Received: 19 September 2023 | Revised: 7 February 2024 | Accepted: 12 February 2024

DOI: 10.1002/edn3.528

SPECIAL ISSUE ARTICLE

Environmental DNA Open Access
Dedicated to the study and use of environmental DNA for basic and applied sciences

WILEY

Lessons learned from eDNA adoption in the management of bigheaded carps in Chicago IL USA Area Waterways

David M. Lodge

Cornell Atkinson Center for Sustainability, and Department of Ecology and Evolutionary Biology, Cornell University, Ithaca, New York, USA

Correspondence
David M. Lodge, Cornell Atkinson Center for Sustainability, Cornell University, Ithaca, NY 14850, USA.
Email: dml356@cornell.edu

Funding information
Oceankind

Abstract

The Chicago Area Waterway System (CAWS) connects the Great Lakes watershed with the Mississippi watershed via canals that withdraw water from Lake Michigan. From 2009 through 2011, collaborators and I provided research, development, and application of eDNA to invasive species management in the CAWS in cooperation with the US Army Corps of Engineers (USACE). The research team's approach was a high-stakes test of a novel combination of proven technologies (field sampling techniques and laboratory genetics). In the first application of eDNA to a large scale, urgent management goal, we quickly discovered eDNA of two species of bigheaded carps in parts of the waterway where traditional tools had not captured fish. The central research question was whether the sensitivity (probability of detecting a fish when it was present) of eDNA was higher than that of traditional fish sampling tools (e.g., nets, electrofishing). The effort was part of what became a very large, complex, on-going initiative to reduce access by invasive species to Lake Michigan. This immediately garnered much attention, initiating a dialog about the reliability of eDNA, public discussion about the benefits and costs of the CAWS, and skepticism from industries that use the CAWS. Government agencies formed the Asian Carp Rapid Response Workgroup, which eventually became the Invasive Carp Regional Coordinating Committee (ICRCC). The ICRCC continues its coordinating role on the use of eDNA and other management responses in the CAWS. With the benefit of hindsight, I draw several lessons from the experience that may help in other settings where eDNA is now being deployed with increasing confidence and acceptance; evaluate the on-going CAWS surveillance and management effort; and recommend strengthening the current approach by broadening and deepening participation in a collaborative governance approach. Stronger public-private partnerships would accelerate research, development, commercialization, and application of eDNA analysis to the benefit of society.

KEYWORDS
Asian carp, eDNA, governance, lessons, management, policy, technology adoption

1 | THE CHICAGO AREA WATERWAY SYSTEM AND BIGHEADED CARPS

The US Army Corps of Engineers (USACE) has authority over much of the infrastructure regarding navigation, flood control, and containment of invasive species in the Chicago Area Waterway System (CAWS; Figure 1). The CAWS is a waterway network including both natural channels and canals that reversed the flow of the Chicago River and other tributaries starting in 1900 so that water now flows out of Lake Michigan (Invasive Carp Regional Coordinating Committee, 2023). In 2002, USACE began operating the first electric barrier in the CAWS, which was intended to prevent invasive fishes (Round Goby, *Neogobius melanostomus*, being the initial species of concern) from moving downstream from the Great Lakes into the Mississippi watershed (Invasive Carp Regional Coordinating Committee, 2023; Figure 1).

In 2008, when my collaborators and I received support from USACE to conduct risk assessments of the potential spread of nonindigenous species in both directions through the CAWS, a growing concern of USACE was the prevention of the upstream spread of bigheaded carps (specifically two species of bigheaded carps, Bighead Carp, *Hypopthalmichthys nobilis*, and Silver Carp, *H. molitrix*) into Lake Michigan from river reaches further south in the Illinois River. In the mid-1970s, the species were intentionally introduced from Asia to control water quality in ponds in the lower Mississippi River, from whence they escaped into Mississippi River tributaries during flooding (Kolar et al., 2007).

