from underutilized silver carp (SPH) were prepared using Flavourzyme (F-15 to F-60) and Alcalase (A-15 to A-60) at 15, 30, 45 and 60 min, respectively. SPH F-30 and A-60 showed promising chemical-based antioxidant activity and were further fractionated according to size to evaluate caco-2 cell based antioxidant activity. F-30 and A-60 peptide fractions with <3 kDa (F-30<3, A-60<3) showed higher cell-based antioxidant activity under stressed and non-stressed conditions. Further, IC50 values of

F-30<3 (1–3 mg/mL) was lower than A-60<3 fractions (4 to 12 mg/mL), indicating higher cellular antioxidant activity of F-30<3 compared to A-60<3 under all conditions. The presence of active peptides with desired amino acid sequence in F-30<3 compared to A-60<3 may have contributed to its higher cellular antioxidant activity. Overall, SPH exhibited antioxidant capacity, hence using an underutilized, invasive fish for environmental and economic gain in the form of promising functional ingredients.

116.) Mueller, J.P., and Liceaga, A.M. 2014. Characterization and cryoprotection of invasive silver carp (*Hypophthalmicthys molitrix*) protein hydrolysates. *Journal of Aquatic Food Product Technology* (in press).

Silver carp is regarded as an invasive, underutilized freshwater fish causing environmental and economic complications along the U.S. Mississippi River System. In this study, silver carp protein hydrolysates (FPH) were obtained from 30, 60, 90, 120, and 240 min hydrolysis with Protamex®. Amino acid composition showed polar amino acids, including Asp and Glu, and freed hydrophobic residues in FPH-90 and FPH-240. Protein surface hydrophobicity of FPH increased with increasing degree of hydrolysis. Cryoprotection was evaluated using a muscle (mince) food system with 6 percent FPH (w/w) from each hydrolysis time condition, an untreated mince (CTRL), and 8 percent (w/w) 1:1 sucrose-sorbitol (SUSO), respectively. After 6 freeze-thaw cycles (D7), all FPH treatments had lower ($P<0.05$) expressible moisture, indicating strong water holding capacity by the FPH. FPH formulations also imparted antifreeze activity equal to or better than SUSO, with the FPH-90 exhibiting higher ($P<0.05$) proportion (43.9 percent) of unfrozen water at D7. Results from this study provide preliminary evidence for development of effective cryoprotectants using an underutilized, invasive fish species that can be exploited for environmental and economic gain in the form of value-added ingredients and further provide opportunities to understand the fundamental physicochemical properties governing cryoprotection of FPH in a frozen mince system.

117.) Stone, N.M., Engle, C., Heikes, D., Freeman, D.W. 2000. Bigheaded Carp. Southern Regional Aquaculture Center. SRAC Publication No. 438.

Because the word "carp" has a negative connotation to some consumers, alternative names proposed for bigheaded include "noble fish," "speckled amur," and "lake fish." In the United States, bigheaded are polycultured with channel catfish in approximately 5,100 acres of earthen ponds, including an estimated 4,000 acres in Arkansas, 500 in Mississippi, and 600 in Alabama. Bigheaded are an important source of additional income that, at times of low catfish prices, has kept some fish farmers in business. The current U.S. market is limited and easily saturated. Bigheaded have a pleasant, mild tasting flesh, but are too bony for most U.S. consumers. The potential for canned and surimi products is being studied. Producing bigheaded with catfish requires that the bigheaded be handsorted and seined separately from catfish before the catfish can be harvested. This is a significant disadvantage in multiple-batch catfish production. Other disadvantages of polyculture are that bigheaded consume pelleted feed intended for catfish, compete for aerated water, and may be vectors of fish parasites.

118.) Thomson, S.P., Liceaga, A.M., Applegate, B.M., Martyn, R.D. 2015. Analysis of seed vigor responses in soybean to invasive silver carp (*Hypophthalmichthys molitrix*) protein hydrolysate treatments. *American Journal of Experimental Agriculture* 5(3): (in press).

The aim of this study was to produce fish protein hydrolysates (FPH) from invasive silver carp under controlled hydrolysis conditions, and to examine the effects of FPH on seed vigor, using standard vigor tests. Soybeans were treated with FPH hydrolyzed for 1, 5.5, and 10 hrs with papain (FPH-Pa), pepsin (FPH-P), and trypsin (FPH-T), respectively. Overall vigor tests (accelerated aging and warm and cold germination dry weight, height, total phenolics, and guaiacol peroxidase assessment-GuPx) were compared to a distilled-water control over a 12-day germination period. Seeds treated with FPH-P and FPH-Pa at 1 hr (23 percent degree of hydrolysis) elicited the greatest growth responses. FPH-Pa at 1 hr increased weight and height compared to water control. FPH-Pa at 1 hr also had the highest GuPx values, which are indicative of lignification. FPH-Pa appeared to stimulate lignification and thus enhance weight and height of the seedling. FPH-P elicited the greatest phenolic response, with the highest total phenolic content on day 4 and day 12 compared to water control. Higher phenolic content may have protected against oxidation during accelerated aging vigor test, resulting in higher germination rates (53.8 percent germination) for soybeans primed with FPH-P at 1 h compared to water controls (32.2 percent germination). Most FPH treatments increased germination under warm conditions, compared to water control. GuPx values overall were higher in FPH-treated soybeans. Results suggest that the use of FPH produced with the enzymes papain and pepsin at 1 hour of hydrolysis are comprised of free amino acids and peptides that are beneficial to the stimulation of the proline-linked pentose phosphate pathway, which enhanced the vigor parameters measured. This research supports the use and exploitation of an underutilized invasive fish species, offering insight into different avenues for human consumption.

119.) Xie, L., Xie, P., Ozawa, K., Honma, T., Yokoyama, A., Park, H.D. 2004. Dynamics of microcystins-LR and -RR in the phytoplanktivorous silver carp in a sub-chronic toxicity experiment. *Environmental Pollution* 127(3):431–439.

A sub-chronic toxicity experiment was conducted to examine tissue distribution and depuration of two microcystins (microcystin-LR and microcystin -RR) in the phytoplanktivorous filter-feeding silver carp during a course of 80 days. Two large tanks (A, B) were used. In Tank A, the fish were fed naturally with fresh *Microcystis viridis* cells (collected from a eutrophic pond) throughout the experiment, while in Tank B, the fish were fed *M. viridis* cells for the first 40 days and then changed to artificial carp feed. High Performance Liquid Chromatography (HPLC) was used to measure MC-LR and MC-RR in the *M. viridis* cells, the seston, and the intestine, blood, liver, and muscle tissue of silver carp at an interval of 20 days. MC-RR and MC-LR in the collected *Microcystis* cells varied between 268 and 580 and 110 and 292 $\mu g\ g^{-1}$ DW, respectively. In Tank A, MC-RR and MC-LR varied between 41.5 and 99.5 and 6.9 and 15.8 $\mu g\ g^{-1}$ DW in the seston, respectively. The maximum MC-RR in the blood, liver, and muscle of the fish was 49.7, 17.8, and 1.77 $\mu g\ g^{-1}$ DW, respectively. No MC-LR was detectable in the muscle and blood samples of the silver carp in spite of the abundant presence of this toxin in the intestines (for the liver, there was only one case when a relatively minor quantity was detected). These findings contrast with previous experimental results on rainbow trout. Perhaps silver carp has a mechanism to degrade MC-LR actively and to inhibit MC-LR transportation across the intestines. The depuration

of MC-RR concentrations occurred more slowly than uptakes in blood, liver, and muscle, and the depuration rate was in the order of blood > liver > muscle. The grazing ability of silver carp on toxic cyanobacteria suggests an applicability of using phytoplanktivorous fish to counteract cyanotoxin contamination in eutrophic waters.

Management – Barrier Options & Other Management Approaches

120.) Hamel, M.J., Brown, M.L., Chipps, S.R. 2008. Behavioral responses of rainbow smelt to *in situ* strobe lights. *North American Journal of Fisheries Management* 28(2):394–401.

In this study the authors conducted *in situ* testing of strobe lights as a potential fish deterrent by examining avoidance and acclimation behaviors of rainbow smelt *Osmerus mordax* in Lake Oahe, South Dakota. Split-beam hydroacoustics were used to assess the effectiveness of the deterrent system by comparing proximal densities of rainbow smelt before and after the device was activated. In summer 2005, strobe lights successfully repelled rainbow smelt to a minimum horizontal distance of 21 m at both 1 hr and 4 hr postactivation; the model AGL-FH 920 flashhead produced a light intensity of 6,585 lumens per flash. Similarly in 2004, a model AGL-FH 901 flashhead, which produced a light intensity of 2,634 lumens per flash, repelled rainbow smelt to a horizontal distance of 15 m. A comparison of strata 10 m above and below the strobe light system showed that rainbow smelt were vertically displaced to approximately 6 m. The authors conclude that strobe lights elicit behavioral avoidance by rainbow smelt and may provide an effective means for reducing entrainment losses through Oahe Dam.

121.) Lovell, J.M., Findlay, M.M., Nedwell, J.R., Pegg, M.A. 2006. The hearing abilities of the silver carp (*Hypopthalmichthys molitrix*) and bigheaded carp (*Aristichthys nobilis*). *Comparative Biochemistry and Physiology* 143(3):286–291.

Concern regarding the spread of silver carp and bigheaded carp through the Illinois River has prompted the development of a Bioacoustic Fish Fence (BAFF) to act as an acoustic fish deterrent. It is important to understand the auditory physiology of the target species in order to maximize the effect of the barrier on the nonindigenous carp species, while minimizing the effect on indigenous fish populations. Therefore, the hearing thresholds of 12 *H. molitrix* and 12 *A. nobilis* were defined using the Auditory Brainstem Response (ABR) technique, in a pressure-dominated sound field generated by submerged transducers of the type used in the construction of the BAFF system. The results clearly show that these fish are most sensitive to sounds in a frequency bandwidth of between 750 Hz and 1500 Hz, with higher thresholds below 300 Hz and above 2000 Hz.

122.) Moyv, P.B., Polls, I., Dettmers, J.M. 2011. The Chicago sanitary and ship canal aquatic nuisance species dispersal barrier. *In:* Chapman, D.C., and Hoff, M.H. (eds). Invasive Asian Carps of North America. American Fisheries Society Symposium 74:121–137.

The Chicago Sanitary and Ship Canal is a 50 km-long, manmade canal that connects the Great Lakes and Mississippi River drainages. The canal, which is important for navigation and storm and wastewater drainage, forms an aquatic pathway for nonnative aquatic species to spread between these two major Midwestern ecosystems. The National Invasive Species Act of 1996 authorized construction of the Chicago Sanitary and Ship Canal aquatic nuisance species dispersal barrier. The barrier currently consists of a micropulsed DC electric array. A demonstration barrier began operation in April 2002 and is nearing the end of its design life; a larger, longer-lasting barrier is now under construction. The demonstration barrier has been effective in repelling radio-tagged common carp *Cyprinus carpio* and is expected to have similar effectiveness on other large fish. The new, more powerful barrier will be more effective in repelling small fish. In the near term, addition of alternative technologies such as acoustic bubble arrays may augment effectiveness of the electric barrier. In the long term, separation of the Lake Michigan and Mississippi River drainages will provide the surest means of preventing the range expansion of aquatic invasive species via this pathway. Funding, authorization, and existing waterway uses will continue to challenge development of a fully effective barrier system.

123.) Noatch, M.R., and Suski, C.D. 2012. Non-physical barriers to deter fish movements. *Environmental Reviews* 20(1):71–82.

Non-physical barriers, which obstruct fish from an undesirable location without influencing the waterway, are one management approach to protecting valuable fish stocks and deterring biological invasions. Because many methods of behavioral deterrence have been employed against fish, there is a need to summarize and compare existing and developing technologies. This review details the use and application of electrical, visual, acoustic, chemical, and hydrological deterrence techniques that may be used to prevent fish movements. Site requirements are discussed, and a critical assessment of benefits and limitations to each technique is given. This review of non-physical fish barrier technology will benefit managers and researchers attempting to develop a best-fit strategy on a case-by-case basis.

124.) Patrick, P.H., Christie, A.E., Sager, D., Hocutt, C., Stauffer Jr., J. 1985. Responses of fish to a strobe light/air-bubble barrier. *Fisheries Research* 3:157–172.

The responses of selected freshwater (*Alosa pseudoharengus*, *Osmerus mordax*, *Dorosoma cepedianum*) and estuarine (*Morone americana*, *Leiostomus xanthurus*, *Brevoortia tyrannus*) species to air bubbles alone, strobe light alone, and a combined strobe light/air-bubble barrier were investigated under laboratory conditions. Gizzard shad, alewife and smelt avoided an air-bubble barrier. Avoidance response varied with air-bubble spacing and illumination. All species tested exhibited avoidance behavior to strobe lights, which varied with current velocity, strobe flash rate, and acclimation of fish. Increased avoidance was evident for most species when strobe lights were combined with air bubbles as an exclusion barrier. The authors found that a combined strobe light/air-bubble scheme shows potential for application in fish management and that strobe lights are more effective than continuous light.

125.) Rasmussen, J.L., Regier, H.A., Sparks, R.E., Taylor, W.W. 2011. Dividing the waters: The case for hydrologic separation of the North American Great Lakes and Mississippi River basins. *Journal of Great Lakes Research* 37(3):588–592.

Legislation has been introduced in the U.S. Congress that would direct the U.S. Army Corps of Engineers to study options to prevent the spread of aquatic nuisance species between the Great Lakes and Mississippi River basins. Hydrologic separation is the only option that closes the aquatic connection between the two basins and does not require continuous operation and maintenance of various technologies that have some risk of failure. The one-time capital cost to separate the two basins is widely acknowledged to be high, and the

outstanding question is whether the costs are justified given the significant risk of future ecological damages and long-term economic losses. Interests opposing separation have mounted a public campaign that the news media have picked up to deny that hydrologic separation should be considered or that a problem even exists. The campaign rests on four assertions: (1) existing electric barriers in the Chicago canals are effective; (2) it is too late—the carps are already in the Great Lakes or soon will be; (3) Asian carps will not thrive in the Great Lakes due to inadequate food and spawning habitat; and (4) Asian carps are unlikely to cause serious harm. This review of these assertions and the ecological and socio-economic threats to both basins supports the authors' recommendation that legislation be passed and that it include analysis of hydrologic separation of the two basins.

126.) Richards, N.S., Chipps, S.R., Brown, M.L. 2007. Stress response and avoidance behavior of fish as influenced by high-frequency strobe lights. *North American Journal of Fisheries Management* 27(4):1310–1315.

The authors examined the effects of strobe lights on plasma cortisol concentrations and avoidance behavior across a broad range of fish taxa. Representative fish taxa from five families were evaluated and included: Centrarchidae (largemouth bass), Cyprinidae (fathead minnow), Ictaluridae (channel catfish), Percidae (yellow perch), and Salmonidae (Chinook salmon). Mean plasma cortisol concentrations for channel catfish, yellow perch, and Chinook salmon increased significantly compared with those in control groups after 1 h of exposure to strobe lights. After 7 h of exposure, plasma cortisol levels were similar to those in control groups for all fish taxa. Fathead minnow showed no detectable response to strobe lights at either 1 or 7 h of exposure. Behavior experiments showed that the mean distance moved from the strobe light varied significantly between test and control fish and was highest for largemouth bass (mean distance after 1 h = 8.3 m), followed by Chinook salmon (7.3), yellow perch (7.3), and channel catfish (5.1). In contrast, avoidance behavior by fathead minnow exposed to strobe lights did not differ from that of controls. Although a significant increase in plasma cortisol level was useful for predicting an avoidance response, relative change in cortisol concentration was a poor indicator of sensitivity of individual fish taxa to strobe lights. Direct observations of avoidance behavior revealed that largemouth bass, Chinook salmon, and yellow perch were more sensitive to strobe lights than channel catfish and fathead minnow. The authors conclude that lack of both a cortisol response and avoidance behavior by fathead minnow indicates low sensitivity of this species to strobe lights and warrants further investigation into the effectiveness of strobe lights on cyprinids.

127.) Ruebush, B.C. 2011. *In-situ* tests of sound-bubble-strobe light barrier technologies to prevent the range expansions of Asian carp. Thesis. University of Illinois.

Bigheaded and silver carp have invaded the Mississippi River Basin and have successfully established populations in the Illinois River. Correlative studies have suggested that Asian carp in the Illinois River have negatively influenced native planktivorous fish and that they now pose an imminent threat of invading Lake Michigan through the Chicago Sanitary and Ship Canal. Sound-bubble-strobe light barrier (SBSLB) technologies may have the potential to slow Asian carp range expansions. A sound-bubble barrier was 95 percent effective at deterring adult bigheaded carp passage in a hatchery raceway experiment. In 2009–10, the author tested the effectiveness of a SBSLB at repelling Asian and non-Asian carp (all other fish tested) within Quiver Creek, a tributary to the Illinois River. To test barrier effectiveness, Asian carp and non-Asian carp were removed from upstream of the barrier, marked, and released downstream of the SBSLB. Asian carp were also collected from the main-stem Illinois River and transplanted downstream of the barrier. Trials were conducted with the SBSLB on and off to test upstream passage rates. Short-term and extended trials were also conducted to test for differences in upstream passage rates using sound, bubbles, and strobe lights (flashing and not flashing) versus sound and bubbles only. Barrier effectiveness was evaluated by upstream recaptures. Two of 575 marked silver carp and 85 of 2,937 marked non-Asian carp breached the barrier and were recaptured. No marked bigheaded carp (n=101) were recaptured. These results suggest that SBSLB technologies could be used as a deterrent system to repel Asian carp but should not be used as an absolute barrier to prevent range expansions. The author recommends that the potential negative influences of this technology on non-target fish must also be considered prior to implementation as a management tool.

128.) Sand, O., and Karlsen, H.E. 2000. Detection of infrasound and linear acceleration in fishes. *Philosophical Transactions Royal Society London. Series B: Biological Sciences* 355(1401):1295–1298.

Fish have an acute sensitivity to extremely low-frequency linear acceleration, or infrasound, even down to below 1Hz. The otolith organs are the sensory system responsible for this ability. The hydrodynamic noise generated by swimming fish is mainly in the infrasound range and may be important in courtship and prey–predator interactions. Intense infrasound has a deterring effect on some species and has a potential in acoustic barriers. In this study the authors hypothesize that the pattern of ambient infrasound in the oceans may be used for orientation in migratory fishes, and that pelagic fish may detect changes in the surface wave pattern associated with altered water depth and distant land formations. They suggest that the acute sensitivity to linear acceleration could be used for inertial guidance and to detect the relative velocity of layered ocean currents. Sensitivity to infrasound may be a widespread ability among aquatic organisms and has also been reported in cephalopods and crustaceans.

129.) Sonny, D., Knudsen, F.R., Enger, P.S., Kvernstuen, T., Sand, O. 2006. Reactions of cyprinids to infrasound in a lake and at the cooling water inlet of a nuclear power plant. *Journal of Fish Biology* 69(3):735–748.

Behavioral effects of infrasound on cyprinids were tested. In Lake Borrevann, Norway, acute avoidance responses, at a distance up to 10 m from a 16 Hz infrasound projector were revealed by echosounding. At 10 m distance, a coarse estimate of the stimulus level (measured as the acceleration component of the particle motions) was c. 10^{-3} m s^{-2}. Habituation was not evident during these tests. Two synchronized infrasound units were also installed 6 m apart in front of a cooling water intake of a nuclear power plant on the River Meuse, Belgium. Echosounding was used to compare the number of fish entering the intake canal during on–off infrasound sequences. Relative to off-periods, the reduction of the number of fish entering during on-periods was >80 percent at a distance of 0–12 m from the units. A significant reduction of 48 percent was observed considering the whole width (54 m) that was monitored. Fish impingement on the mechanical screens during the study revealed that >90 percent of the fish entering the intake were cyprinids.