Beginning in 2009, in the year following the publication of the first demonstration of environmental DNA (eDNA) on macrofauna (Ficetola et al., 2008), three collaborators and I—all then based at the University of Notre Dame (ND)—took and analyzed samples from parts of the Illinois River where bigheaded carps were known to occur. Lindsay Chadderton (employed by The Nature Conservancy and co-located at ND's Center for Aquatic Conservation) had asked whether we could detect fish DNA from water samples, and then brought Ficetola et al. (2008) to the attention of Andrew Mahon, Christopher Jerde, and me. Chadderton's mind was fertile ground for eDNA because he had faced similar challenges as an advisor to a New Zealand federal conservation agency attempting to detect the extent of illegal introductions of invasive fishes in New Zealand (Dean et al., 2001). At the time of our collaboration, he was attending meetings on the CAWS convened by USACE, and knew that USACE had growing concerns about the location of the leading edge of the carp invasion and the sensitivity of the traditional tools (netting and electrofishing) being employed. Scientifically we were prepared to pursue eDNA immediately because some of us had already been working with other collaborators for several years on genetic-based detection approaches for invasive species (Table 1).

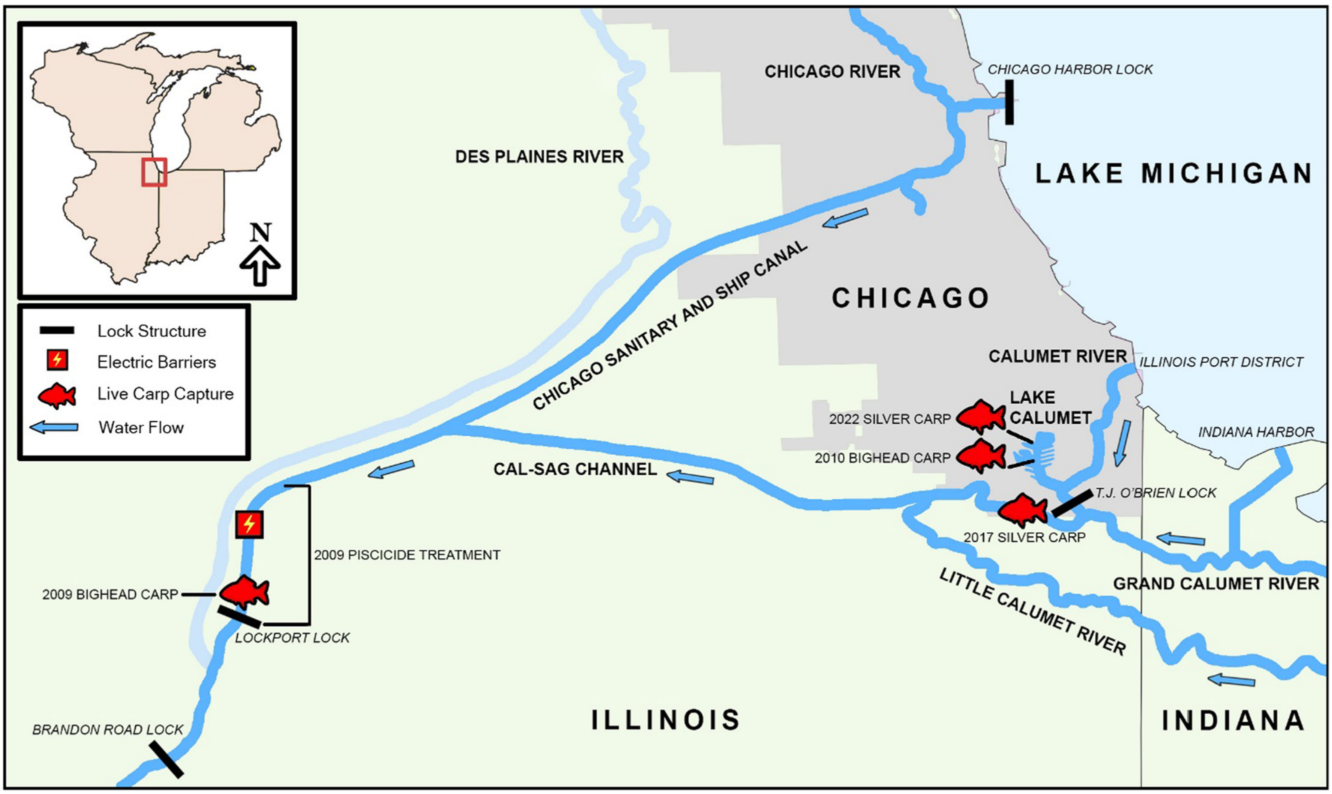

FIGURE 1 Chicago Area Waterway Systems (CAWS), which beginning in 1900 reversed the flow of several rivers that had been tributaries of Lake Michigan, including the Chicago River and the other rivers indicated in darker blue. The CAWS now drains Lake Michigan and connects the Great Lakes watershed to the Mississippi River watershed. Sources: Fish captures for 2009, 2010, and 2017 are mapped in ICRCC (2023), while the 2022 capture is reported at https://invasivecarp.us/News/silver-carp-lake-calumet.html; site of the 2009 piscicide taken from Jackson and Lageman (2014).

Environmental DNA Open Access
Dedicated to the study and use of environmental DNA for basic and applied sciences

TABLE 1 Timeline of selected significant background and developments of eDNA research and management of bigheaded carps in the Chicago Area Waterway System.

2006. Lodge et al. (2006) recommended research and development of genetic-based early detection tools for invasive species.
October 2007. Great Lakes Protection Fund grant to David Lodge (University of Notre Dame, ND), Jeff Feder (ND), Chia Chang (ND), and Lindsay Chadderton (The Nature Conservancy, TNC) on "Developing and applying a portable real-time genetic probe for detecting aquatic invasive species in ships' ballast water," with multiple methods developed (Egan et al., 2013; Mahon et al., 2011; Senapati et al., 2009). This and previous genetics-based grants prepared our minds and our laboratory infrastructure for the eDNA work to follow.
July 2008. US Army Corps of Engineers (USACE) cooperative agreement to David Lodge (ND), Christopher Jerde (ND), and Lindsay Chadderton (TNC) on "Aquatic invasive species risk assessment for the Chicago Area Waterway System (CAWS)"; the agreement was modified multiple times (with later modifications including Andrew Mahon), lasting through December 2010.
2008. Ficetola et al. (2008) was the first publication to demonstrate that macro-organisms (frogs in this case) could be detected from eDNA in water samples.
Spring 2009. After preliminary in silico and wet laboratory work to develop methods, we collected the first exploratory water samples for eDNA from the Upper Illinois River (south of the CAWS). Eureka: On the first try, eDNA from Bigheaded Carps was detected where they were known to exist. Samples taken on 29 June were the first taken as a part of our formal reporting to USACE.
10 July 2009–May 2010. We took over 3000 water samples from multiple parts of the CAWS upstream of the electric barriers and selected other tributaries of southern Lake Michigan, with 66 samples testing positive for Bighead Carp and 72 samples testing positive for Silver Carp, including further upstream (closer to Lake Michigan) in the CAWS than traditional sampling had suggested (Jerde, 2021).
August 10, 2009. First of 31 often weekly reports to USACE on eDNA sampling, sample processing, preliminary results, and final results.
Late 2009. The Asian Carp Rapid Response Workgroup was created in response to our eDNA evidence that the invasion front of Bigheaded Carps was closer than expected to Lake Michigan. It became the Asian Carp Regional Coordinating Committee, and finally became the Invasive Carp Regional Coordinating Committee (ICRCC), co-chaired by USEPA and USFWS, consisting of a consortium of US federal, state, and municipal agencies, US tribal authorities, and Canadian provincial agencies. In 2024, ICRCC continues to coordinate the monitoring and management actions against bigheaded carps in the CAWS and Great Lakes.
December 2, 2009. The Asian Carp Rapid Response Workgroup treated 10 km of the CAWS with the piscicide rotenone. Bigheaded carp eDNA had been detected in the treated section of waterway but no bigheaded carp had previously been captured despite intensive efforts with traditional gears. During the poisoning, one Bighead Carp was recovered upstream from the electric barrier, confirming eDNA evidence that the carp were upstream of the barrier and much closer (<64 km) to Lake Michigan than previously believed. A large number of dead fish, potentially including additional bigheaded carps, were not recovered.