130.) Sparks, R.E., Barkley, T.L, Creque, S.M., Dettmers, J.M., Stainbrook, K.M. 2010. Evaluation of an electric fish dispersal barrier in the Chicago Sanitary and Ship Canal. *In:* Chapman, D.C. and M.H. Hoff (eds) Invasive Asian Carps of North America. American Fisheries Society Symposium 74: 139–161.

Here, the authors surgically implanted combined radio-and-acoustic transmitters in 130 common carp that were released 20 m downstream of the demonstration barrier in the Chicago Sanitary and Ship Canal to assess the ability of the barrier to prevent upstream passage of fish. Movements of these fish were monitored from April 2002 through December 2006, within and beyond the 8.7-km reach bounded upstream by the electrical barrier and downstream by the Lockport Dam and Lock. Fixed hydrophones and radio antennas continuously monitored the canal immediately upstream and downstream of the barrier for signals from the transmitters. In addition, 32 surveys were conducted with boat-mounted receivers to locate transmitters that were out of range of the fixed receivers. The fixed receivers detected 109 of the 130 transmitters; most detections occurred within a few days after release of the fish. The tracking boat located 120 of the transmitters at least once and 100 at least twice. Most of the transmitters remained well downstream of the barrier and upstream of the lock, but one moved downstream beyond the lock, one passed upstream through the barrier, four moved upstream within 60–400 m of the barrier after moving downstream, and three remained at the release point for their entire battery life, indicating that the fish had died or the transmitters had been expelled. On two occasions, common carp were visually observed within half a meter of the surface (the limit of visibility) at the barrier. These fish were not observed to move beyond the downstream margin of the electric field. The traverse of the barrier on April 3, 2003, occurred at the same time as a tow was passing. The tow may have facilitated the passage of the fish, either by entraining the fish or by distorting the electric field. The tracking boat detected the transmitter upstream of the barrier on April 10, 2003. The transmitter did not move more than 100 m during the remaining life of the transmitter, indicating that the fish was probably dead. After the authors reported the passage, Smith-Root Inc. (operators of the electric barrier, under contract with the U.S. Army Corps of Engineers) increased the strength of the electric field by 50 percent. Since then, the authors have not detected any further passages of transmitters, suggesting that the existing electric field (Barrier 1) may be preventing upstream movement of adult common carp and that the new, improved barrier will likely be effective against the more recently introduced Asian carps. Despite this apparent success, the response of Asian carps to electric barriers needs further study. The authors acknowledge that there are ways these carps could bypass Barriers 1 and 2 and recommend that they be addressed.

131.) Taylor, R.M., Pegg, M.A., Chick, J.H. 2003. Some observations on the effectiveness of two behavioral fish guidance systems for preventing the spread of bigheaded carp to the Great Lakes. *Aquatic Invaders* 14:1–5.

In this study the authors evaluated the effectiveness of two behavioral fish guidance systems in deterring bigheaded carp in outdoor experimental raceways. The first system evaluated was a Sound Projection Array-driven BioAcoustic Fish Fence (SPA-driven BAFF). A total of 3,219 attempts were made to cross this behavioral guidance system. Of those attempts, 57 percent were repels. The second system evaluated was a Sound Projection Array-driven BioAcoustic Fish Fence (SPA-driven BAFF) integrated with a Graduated Electric Field Barrier (GEFB). In contrast, only 87 attempts were made by bigheaded carp to cross this guidance system. Of those attempts, 83 percent were successful repels.

132.) Taylor, R.M., Pegg, M.A., Chick, J.H. 2005. Response of bigheaded carp to a bioacoustic behavioral fish guidance system. *Fisheries Management and Ecology* 12(4):283–286.

The objective of this study was to test the efficacy of the Sound Projecter Array-driven BioAccoustic Fish Fence system (SPA-driven BAFF) in restricting the movements of bigheaded carp. Three treatments were used: (1) a raceway containing a functional SPA-driven BAFF array centered at the midpoint in one of the three raceways; (2) a raceway containing a non-functional barrier array that was similar in all aspects to the functional treatment but not turned on during experiments; and (3) a control raceway containing no barrier equipment or other visible or physical cues. The latter two treatments were used to ensure that the responses by bigheaded carp were solely related to the function of the SPA-driven BAFF. The foremost intent of this analysis was to illustrate that most fish were retained above the barrier in the functional treatment but that fish in the other treatments were able to freely move throughout the raceway. Results suggest that there may be opportunities to use this barrier technology as a supplement with other control methods (e.g., electric barriers) where fish can be trained or conditioned to avoid areas where their presence is unwanted. The mean number of bigheaded carp found above the functional barrier was significantly greater than both the non-functional barrier and control barrier, which were not significantly different from each other. Visual observations during the trials also support this result as individuals from the control and non-functional raceways were routinely observed swimming the lengths of their respective raceways. The authors conclude by recognizing that further research on the effects of prolonged exposure to this technology, responses to the barriers in flowing water, identifying the precise hearing range of this and other species of interest, and evaluating combinations of various barrier technologies will further refine and improve the applicability of this management tool.

133.) Verrill, D.D., and Berry Jr, C.R. 1995. Effectiveness of an electrical barrier and lake drawdown for reducing common carp and bigmouth buffalo abundances. *North American Journal of Fisheries Management* 15(1):137–141.

Common carp were radio-tracked in both lakes during the winters of 1991 and 1992 to monitor their movements and survival. Four of six radio-tagged fish died during the first winter because of low water, but all of an additional 12 radio-tagged common carp survived the second winter. The fish overwintered in water 28–50 cm deep under about 40 cm of ice cover. To assess the ability of an electrical barrier across the outlet stream to prevent migration into the Heron lakes basin, 1,600 common carp and bigmouth buffalo were marked with dart tags and released downstream from the barrier. No tagged fish were among the 3,376 fish caught upstream from the barrier. Catches of the two species per unit gillnetting effort in South Heron Lake were lower in August 1992 than in August 1991, suggesting that lake-level drawdown and the electrical barrier reduced both populations.

134.) Zielinski, D.P 2013. An engineering perspective on invasive fish control: A study of bubble curtain deterrent systems to control carp movement. Dissertation. University of Minnesota.

The objective of this research was to investigate the ability of bubble curtain deterrent systems to inhibit the movement of invasive fish. Bubble curtains, which consist of a wall of bubbles (e.g., produced by forcing air through perforated pipes), fall into the category of behavioral deterrent systems that rely on aversive stimuli (e.g., sound and light) to guide fish in taxon-specific manners. These sys-

tems provide advantages over physical/mechanical screens because they do not restrict fluid flow or negatively impact navigation. Bubble curtains are particularly appealing, because they are less expensive than other electrical or sonic barriers, they are easily maintained and safe, and they produce complex acoustic and hydrodynamic stimuli that may be optimized to deter fish movement. However, few studies have examined whether or how bubble curtains might work. In three studies, the common carp (a cyprinid responsible for water-quality degradation in shallow-water ecosystems) was used to investigate how bubble curtains influence fish behavior and might be optimized. First, through a laboratory experiment, two different bubble curtains were shown to reduce passage of common carp by 75–80 percent in both up- and down-stream directions. These findings also suggested that avoidance behaviors were attributed to fluid motion and sound stimuli. Second, a field test demonstrated that the performance of a bubble curtain under natural conditions was consistent with laboratory results, blocking 57±12 percent of downstream swimming carp, versus 75–80 percent in the laboratory. Third, a fish-movement model based on diffusion theory and phonotaxic response was derived. In a novel application, a stability analysis of the fish movement model demonstrated that acoustic stimuli produced by the bubble curtains can be sufficient to disrupt movement (i.e., deter passage) of common carp. Overall, these results have shown through rigorous experimental and holistic quantitative analysis that bubble curtains can indeed deter common carp movement, but improvements must be identified in order for bubble curtains to remain a viable management tool in the future.

Management – Biological Control

135.) Chapman, D., Fairchild, J., Carollo, B., Deters, J., Feltz, K., Witte, C. 2003. An examination of the sensitivity of bighead carp and silver carp to antimycin *a* and rotenone. U.S. Geological Survey, Columbia Environmental Research Center, 22 p., (91293).

An electrical barrier has been constructed in the Chicago Ship and Sanitary Canal (CSSC) to prevent movement of invasive species between the Great Lakes and the Mississippi River system. Bighead and silver carp that are present downstream of the barrier may be able to eventually penetrate this barrier. If the fish are near the barrier, it may be necessary to remove the fish from the immediate vicinity. The only reasonable method to affect the complete removal of the fish is the use of a piscicide. The authors tested the sensitivity of bighead and silver carp to two piscicides, rotenone and antimycin *a*. The fish were sensitive to rotenone, falling near the middle of the range of sensitivities reported for various species. A concentration of 250 micrograms/L, the highest concentration permitted for control of fishes, killed all bighead and silver carp within 4 hours. Both large and small fish were sensitive to rotenone. Rotenone should be a suitable toxicant for the removal of bighead and silver carp from the CSSC. Bighead and silver carp were fairly insensitive to antimycin *a*. Compared to values in the literature, they were more sensitive than black bullheads but less sensitive than most other species. A concentration of 20 micrograms/L, the highest concentration permitted for control of fish at the pH and temperatures likely in the CSSC, required 32 hours to kill all bighead and silver carp. In conclusion, the authors acknowledge that the canal is important for commercial transportation and the duration of exposure required to affect the removal of bighead and silver carp with antimycin would be unacceptably long.

136.) Davis, S.A., Catchpole, E.A., Fulford, G.R. 2000. Periodic triggering of an inducible gene for control of a wild population. *Theoretical Population Biology* 58(2):95–106.

In this study the authors investigate the effectiveness of various strategies for control using transgene technology. Their results show that suppression of the population density below any pre-specified level is possible using this technique. At the same time, they show that too frequent or too efficient exposure to the trigger can select for non-transgenic genotypes at an intensity such that the population density will be largely unaffected by the trigger. Choices for management parameters can ensure that the latter scenario is avoided. Overall, their results show that releasing individuals carrying the transgene at more than one locus facilitates density control.

137.) Davis, S.A., Catchpole, E.A., Pech, R.P. 1999. Models for the introgression of a transgene into a wild population within a stochastic environment, with applications to pest control. *Ecological Modelling* 119(2):267–275.

Several forms of control are currently under consideration for pest species in Australia. Perhaps the most novel makes use of either an inducible fatality gene (IFG) or an inducible sterility gene (ISG). The transgene is integrated into the genome of target populations by periodically releasing transgenic animals. When high proportions of the population carry the transgene, then the gene may be induced to reduce abundance. A fundamental feasibility issue is how much time and effort is required before the proportion of the population carrying the transgene reaches values close to 1. It is shown that the speed of introgression may be underestimated if models do not allow for year-to-year variability in natural processes, such as the number of young arising from natural breeding or the number of adults surviving to breed. Furthermore, the improvements in speed of introgression due to variability are magnified for species with lower lifespans. The authors include, as specific examples, application of the model to common carp and mosquitofish, which are major freshwater pests in Australia.

138.) Davis, S.A., and Fulford, G.R. 1999. Modeling the integration of a transgene by stocking. *Theoretical Population Biology* 55(1):53–60.

Simple models for the integration of a selectively neutral transgene into a feral population, by stocking of transgenic individuals, are developed. The impact of stocking individuals having multiple unlinked homozygous locations of the transgene is quantified. Initially it is assumed that there is no overlap between successive generations, but a more general model for species having discrete overlapping generations is also developed. The primary application for this work is biological control. It is found that the integration of a transgene is considerably quickened by stocked transgenics carrying the transgene at multiple sites. In conclusion, the authors recognize that the use of a transgene as a method for control has been shown to constitute a long-term option. They recommend that their results for released individuals carrying the transgene at multiple locations encourages further modeling of transgenic methods and further exploration of stochastic effects.

139.) Gehrke, P.C. 2001. Preliminary assessment of oral rotenone baits for carp control in New South Wales. Managing Invasive Freshwater Fish in New Zealand. DOC Workshop.

Floating pellet baits containing a lethal dose of rotenone were tested to assess their potential for carp control in Australia. Application of

rotenone pellets in three replicated billabongs killed only 12 carp. Approximately 3,000 non-target Australian smelt died in one billabong after feeding on fine dust from the pellets. Failure to achieve significant carp control was ascribed to poor flotation of the pellets, resulting in at least half of the pellets being unavailable to carp at the surface, and low palatability of pellets containing rotenone. Seven other fish species in the billabongs appeared to be unaffected. In aquaria, crimson-spotted rainbowfish, western carp gudgeons, and Australian smelt suffered high mortality (95–100 percent) if pellets were left in the water. However, no mortality of rainbowfish or gudgeons occurred if pellets were removed after 30 min. Three species of decapod crustaceans were relatively unaffected (0–5 percent mortality) by exposure to rotenone pellets. In a pond trial, 5 carp (5 percent) and 37 bony herring (39 percent) died after application of rotenone pellets. All carp, but only 10 bony herring contained traces of pellets in their guts, confirming they had fed on pellets. The cause of death of the other 27 bony herring is unknown. Extending the training period using non-toxic pellets, establishing flotation standards for pellets, and improved palatability may improve the effectiveness of rotenone baits against carp. Screening pellets to prevent fines from entering the water and removing uneaten pellets after 30 min are also recommended to reduce the risk to non-target species. The authors conclude with a discussion that pellet baits have potential for use in carp control, but the current product and application procedures require further development and testing to demonstrate effectiveness in reducing carp populations with acceptably low risk to non-target species in Australia.

140.) Kapuscinski, A.R., and Patronski, T.J. 2005. Genetic methods for biological control of nonnative fish in the Gila River basin: Development and testing of methods, potential environmental risks, regulatory requirements, multi-stakeholder deliberation, and cost estimates. Contract report to the U.S. Fish and Wildlife Service (USFWS agreement number 201813N762).

This report addresses the feasibility of using genetic methods as a new approach for biological control of nonnative fish within the Gila River Basin. The report reviews the status of existing genetic methods including chromosome set manipulations and recombinant DNA techniques; takes a preliminary look at potential ecological and human health risks; outlines policy and regulatory considerations; stresses the need for and presents an approach for multi-stakeholder deliberation; provides general cost and time estimates; and suggests integration of these considerations into a multicomponent research and development program.

141.) Little, E.E., Calfee, R.D., Fabacher, D.L, Sanders, L. 2011. Fright reaction and avoidance induced by exposure to conspecific skin extracts in invasive bigheaded and silver carps. *In:* Chapman, D.C., and Hoff, M.H. (eds.). Invasive Asian Carps in North America. American Fisheries Society Symposium 74:215–255.

The response of bigheaded carp and silver carp to conspecific skin extracts was determined during free-field observations and avoidance tests. The extracts induced freezing/motionlessness, cessation of food-searching activities, and reduced swimming activity in the fish. Silver carp tended to avoid the area where the extract was released, and a strong schooling response was induced in bigheaded carp. In avoidance tests using countercurrent chambers, young bigheaded carp (5–8 cm total length) were unresponsive to the skin extract. However, in both species, older juveniles (12–25 cm total length) spent significantly less time in the side of the chamber receiving skin extract solutions. The extract was effective whether freshly prepared or aged at room temperature for 24 h. Freezing did not alter the effectiveness of fresh or frozen extracts. Their results suggest that bigheaded and silver carp are responsive to conspecific skin extracts and that the use of extracts might be useful to repel carp from habitats of concern.

142.) Marking, L.L., and Bills, T.D. 1981. Sensitivity of four species of carp to selected fish toxicants. *North American Journal of Fisheries Management* 1(1):51–54.

In this study the authors determined the toxicity of four registered or candidate fish toxicants to the carps (common, grass, bigheaded, and silver) and delineated the toxicity of GD-174 (2-[digeranylamino]-ethanol) to the four species under various conditions of temperature, water hardness, and pH. The 96-hour LC_{50}s ranged from 0.570 to 1.00 ppb for antimycin, 1.5 to 9.35 ppb for Salicylanilide I, 0.05 to 0.08 ppm for Noxfish, and 0.05 to 0.55 ppm for GD-174. Toxicity of GD-174 to the four species was little affected by variations in water temperature and water hardness but was increased at higher pHs. All of the test compounds were toxic to the four species; GD-174 was more toxic to common carp than to the others.

143.) Rach, J.J., Boogaard, M., Kolar, C.S. 2009. Toxicity of rotenone and antimycin to silver carp and bigheaded carp. *North American Journal of Fisheries Management* 29(2):388–395.

Due to a lack of available toxicity information on the potential for rotenone and antimycin *a* to control Asian carp, the authors investigate these two chemicals' effectiveness in controlling Asian carp populations. In this study, Prenfish (5 percent rotenone) and antimycin (90 percent antimycin-*a*) toxicities to silver carp and bigheaded carp were assessed in acute toxicity and effective contact time tests. Each acute toxicity test consisted of fish being exposed to nine concentrations of a toxicant for 96 h in a static bath. In effective contact time tests, silver carp and bigheaded carp were exposed to the toxicants for 2, 4, 8, 12, or 24 h in a static bath. After each chemical exposure period, fish were transferred to recovery tanks containing freshwater for a 96-h mortality evaluation period. Tests were conducted at 12, 20, or 27°C, and all concentrations were tested in triplicate. Effective contact time tests more accurately estimated expected field treatment mortality than did acute toxicity tests for exposures of 12 h or less. The acute toxicity trials for silver carp and bigheaded carp underestimated antimycin toxicity for 12-h exposures and overestimated Prenfish toxicity. In effective contact time trials, Prenfish-treated fish became immobilized early in the exposures and appeared moribund; however, many of these fish recovered in freshwater. Antimycin-treated fish that appeared unaffected by the chemical later died when placed in recovery tanks. Some native fish species survived antimycin or Prenfish exposures that killed Asian carp; however, the differences in sensitivity between these native fish species and Asian carp are not sufficient to permit selective removal of Asian carp from natural bodies of water. Their results also showed that Prenfish and antimycin were both more toxic in warmer water than in cooler water, and both compounds would be toxic to Asian carp if applied within label concentration guidelines.

144.) Teem, J.L., and Gutierrez, J.B. 2010. A theoretical strategy for eradication of Asian carps using a Trojan Y Chromosome to shift the sex ratio of the population. *In:* Chapman, D.C., and Hoff, M.H. (eds). Invasive Asian Carps in North America. American Fisheries Society Symposium 74:227–238.

The directed extinction of an exotic fish population is proposed using a genetic approach to drastically reduce the ratio of females to males within the population. In the proposed strategy, sex-reversed female fish containing two Y chromosomes (Fyy) are introduced into a normal fish population. The frequencies of each of the four expected genotypes of fish in the simulated population (Fxx, Fyy, Mxy, and Myy) were modeled with a set of coupled ordinary differential equations. The equations take into account birth rate, death rate, and a fixed carrying capacity of the system. Using computer-generated simulations, it was determined that the continuous introduction of a relatively small proportion of Fyy females to the normal population leads to extinction of the exotic fish over time. The proposed eradication strategy is relevant to fish species with an XY sex-determination system and that tolerate a YY genotype. Published literature suggests that Asian carps are likely to fulfill these criteria. However, technical barriers associated with sex reversal in Asian carps presently exist and must be overcome before implementation of a YY eradication strategy for Asian carps can be considered in practice. An idealized theoretical model for the eradication of Asian carps is thus presented.

145.) Teem, J.L., Gutierrez, J.B., Parshad, R.D. 2014. A comparison of the Trojan Y chromosome and daughterless carp eradication strategies. *Biological Invasions* 16(6):1217–1230.