15–16 December 2009. At the request of USACE, an expert panel from EPA (accompanied by an expert observer from the USACE) conducted a site visit to produce a Laboratory Audit Report at the request of USACE. The visit included the analysis by ND of blind samples provided by the EPA. The final report from EPA was released on 5 February 2010 with this conclusion: *"Our team believes that the eDNA method you [ND]are using is sufficiently reliable and robust in reporting a pattern of detection that should be considered actionable in a management context. We have a high degree of confidence in the basic PCR method you are using for detecting silver and bighead carp environmental DNA."*
January 4, 2010. Lodge and co-authors submitted a declaration to US Supreme Court, which appeared as part of Appendix to US Memorandum in Opposition (to complaints brought by State of Michigan and other states regarding Asian carp threat to Great Lakes).
January 15, 2010. First of several Freedom of Information Act (FOIA) requests received by Lodge for email exchanges, data, and lab notebooks.
February 9, 2010. Lodge provided written and oral testimony in an oversight hearing of the Subcommittee of Water Resources and Environment, Committee on Transportation and Infrastructure, US House of Representatives. Major General John W. Peabody, Commander, the Great Lakes, and Ohio River Division, USACE, also offered testimony.
March 2010. First submission of manuscript that, 1 year later, became Jerde et al., 2011. Two journals rejected the manuscript before *Conservation Letters* accepted it. A reviewer for *Science* stated "I am not convinced that this is a reliable technique." The reason given was that not every water sample was positive where bigheaded carps were known to occur, reflecting a lapse in logic that we also encountered in many management settings, that is, failure to consider that traditional tools also have <100% detection probability, and failure to recognize that the key question is: What is the detection probability of eDNA versus that of traditional tools (Jerde, 2021).
May 2010. As part of a plan to transition the sampling and analysis from ND to USACE, a tour of ND eDNA labs included a demonstration and walk-through for USACE scientists of all eDNA methods. All protocols and methods were also provided in writing to USACE scientists. After the technology transfer, USACE conducted the routine monitoring for bigheaded carps until the monitoring function was shifted to the USFWS, which built the Whitney Genetics Laboratory in Wisconsin for that purpose; the laboratory opened in 2013.
June 2010. Very intensive netting efforts in parts of the canal with positive eDNA results captured a Bighead Carp in Lake Calumet only 11 km from Lake Michigan (Figure 1). eDNA results from 2013-on are available from the USFWS at: https://fws.maps.arcgis.com/apps/dashboards/52b22abe9c4d4575adfe851a946f444d
July 2010. Battelle Memorial Institute panel of experts conducted a site visit to ND as part of an Independent External Peer Review commissioned by USACE. (For results, see 7 December 2010 entry below.)
September 7, 2010. Lodge provided pro bono publico testimony in US District Court in Chicago in a suit brought by Michigan and other states requesting a temporary injunction to force the USACE to close the canal locks in CSSC to deny access by bigheaded carps below the locks to Lake Michigan; the court found Lodge's eDNA data admissible as evidence (Laschever et al., 2023). Both the Supreme Court (see December 2009 above) and federal appeals court have repeatedly denied the relief requested by Michigan and other entities.