Two autocidal genetic biocontrol methods have been proposed as a means to eliminate invasive fish by changing the sex ratio of the population: the Trojan Y Chromosome (TYC) strategy and the Daughterless Carp (DC) strategy. Both strategies were modeled using ordinary differential equations that allow the kinetics of female decline to be assessed under identical modeling conditions. When compared directly in an ordinary differential equation (ODE) model, the TYC strategy was found to result in female extinction more rapidly than a DC strategy (in each of three models tested in which the Daughterless autocidal fish contained an aromatase inhibitor gene in either two or eight copies). The TYC strategy additionally required the introduction of fewer autocidal fish to the target population to achieve local extinction of females as compared to the DC approach. The results suggest that the relatively lower efficiency of female reduction associated with the DC approach is a consequence of a greater capacity to produce females and also a reduced capacity to produce males as compared to the TYC system.

Management – Miscellaneous Management Implications

146.) Ao, M., and Bordoloi, S. 2000. Postcleithrum of silver carp, *Hypophthalmichthys molitrix* (Val. 1844), an authentic indicator for age determination. *Current Science* 79(7):945–946.

This study was designed to evaluate and determine the most accurate and dependable method for aging silver carp. Although different methods like tagging, length–frequency analysis, RNA–DNA ratios, glycine uptake by scales, hepatosomatic index, and structures like scales, otoliths, vertebrae, cleithra, opercular, dentary and frontal bones, fin spines, fin rays, medial nuchal, dorsal scutes, and clavicles 1–10 have been used in the past for the determination of age and growth rates of different fishes, there is no information regarding ageing of cyprinid fish by using cross-sections of the postcleithral bones. Out of all these structures, scales and otoliths have been widely used to assess age and growth. The authors determine that using the above-mentioned methods for age and growth determination can be ineffective when applied to silver carp and that using the postcleithral bones yields the most accurate and authentic estimations. Their results also showed that the long-term storage of these sections does not affect the clarity of the annual marks, which is a valuable attribute in data collection and storage.

147.) Charlebois, P.M., and TePas, K.M. 2011. Comprehensive plan for increasing effectiveness of bigheaded and silver carp outreach. *In:* Chapman, D.C., and Hoff, M.H. (eds). Invasive Asian Carps in North America. American Fisheries Society 74:191–197.

In the United States, a variety of outreach has been done on bigheaded carp and silver carp by a number of organizations and institutions. Because many of these outreach efforts were localized, non-localized entities often are unaware of them. Many of the entities conducting outreach, too, do not have a systematic bigheaded and silver carp (BSC) outreach plan, so their efforts may not be as efficient or effective as possible. To address these issues, the authors surveyed organizations in areas where BSC have been found and compiled the reported BSC outreach activities. They then created a comprehensive outreach plan as a template for those conducting BSC outreach and compared it to existing efforts. In this comparison, it was found that (1) targeted audiences could be more narrowly focused, (2) easily accessible tools could be more fully utilized, and (3) systematic evaluations need to be conducted to ensure that outreach efforts are effective. It is the hope of the authors that this compilation and the comprehensive outreach plan will help improve the collective future BSC outreach, making it more efficient and effective.

148.) Conover, G., Simmonds, R., Whalen, M. (eds). 2007. Management and control plan for bigheaded, black, grass, and silver carps in the United States. Asian Carp Working Group, Aquatic Nuisance Species Task Force, Washington, D.C. 223 pp.

This report summarizes the current concerns and issues associated with bigheaded, black, grass, and silver carp and provides a detailed species overview for each, including their biology, introductions in the U.S., present distribution and abundance in the U.S., current uses within the U.S., and potential adverse effects. The foremost intent of this report was to prioritize research and control efforts. Included is a thorough list of strategy recommendations for (1) preventing accidental and deliberate unauthorized introductions in the U.S.; (2) containing and controlling the expansion of these feral populations; (3) extirpating or reducing to levels of insignificant effect; (4) minimizing potential adverse effects of feral carp populations in the U.S.; (5) providing information to the public, commercial entities, and government agencies to improve effective management and control of these populations; (6) conducting research to provide accurate and scientifically valid information necessary for the effective management and control; and (7) effectively planning, implementing, and evaluating management and control efforts of carp populations throughout the U.S.

149.) Haugen, S. 2012. Preventing the invasion of Asian carps: An analysis of issues in governance and management for the Upper Mississippi River Basin. Thesis. University of Minnesota.

A need was identified to illustrate the cooperating networks of actors that are shaping efforts and managing the aquatic resources for the Upper Mississippi River Basin and to provide a synthesis of the economic ramifications, risks, legal frameworks, and policy instruments currently being considered to control these aquatic pests. A larger implication for this research is to provide a useful guide for analyzing governance dilemmas with high degrees of complexity and interests. Methods begin with isolating suspected pathways of *Hypophthalmichthys*, *Ctenopharyngodon,* and *Mylopharyngodon* introduction and assessing their risk levels, followed by developing a matrix of legal tools and gap analysis, proceeding to surveys of expert stakeholders to gauge preferred alternatives, and, finally, providing a makeup of the federal and state response to the issue area. Results of the survey and subsequent analysis conclude that effort is significant but barriers prevail in the form of unclear jurisdictional authority, lack of robust funding, and divergent interests. The chosen course of action combines biological, physical, and/or behavioral deterrents as subsets of a larger integrated pest management model and incorporates this into a regional management plan that is individualized and idiosyncratic.

150.) Hoff, M.H., Pegg, M.A., Irons, K.S. 2010. Management implications from a stock-recruit model for bigheaded carp in portions of the Illinois and Mississippi Rivers. American Fisheries Society Symposium 74:5–14.

The Aquatic Nuisance Species Task Force, Mississippi River Basin Panel on Aquatic Nuisance Species, Mississippi Interstate Cooperative Resource Association, and other entities established goals to control feral populations of bigheaded carp in the United States. The Asian Carp Working Group recommended development of stock-recruit models for bigheaded carp and other Asian carps to assist in management and control of feral populations. In this study the authors developed a Ricker stock-recruit model, using bigheaded carp relative abundance data collected in the LaGrange Reach of the Illinois River and Pool 26 of the Mississippi River from 2001 to 2004 to guide management and control efforts there. The functional relationship that explained the greatest amount of recruitment variation (83 percent) from July to October of the first year of life used stock size and river discharge. Seventy-two percent of recruitment variation was explained by stock size abundance, while an additional 11 percent was explained by the coefficient of variation of discharge in July. Model predictions and empirical data indicated that management efforts to reduce stock size abundance from the optimum of 0.07 adults per unit of standardized fishing effort to 0.02 adults per unit of effort should be the most effective tool to reduce recruitment over the long term. This level of adult abundance (approximately 25 percent of the mean from 2001 to 2004) should be the target maximum for bigheaded carp control efforts in the study areas. Recruitment was inversely correlated with variation in river discharge, so it is possible to combine control of stock size abundance and management of river discharge in an integrated pest management program for bigheaded carp in the two river reaches.

151.) Johal, M.S., Esmaeili, H.R., Tandon, K.K. 2001. A comparison of back-calculated lengths of silver carp derived from bony structures. *Journal of Fish Biology* 59(6):1483–1493.

Linear relationships were found between body length–scale radius, body length–cleithrum length, and body length–urohyal length (r=0· 949, 0· 984, and 0· 974, respectively) in silver carp. Out of 180 comparisons, which were made between different methods of back-calculating length and ageing structures at ages 2–7 years, the differences were not significant (P≥ 0· 05) in 132 (73· 3 percent) cases. There were no significant differences among different methods in older age classes and between the Fraser-Lee method and body proportional method (BPH) at all ages. The results demonstrated that, in all structures, back-calculated lengths estimated by the scale proportional hypotheses (SPH) were less than the other methods. For scales, SPH was similar to the direct proportional method of Dahl-Lea (DPM), but for cleithra and urohyal bones, it was similar to BPH and Fraser-Lee. As the fish increased in age, the differences between back-calculated lengths decreased. When lengths were back-calculated using cleithra and urohyal bones, differences between the structures at age 2 years were 17 mm from DPM, 33 mm from SPH, 37 mm from BPH, and 37 mm from Fraser-Lee, while at age 8 years, mean differences were 7 mm from DPM and 8 mm from the SPH, BPH, and Fraser-Lee methods. It is suggested that the differences would be less if: (1) back-calculated lengths are based on a large number of random samples; (2) measurements of scale radius, cleithrum length, and urohyal length were more precise; (3) determination of focus or origin were more precise; and (4) the sampling of scales was from the same row.

152.) Meronek, T.G., Bouchard, P.M., Buckner, E.R., Burri, T.M., Demmerly, K.K., Hatleli, D.C., Klumb, R.A., Schmidt, S.H., Coble, D.W. 1996. A review of fish control projects. *North American Journal of Fisheries Management* 16(1):63–71.

In this study the authors searched the fisheries literature to assess the success of fish control projects. They reviewed 250 control projects from 131 papers. Usually each treated body of water was considered a project. Fish control treatments were divided into four categories: chemical applications (145), physical removal and reservoir drawdowns (70), stocking of fish (29), and any combination of chemical and physical methods (6). Success was judged by changes in standing stock, growth, proportional stock density, relative weight values, catch or harvest rates, and other benefits, such as angler satisfaction. Reduction in standing stock was the most common determinant of success. Of the 250 projects, 107 (43 percent) were considered to be successful, 74 (29 percent) to be unsuccessful, and 69 (28 percent) to have insufficient data to determine success. The most successful projects targeted rough fish. Total elimination was more successful (63 percent) than partial reduction (40 percent) in 221 waters. Success was not strongly related to size of water body. Success of chemical application was similar for treatment with rotenone (48 percent) and with antimycin (45 percent). Success rates for physical removal methods (nets, traps, seines, electrofishing, drawdowns, and combinations of physical treatments) ranged from 33 to 57 percent. Stocking certain species of fish to control others was the least successful—7 of 29 water bodies (24 percent). Combined chemical and physical methods were successful in four of six projects (66 percent). Stocking after chemical or physical treatment may have increased success of fish control projects; 10 of 17 such projects (59 percent) were successful, a higher percentage than for chemical treatments, physical treatments, or stocking alone. An overall success rate of less than 50 percent for such a large number and wide variety of projects indicates that there is considerable room for improvement of fish control projects.

153.) Norman, J.D. 2013. Identifying environment of origin of Illinois River Asian carp via otolith microchemistry and stable isotope analyses. Thesis. Southern Illinois University.

The primary objective of this study was to identify differences in natal river origin and floodplain habitat use through the incorporation of trace elements (Sr:Ca) and stable isotopes ($\delta^{18}O$ and $\delta^{13}C$). Silver and bigheaded carp were collected via electrofishing and trammel netting along four reaches of the Illinois River from the Mississippi-Illinois River confluence at Grafton, Illinois, to the upper segment of the Illinois River upstream of Starved Rock State Park. Sagittal otoliths were removed from both silver and bigheaded carp collected from each of the four reaches of the Illinois River for analysis of stable isotope ratios and trace element concentrations. Water samples were collected seasonally from the four reaches of the Illinois River and several of its associated floodplain lakes in addition to the Missouri, Upper Mississippi, and Middle Mississippi Rivers to validate water signatures of the various river reaches. Results indicated the majority of adult Asian carp caught in the Illinois River originated from the Illinois. However, there was strong evidence indicating roughly 20 percent of captured adults were in fact immigrants from other sources; primarily the Middle Mississippi River and, to a lesser extent, the Missouri River. Stable isotope results indicated that Asian carps primarily used river channel rather than floodplain lake habitats during early life. The findings of this study suggest current Asian carp removal efforts should continue to be primarily directed within the Illinois River; however, the evidence of immigrant silver carp indicate expanding the control efforts into other rivers (Middle Mississippi River and Missouri River) will further support the control of Asian carp within the Illinois River.

154.) Rasmussen, J.L. 2011. Regulations as a tool in Asian carp management. *In:* Chapman, D.C. and Hoff, M.H. (eds). Invasive Asian Carps in North America. American Fisheries Society Symposium 74:175–189.

Regulations are one of the few tools available in the aquatic invasive species (AIS) management toolbox. Ideally, they could be used to effectively prevent spread of AIS from watershed to watershed or from continent to continent. But the regulations needed to prevent invasions by species such as Asian carps in North America and the United States are slow to evolve and used reluctantly by federal authorities because they are heavily influenced by regional and national political and economic considerations. State regulations, on the other hand, suffer from the influence of their own local and regional political and economic issues. Some states maintain strict policies and regulations with regard to Asian carp possession and use, but neighboring states may not. And since a vast network of rivers, waterways, streams, and roadways connects 48 of the 50 U.S. states, invasions continue to occur and spread. Consequently, Asian carp management in the United States is largely controlled by "least common denominator" state regulation that applies in a given watershed and beyond. This paper presents an overview of Asian carp regulations in the 50 U.S. states and offers suggestions for improved regulations.

155.) Seibert, J.R., and Phelps, Q.E. 2013. Evaluation of aging structures for silver carp from midwestern U.S. rivers. *North American Journal of Fisheries Management* 33(4):839–844.

The primary objective of this study was to determine which aging structure should be used when determining age of silver carp. The authors collected 120 silver carp from the Illinois, Mississippi, Missouri, and Ohio Rivers via electrofishing to evaluate aging structures. Removal time, processing time, and discernible annuli were evaluated for scales, opercles, vertebrae, pectoral fin rays, postcleithra, and asterisci and lapilli otoliths. Asteriscus otolith, opercle, and scale annuli were difficult to discern and not evaluated further. Total processing times for postcleithra (246.1 s) and lapilli (251.2 s) were the most efficient; pectoral fin rays and vertebrae were more time-intensive. Between-reader precision and agreement rates resulted in lapilli being the most precise, followed by postcleithra, pectoral fin rays, and vertebrae. Comparisons of structures with lapilli revealed that pectoral fin rays exhibited 78 percent agreement, 49 percent agreement with postcleithra, and 53 percent agreement for vertebrae. In terms of agreement ±1 year to lapilli, pectoral fin ray, postcleithrum, and vertebra resulted in high agreement (>85 percent). Age bias plots revealed that these discrepancies consistently underestimated ages compared with lapilli. Discrepancies may be attributed to erosion of the central lumen of fin rays and postcleithra, while locating the first annulus on vertebrae may have led to this disparity. Based on previous studies, evaluation of overall processing times, assessment of between-reader precision, between-reader agreement rates, and bias that may be involved with alternative structures, the authors recommend that lapilli otoliths be used for estimating age of silver carp. In conclusion, they recommend that future efforts should focus on validating accuracy of lapilli for estimating silver carp ages.

156.) Wilson, C., Wright, E., Bronnenhuber, J., MacDonald, F., Belore, M., Locke, B., MacNeil, C., Campbell, M. 2014. Tracking ghosts: Combined electrofishing and environmental DNA surveillance efforts for Asian carps in Ontario waters of Lake Erie. *Management of Biological Invasions* 5(3):225–231.

In this study the authors developed and applied environmental DNA (eDNA) markers to screen for occurrences of bigheaded, silver, and grass carp in Lake Erie, Lake St. Clair, and their tributaries, as part of ongoing efforts to prevent these carps from becoming established in the Great Lakes. A network of 180 sites was sampled using both boat electrofishing and/or eDNA sampling throughout the 2012 open-water season. No indications of carps were found via either method. These combined results suggest that these species are not yet established in Ontario waters of Lake Erie or Lake St. Clair.

Management – Commercial Harvest

157.) Garvey, J.E., Sass, G.G., Trushenski, J., Glover, D., Charlebois, P.M., Levengood, J., Roth, B., Whitledge, G., Small, B.C., Tripp, S.J. 2012. Fishing down the bigheaded and silver carps: Reducing the risk of invasion to the Great Lakes. Illinois Department of Natural Resources. http://asiancarp.us (184 pages).

In this study the authors used telemetry to quantify the movement of Asian carp from the adjacent Mississippi River into the Illinois River, which allowed them to determine the factors affecting upstream movement and the replenishment rate of carp from downstream as they are removed from the Illinois River. The density and biomass of Asian carp and native fish were unknown in the Illinois River. They conducted the most comprehensive estimate of a main-channel fish assemblage in history using research-grade, down-looking hydroacoustics coupled with other sampling techniques. Mortality and reproductive potential of the Asian carp were determined to assess how resilient Asian carp would be to control by harvest and other methods. Asian carp are harvested and a market is currently growing. The authors determined nutrient content, conta-

minant concentration, and quality of these fish throughout the river. To date, fishing is the only feasible and effective control mechanism in the Illinois River. Research was conducted to determine how marketing plus incentives might help facilitate fishing as an effective way to reduce Asian carp while enhancing sustainable harvest of native fishes. The results of this research effort showed that Asian carp densities and biomass in the Illinois River are high, but relative to major fisheries and aquaculture production of the world, they are well smaller than those in fisheries that have collapsed, including the one in the species' native Yangtze River.

158.) Tsehaye, I., Catalano, M., Sass, G., Glover, D., Roth, B. 2013. Prospects for fishery-induced collapse of invasive Asian carp in the Illinois River. *Fisheries* 38(10):445–454.

The state of Illinois initiated a fishing program aimed at reducing Asian carp densities through intensive commercial exploitation on the Illinois River. In this study, the authors explore prospects for the "collapse" of Asian carp in the Illinois River through intensive fishing. Based on a meta-analysis of demographic data, they developed a dynamic simulation model to compare the performance of existing and alternative removal strategies for the Illinois River. Their model projections suggest that Asian carp in the Illinois River are unlikely to collapse if existing harvest rates are kept below 0.7 or fishing continues to be size-selective (targeting only fish >500 mm or <500 mm) or species-selective (targeting mostly bigheaded carp), although their biomasses could be greatly reduced. The authors argue that it would still be possible to achieve fishing effort targets predicted by their model to collapse the Asian carp populations if efforts to expand commercial fishing are combined with economic incentives to improve size selectivity and species targeting.

159.) Varble, S., and Secchi, S. 2013. Human consumption as an invasive species management strategy. A preliminary assessment of the marketing potential of invasive Asian carp in the U.S. *Appetite* 65:58–67.

This study analyzes the results of the first national survey on the attitudes of U.S. fish consumers toward Asian carp. Results were encouraging and found that most respondents (72 percent) would be willing to try a free sample and would be willing to pay for Asian carp. Because of the negative connotation attached to carp in general, this figure is encouraging. Creating demand for Asian carp could be a market-based, cost-effective solution for a problem that is typically dealt with through command and control policies, but it should be coupled with appropriate policies and safeguards to ensure the fish is eventually eradicated and not cultivated for profit after removal from U.S. rivers and lakes.