(Continues)

TABLE 1 (Continued)

September 2010. President Obama appointed John Goss an "Asian carp czar" in the White House Council of Environmental Quality, reflecting the national attention to the issue, and the conflicts among different jurisdictions that required political management; Goss visited ND on 5 October.
October 15, 2010. Email written by USACE attorney to EPA recommends that EPA "reconsider the grants" recently awarded to ND by EPA and USFWS as part of the Great Lakes Restoration Initiative.
October 2010. Brief by USG in Case No. 10-c-4457 (Doc #: 141) stated that Lodge had pecuniary interests in eDNA, when in fact, Lodge did not have (and has never had) any financial interest in eDNA related companies. Here I correct the record.
December 7, 2010. Battelle's Independent Expert Peer Review report was released. Conclusions included the following two sentences. *"The overall methodology to detect eDNA in the water column and attribute that eDNA in the form of mtDNA back to silver and bighead maternal lineages is sound." "In the Panel's opinion, no other single method provides this suite of advantages offered by eDNA samples."*
March 31, 2011. ND submitted final report to USACE, which covered the original cooperative agreement and seven modifications.
April 2011. Jerde et al. (2011) published, concluding from water samples taken in multiple pools of the CAWS that eDNA was a more sensitive tool for the detection of bigheaded carps than the traditional tools (netting, electrofishing) that had been previously used by USACE contractors; results included the detection of eDNA from bigheaded carps farther upstream (i.e., closer to Lake Michigan) than previously detected.
January 2013. In their annual horizon scan of global conservation topics, Sutherland et al. (2013) cited Jerde et al. (2011) to identify, "Detecting aquatic species with environmental DNA" as an emerging global conservation issue for 2013. In their most recent horizon scan, Sutherland et al. (2023) highlighted their 2013 prediction about eDNA as having been realized.
January 2019. In 2019, Ausubel, Stoeckle, and Gaffney provided a succinct executive summary of the 1st US National Conference on Marine Environmental DNA (eDNA), held at Rockefeller University: "eDNA works. Get going."
15–19 July 2019. The Fisheries Society of the British Isles hosted a symposium on *Advances in eDNA-based Approaches to Fish Ecology and Management* at the University of Hull, UK. The keynote talk by Jerde (2021) assessed the advances and challenges emerging from the eDNA work on Bigheaded Carps in the Great Lakes.
2019. John Wiley and Sons began publication of *Environmental DNA*, a journal dedicated to the science of environmental DNA.
2022. USFWS began a five-year program to integrate eDNA metabarcoding into their regional Great Lakes aquatic invasive species surveillance program.

In the subsequent 15 years, research using eDNA has proliferated (Pawlowski et al., 2020), the number of companies providing materials and supplies for eDNA sampling and analysis is growing, and calls for more rapid adoption of eDNA for natural resource decision-making by government agencies are strengthening (Lee et al., 2023). This is true, for example, in Canada (National Standards of Canada, 2021), New Zealand (Bunce & Freeth, 2022), Europe (Bruce et al., 2021), and the United States (Kelly et al., 2023; Lodge, 2022; Morisette et al., 2021; Sepulveda et al., 2020). This was the motivation behind the 2nd Annual Workshop on Marine Environmental DNA, held in 2022, which led to this special issue of this journal. In this commentary, I will draw lessons on the use of eDNA in early detection of aquatic invasive species from the perspective of a US-based researcher leading eDNA research projects on Bighead Carp and Silver Carp in the Chicago Area Waterway System (CAWS).

I will focus primarily on 2009–2011, and on projects in my laboratory funded by cooperative agreements from the USACE under a Cooperative Ecosystems Studies Unit agreement. Starting in 2010, other government agencies and funders allowed us to continue to expand the work, often under the funding umbrella of the US Great Lakes Restoration Initiative. These agencies included the US National Oceanic and Atmospheric Administration (NOAA), US Environmental Protection Agency, US Fish & Wildlife Service (USFWS), Indiana Department of Natural Resources, Illinois Department of Natural Resources, and the Great Lakes Fisheries Trust.