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Appendix A – List of Species Mentioned in Annotations

Vertebrates (Fish):

Alewife	*Alosa pseudoharengus*
American paddlefish	*Polyodon spathula*
Atlantic menhaden	*Brevoortia tyrannus*
Australian smelt	*Retropinna semoni*
Bigheaded carp	*Hypophthalmichthys nobilis*
Bigmouth buffalo	*Ictiobus cyprinellus*
Black buffalo	*Ictiobus niger*
Black carp	*Mylopharyngodon piceus*
Bluegill	*Lepomis macrochirus*
Blue catfish	*Ictalurus furcatus*
Bony herring	*Nematalosa erebi*
Catla	*Catla catla*
Channel catfish	*Ictalurus punctatus*
Chinook salmon	*Oncorhynchus tshawytscha*
Common carp	*Cyprinus carpio*
Crimson spotted rainbowfish	*Melanotaenia duboulayi*
Emerald shiner	*Notropis atherinoides*
Fathead minnow	*Pimephales promelas*
Freshwater drum	*Aplodinotus grunniens*
Gizzard shad	*Dorosoma cepedianum*
Grass carp	*Ctenopharyngodon idella*
Largemouth bass	*Micropterus salmoides*
Largescale silver carp	*H. harmandii*
Mosquitofish	*Gambusia affinis*
Nile tilapia	*Oreochromis niloticus*
Northern snakehead	*Channa argus*
Quillback carpsucker	*Carpiodes carpio*
Rainbow smelt	*Osmerus mordax*
Rainbow trout	Oncorhynchus mykiss River shiner
	Notropis blennius
Shovelnose sturgeon	*Scaphirhynchus platorynchus*
Silver carp	*H. molitrix*
Smallmouth buffalo	*Ictiobus bubalus*
Spot	*Leiostomus xanthurus*
Tench	*Tinca tinca*
Western carp gudgeon	*Hypseleotris klunzingeri*
White perch	*Morone americana*
Yellow perch	*Perca flavescens*

Vertebrates (Birds):

Brown pelican	*Pelecanus occidentalis*
Great-blue heron	*Ardea herodias*
White pelican	*Pelecanus erythrorhynchos*

Invertebrates (Plankton):

Anuraeopsis fissa
Asplanchna sp.
Brachionus spp.
Cyclops vicinus
Daphnia galeata sars.
Diaphanosoma brachyurum
Keratella cochlearis
Mescyclops notiius
Moina micrura
Polyarthra dolichoptera
Polyarthra vulgaris
Scapholeberis kingi
Sinodiaptomus sarsi
Synchaeta oblonga
Theromcyclops brevifuratus
Theromcyclops taihokuensis
Trichocerca pusilla

Invertebrates (Algae and Bacteria):

Ankistrodesmus
Chlamydomonas
Cosmarium
Cryptomonas
Kirchneriella
Microcystis viridis
Rhodomonas
Proteus rettgeri

Invertebrates (Diatoms and Dinoflagellates):

Cyclotella
Navicula
Synedra
Peridinium

Appendix B – Glossary of Terms Used in Bibliography

Abiotic: the component of the environment that includes soil, water, air, light, nutrients, and the like; the nonliving.

Acclimatized: a physiological or behavioral response to changes in a complex of environmental factors and/or conditions.

Acute toxicity: adverse effects of a substance that result either from a single exposure or from multiple exposures in a short space of time (usually less than 24 hours).

Akaike's information criteria: a measure of the relative quality of a statistical model for a given set of data.

Alimentary tract: pathway by which food enters the body and solid wastes are expelled.

Allozyme: variant forms of an enzyme that are coded by different alleles at the same locus.

Amino acid: a simple organic compound containing both a carboxyl (—COOH) and an amino (—NH2) group.

Annulus: a ringlike figure, part, structure, or marking, such as a growth ring on the scale of a fish.

Anthropogenic: of, relating to, or resulting from the influence of human beings on nature; originating from human activity.

Antioxidant: a substance that inhibits oxidation, especially one used to counteract the deterioration of stored food products.

Aromatase inhibitor gene: genes that stop the production of estrogen.

Assimilation efficiency: the efficiency with which energy is transferred from one trophic level to the next.

Atresia: absence or abnormal narrowing of an opening or passage in the body; the degeneration of those ovarian follicles that do not ovulate during the menstrual cycle.

Autocidal: effected by the introduction of sterile or genetically altered individuals into the wild population.

Backwater: a temporarily isolated area of a river that is not reached by current or the main channel except during periods of high water.

Benthic: the behavior of an organism that inhabits the bed or substrate of an aquatic ecosystem.

Billabong: a branch of a river forming a backwater or stagnant pool, made by water flowing from the main stream during a flood.

Bimodal distribution: a continuous probability distribution with two different modes.

Biological control: the control of a pest by the introduction of a natural enemy or predator.

Biomanipulation: the deliberate alteration of an ecosystem by adding or removing species, typically of a specific trophic level.

Biomass: the total mass of organisms in a given area or volume.

Biotic: the living component of an ecosystem.

Biotic resistance: the ability of a resident species in a community to reduce the success of exotic invasions.

Carrying capacity: the maximum population size of the species that the environment can sustain indefinitely, given the food, habitat, water, and other necessities available in the environment.

Calanoid: an order of copepods.

Cephalopods: an active predatory mollusk of the large class *Cephalopoda*, such as an octopus or squid.

Cessation: the fact or process of ending or being brought to an end.

Chlorophyll a: a green pigment, present in all green plants and in cyanobacteria, responsible for the absorption of light to provide energy for photosynthesis.

Chlorophytes: a division of eukaryotic green algae.

Chromatography: the separation of a mixture by passing it in solution or suspension or as a vapor through a medium in which the components move at different rates.

Chronic toxicity: a property of a substance that has toxic effects on a living organism, when that organism is exposed to the substance continuously or repeatedly.

Chydrorids: a family of small water fleas.

Cladoceran: an order of small crustaceans commonly called water fleas.

Clavicle: a bone of the pectoral girdle that links the scapula and sternum, situated just above the first rib on either side of the neck.

Cleithra: bone external to and beside the clavicle in the pectoral arch of some fishes, stegocephalians, and primitive reptiles.

Cohort: a group of individuals of the same age.

Competition: any interaction that is mutually detrimental to both participants, occurring between species that share limited resources.

Concomitant: naturally accompanying or associated.

Condition factor (K): a measure of an individual fish's health that uses standard weight.

Confluence: the junction of two rivers.

Conspecific: a member of or belonging to the same species.

Copepod: a group of small crustaceans found in nearly every aquatic habitat.

Cryoprotection: a method that uses a substance to protect biological tissue from freezing damage.

Cyanotoxin: toxins produced by bacteria called cyanobacteria.

Depuration: the action or process of freeing something of impurities.

Diatoms: unicellular, major group of algae; producers that typically exist as colonies.

Diel: denoting or involving a period of 24 hours.

Diploid: containing two complete sets of chromosomes, one from each parent.

Discharge: the release of a fluid that has been previously confined.

Discriminant function analysis: a statistical analysis to predict a categorical dependent variable by one or more continuous or binary independent variables.

Dissolved solids: minerals, salts, metals, cations, or anions dissolved in water.

Earthen pond: any pond that is sealed with soil such as clay.

Effluent: liquid waste or sewage discharged into an aquatic ecosystem.

Electrofishing: method of sampling using an electrical field to stun and count or collect aquatic organisms, typically fish.

Electrophoresis: the movement of charged particles in a fluid or gel under the influence of an electric field.

Embayment: a recess in a coastline forming a bay.

Enemy release: a decrease in regulation by predators and other natural enemies, resulting in a rapid increase in distribution and abundance.

Eradicate: the complete removal or destruction of an organism.

Estuaries: the tidal mouth of a large river, where the tide meets the stream.

Eutrophic: a lake or other body of water rich in nutrients and so supporting a dense plant population, the decomposition of which kills animal life by depriving it of oxygen.

Eutrophication: excessive richness of nutrients in a lake or other body of water, frequently due to runoff from the land, which causes a dense growth of plant life and death of animal life from lack of oxygen.

Extirpation: the condition of a species that ceases to exist in the chosen geographic area of study, though it still exists elsewhere; local extinction.

Fecundity: the number of live offspring produced by an organism; the state of being fertile; capable of producing offspring.

Fingerling: a small, juvenile fish.

Floodplain: an area of low-lying ground adjacent to a river, formed mainly of river sediments and subject to flooding.

Flood pulse: a biologically productive feature in a river's ecosystem in which there are periods of water rise causing an influx of new organic matter.

Flow velocity: a vector quantity used to describe the motion of a fluid.

Fork length: the length of a fish measured from the most anterior part of the head to the deepest point of the notch in the caudal (tail) fin.

Gas bladder: swim bladder; an internal gas-filled organ that contributes to the ability of a fish to control its buoyancy.

Genetic divergence: the process in which two or more populations of an ancestral species accumulate independent genetic changes (mutations) through time, often after the populations have become reproductively isolated for some period of time.

Gill arches: any of a series of bony or cartilaginous curved bars along the pharynx, supporting the gills of fish and amphibians.

Gill raker: bony or cartilaginous processes that project from the branchial arch (gill arch) and are involved with suspension feeding tiny prey.

Gonadosomatic index: the calculation of the gonad mass as a proportion of the total body mass.

Gram-negative bacteria: a class of bacteria that do not retain the crystal violet stain used in the Gram staining method of bacterial differentiation, making positive identification possible.

Haplotype: a set of DNA variations, or polymorphisms, that tends to be inherited together.

Helminth: a parasitic worm; a fluke, tapeworm, or nematode.

Hepatosomatic index: the ratio of liver weight to body weight.

Herbivorous: behavior of feeding on matter of plant origin.

Heterotroph: an organism that cannot fix carbon and must use organic carbon obtained from feeding on plant or animal matter for growth.

Homozygous: having the two genes at corresponding loci on homologous chromosomes identical for one or more loci.

Hydrodynamics: the motion of fluids and the forces acting on solid bodies immersed in fluids and in motion relative to them.

Hydrographs: a graph showing the rate of flow (discharge) versus time past a specific point in a river or other channel or conduit carrying flow.

Hydrology: branch of science concerned with the properties of the earth's water, especially its movement in relation to land.

Hydrolysis: the chemical breakdown of a compound due to reaction with water.

Hydrophilic: having a tendency to mix with, dissolve in, or be wetted by water.

Hydrophobic: tending to repel or fail to mix with water.

Hydrophone: a microphone that detects sound waves under water.

Hypoxia: Depletion of dissolved oxygen in aquatic environments to levels that are detrimental or fatal to aerobic organisms, often caused by eutrophication.

Ichthyoplankton: the eggs and larvae of fish.

Incipient invasion: the initial stage or state of an invasive species or population moving into a new area.

Independent sampling: two or more samples selected from the same population or different populations that have no effect on one another.

Indigenous: originating or occurring naturally in a particular place; native.

Inducible gene: a gene whose expression is either responsive to environmental change or dependent on the position in the cell cycle.

Infrasound: sound waves with frequencies below the lower limit of human audibility.

Inoculation: to introduce a serum, vaccine, or antigenic substance into the body of an organism.

Integrated pest management: an ecosystem-based strategy that focuses on long-term prevention of pests or their damage through a combination of techniques such as biological control, habitat manipulation, modification of cultural practices, and use of resistant varieties.

Intersex: the abnormal condition of being intermediate between male and female; hermaphroditism.

Introgression: the transfer of genetic information from one species to another as a result of hybridization between them and repeated backcrossing.

Inundation: to flood; cover or overspread with water; deluge.

Invasibility: the ability or success of an invader.

In-vitro incubation: a process of the incubation of egg and sperm within a laboratory setting or a controlled environment.

Isotope: each of two or more forms of the same element that contain equal numbers of protons but different numbers of neutrons in their nuclei, and hence differ in relative atomic mass but not in chemical properties.

Lagrangian model: a function that describes the state of a dynamic system in terms of position coordinates and their time derivatives; equal to the difference between the potential energy and kinetic energy.

Lignification: the process of converting into wood or woody tissue.

Limnetic zone: the well-lit, open surface waters in an aquatic ecosystem.

Littoral zone: the area of an aquatic ecosystem that is close to the shore.

Locus (plural loci): the specific location of a gene, DNA sequence, or position on a chromosome.

Macrozooplankton: any relatively large plankton, visible to the naked eye; the minimum size is defined in various sources as from 0.5 mm to 5.0 mm.

Meristic: an area of ichthyology that relates to counting quantitative features of fish, such as the number of fins or scales.

Mesocosm: an experimental tool that brings a small part of the natural environment under controlled conditions.

Microcrustacean: very small crustaceans.

Microhabitat: a habitat that is of small or limited extent and that differs in character from some surrounding, more extensive habitat.

Microscopy: the use of the microscope.

Microspheres: a microscopic hollow sphere, especially of a protein or synthetic polymer.

Mitogenome: mitochondrial genome.

Monoculture: the cultivation of a single organism in a given area.

Morphometric: the quantitative measurement of the form especially of living systems or their parts.

Myotomes: the dorsal part of each somite in a vertebrate embryo, giving rise to the skeletal musculature.

Nauplii: the first larval stage of many crustaceans, having an unsegmented body and a single eye.

Navigation pools: the area between navigation dams.

Negative binomial distribution: a discrete probability distribution of the number of successes in a sequence of independent and identically distributed Bernoulli trials before a specified (non-random) number of failures occurs.

Nematode: an unsegmented worm of the large phylum *Nematoda*, such as a roundworm or threadworm.

Niche: the area in which an organism or population responds to the distribution of resources and competitors and how the organism in turn affects those same factors; functional role of a species in the community, including activities and relationships.

Niche modeling: the process of using computer algorithms to predict the distribution of species in geographic space on the basis of a mathematical representation of their known distribution in environmental space.

Nonindigenous: member (i.e., individual, group, or population) of a species that enters a body of water or aquatic ecosystem outside of its historic or native range.

Novel ecosystem: human-built, modified, or engineered niches in an environment; places that have been altered in structure and function by human agency.

Nucleotide: a compound consisting of a nucleoside linked to a phosphate group that forms the basic structural unit of nucleic acids such as DNA.

Nursery: a subset of all habitats where juveniles of a species occur, having a greater level of productivity per unit area than other juvenile habitats.

Omission error: a mistake that consists of not doing something that should have been done, or not including something (such as an amount or fact) that should be included.

Omnivorous: behavior of feeding on food of both plant and animal origin.

Ontogeny: the development or course of development of an individual organism.

Opercula: a structure that closes or covers an aperture, in particular.

Osmoregulation: the active regulation of the osmotic pressure of an organism's fluids to maintain the homeostasis of the organism's water content.

Ostracod: a class of crustaceans sometimes known as seed shrimp.

Otolith: each of three small oval calcareous bodies in the inner ear of vertebrates, involved in sensing gravity and movement.

Oxbow lake: a U-shaped body of water that forms when a wide meander from the main stem of a river is cut off, creating a free-standing body of water.

Pelagic: behavior of inhabiting the open water; being neither close to the bottom nor near the top.

Peptides: a compound consisting of two or more amino acids linked in a chain, the carboxyl group of each acid being joined to the amino group of the next by a bond of the type -OC-NH-.

Periodicity: the quality or character of being periodic; the tendency to recur at intervals.

Phenotypic plasticity: the ability to change form under different environmental conditions and pressures.

Phonotaxic: The ability to move in an orientation with respect to a source of sound.

Phylogeny: the evolution of a genetically related group of organisms as distinguished from the development of the individual organism.

Phytophagous: an organism that feeds on plant materials.

Piscivorious: a carnivorous organism that primarily consumes fish.

Planimetric: of, relating to, or made by means of a planimeter; planimetric measurements of a map.

Planktivorous: an aquatic organism that feeds on planktonic food, including zooplankton and phytoplankton.

Platymonas: a genus of algae.

Ploidy: the number of sets of chromosomes in a cell or in the cells of an organism.

Polyculture: the simultaneous cultivation or exploitation of several crops or kinds of animals.

Principle component analysis: a statistical procedure that uses an orthogonal transformation to convert a set of observations of possibly correlated variables into a set of values of linearly uncorrelated variables called principal components.

Proportional size distribution: indices that are convenient measures for numerically summarizing size structure of fish populations.

Protein hydrolysate: a mixture of amino acids obtained by the hydrolysis of various animal and plant proteins and used as a source of amino acids, as a seasoning agent, and in nutrition.

Protozoans: a single-celled microscopic animal of a group of phyla of the kingdom Protista, such as an amoeba, flagellate, ciliate, or sporozoan.

Protracted spawning: spawning in which a species extends or draws out and lengthens the duration of the spawn, typically dependent on environmental conditions.

Radiotelemetry: the use of radio waves for transmitting information from a distant instrument to a device that indicates or records the measurements

Rarefaction: diminution in the density of something; the lessening of density of tissue or air and gas.

Recruitment: increase in a natural population as progeny grow, develop, and are admitted to the population.

River basin: portion of land drained by a river and its tributaries that encompasses all of the land surface dissected and drained by all associated watersheds.

River channel: a type of landform consisting of the outline of a path of relatively shallow and narrow body of fluid, most commonly the confine of a river, river delta, or strait.

River mainstem: the primary downstream segment of a river, as contrasted to its tributaries.

Rotifer: organism of the phylum *Rotifera* that is made up of microscopic and near-microscopic pseudocoelomate plankton.

Sagittal: relating to or denoting the suture on top of the skull that runs between the parietal bones in a front to back direction.

Scute: a thickened, horny or bony plate on the external surface of an organism.

Secchi disk: a disk, divided into black and white quarters, used to gauge water clarity by measuring depth at which it is no longer visible from the surface.

Seed vigor: the sum total of those properties of the seed that determine the level of activity and performance of the seed or seed lot during germination and seedling emergence.

Seine: a large net with sinkers on one edge and floats on the other that hangs vertically in the water and is used to enclose and catch fish or other aquatic organisms when its ends are pulled together or are drawn ashore.

Seston: the organisms and non-living matter swimming or floating in a water body.

Settling velocity: the rate at which suspended solids subside and are deposited.

Shear dispersion: results from lateral and/or vertical variability in current velocities that tend to "smear" the distribution of constituents throughout an aquatic environment.

Sink: an unfilled, submarginal, or marginal habitat where the population can persist only by immigration from other habitats because it experiences low reproduction or high mortality.

Sinuosity: the ability to curve or bend easily and flexibly.

Soft water: water that is free from dissolved salts of such metals as calcium, iron, or magnesium, which form insoluble deposits.

Spatial variation: variation within a system in relation to distribution.

Species composition: the identity of all different organisms that make up a community.

Species diversity: a measurement that relates the density of organisms of each type present in a habitat to the number of species in a habitat.

Species evenness: a component of species diversity index; it is a measure of distribution of individuals among total species occupying a given area.

Species richness: number of species in a given area.

Standard length: the distance on a fish from the tip of the snout, or of the lower jaw if projecting forward, to the base of the caudal (tail) fin.

Stenohalinity: the ability of aquatic organisms to tolerate only a narrow range of salinity.

Sterility: the quality or condition of being unable to reproduce.

Stream order: a measure of the relative size of streams ranging from the smallest, first-order, to the largest, twelfth-order.

Substrate: the stratum that comprises the bottom of a marine habitat, or one that forms the bed of a stream or river.

Taxonomy: the study of the general principles of scientific classification; systematics.

Telemetry: the wireless transmission and reception of measured quantities for the purpose of remotely monitoring environmental conditions or equipment parameters.

Temporal variation: variation within a system in relation to time.

Trammel net: a set-net consisting of three layers of netting, designed so that a fish entering through one of the large-meshed outer sections will push part of the finer-meshed central section through the large meshes on the farther side, forming a pocket in which the fish is trapped.

Transgene: a gene or genetic material that has been transferred naturally, or by any of a number of genetic engineering techniques from one organism to another.

Tributary: a river or stream flowing into a larger river or lake.

Triploid: containing three homologous sets of chromosomes.

Trophic: of or relating to feeding and nutrition.

Turbidity: a measure of water clarity by how much the material suspended in water decreases the passage of light through the water.

Turbulent diffusion: the transport of mass, heat, or momentum within a system due to random and chaotic time-dependent motions.

Von Bertalanffy growth equation: a measure that predicts the length of an organism as a function of its age.

Water column: a conceptual column of water from the surface of a sea, river, or lake to the bottom sediments.

Water hardness: a measure of the amount of calcium and magnesium salts in water.

Wing dike: a manmade barrier that, unlike a conventional dam, only extends partway into a river and forces water into a fast-moving center channel; reduces the rate of sediment accumulation while slowing water flow near the riverbanks.

Young-of-year: Age-0 fish, or those animals born within the past year, from transformation to juvenile until January 1 in the Northern Hemisphere or July 1 in the Southern Hemisphere, which have not yet reached 1 year of age; abbreviated YOY.

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