Aspects of this story, including some lessons learned, have been excellently told by some of my collaborators (Jerde, 2021; Mahon & Jerde, 2016), a member of one of the panels that conducted formal site reviews of my laboratory (Darling, 2019), and journalists (Annin, 2018; Egan, 2018; Reeves, 2019). In addition, a large group of coauthors from provincial, state, and federal agencies, along with members of our collaboration research team, described how many state and federal agencies established a Management Advisory Board, with financial support from NOAA, that subsequently overcame the early challenges described below (Newcomb et al., 2021). Here I provide background on the system and issue, including an overview of our research group's experience during 2009–2011, providing some previously unreported details, including at least one correction of the record; bring the story up to date in terms of the continued use of eDNA in the management of bigheaded carps; draw out some lessons that will apply to many eDNA use cases; and conclude by putting this topic in the broader context of the process of technology adoption. The lessons learned can help inform the building momentum to accelerate the use of eDNA in management applications.

2 | BIGHEADED CARPS AND eDNA

After successful preliminary experiments with goldfish in the laboratory, our first water sampling trip to the Illinois River was an attempt to test an idea that seemed almost too good to be true—that we could detect bigheaded carps from the DNA in water samples. The results were the most stunning eureka moment in my career: we detected eDNA of bigheaded carps in water samples taken where the carps were known to occur and found no eDNA of bigheaded carps in negative control samples.

The potential for large-scale application to the urgent invasive species problem of bigheaded carps in the CAWS was immediately apparent. Our effort became the first large-scale application of eDNA to inform management decisions in real time. Our subsequent discoveries of eDNA of bigheaded carps in parts of the CAWS closer to Lake Michigan, and our cooperation with USACE in their announcements of those results, sounded a public alarm. In response to the eDNA detections, an Asian Carp Rapid Response Workgroup, consisting of federal and state agencies, was created in late 2009 to implement a rapid response plan (https://invasivecarp.us/about-ICRCC.html). (This group eventually became the Invasive Carp Regional Coordinating Committee or ICRCC.)

The eDNA results and subsequent government actions raised concerns among Great Lakes states, CAWS users, including commercial navigation companies, and environmental groups. These concerns were manifest in many ways, including calls to re-separate the Great Lakes and Mississippi River watersheds (Rasmussen et al., 2011), and multiple legal actions in the US Supreme Court and federal district and appellate courts (Laschever et al., 2023).

As part of the government's rapid response plan, when USACE needed to shut down the electric barrier for maintenance in December 2009, the piscicide rotenone was applied to a 10 km stretch of the canal from above the electric barrier downstream to the Lockport Lock and Dam (Jackson & Lageman, 2014; Figure 1). This was to prevent any bigheaded carp from going upstream through the barrier while it was turned off. During the period of the piscicide application, multiple crews collected all the dead and dying fish they could see, including one Bighead Carp captured “500 feet above the Lockport Lock and Dam” (Illinois Department of Natural Resources December 3, 2009 press release, https://invasivecarp.us/News/carpincssc.html). This capture, while bad news for the efforts to protect the Great Lakes, was an important public confirmation of the eDNA detections we had reported to USACE earlier in the year. Table 1 provides a timeline of this and other key results, management and legal actions, and consequences.

Three axes of strong tension around our scientific results developed quickly, and deciding how to respond appropriately was challenging. First, USACE wanted us to provide the results in real time, which we did, because our results were of immediate relevance to management decisions, including the piscicide application described above. That led to criticism from our academic peers, which was understandable, because scientific results are normally subject to peer review and publication before being accepted as a sound basis for action.

Second, our research team wanted to be fully transparent about the design and rationale of the sampling program, the locations of all the results (positive and negative results), and fully evaluate the uncertainties of the method and potential alternative interpretations of the results. That led to tension with USACE because they sometimes reported analyses in ways that the research team believed inappropriately minimized the threat of bigheaded carp invasion. USACE had an understandable temptation to do this because the eDNA results cast doubt on the effectiveness of the previous surveillance program and of the electric barrier.

Third, USACE immediately came under intense pressure from environmental groups to close the canal (or take other drastic action). Simultaneously USACE experienced intense criticism from potentially affected industries (e.g., commercial and recreational shipping and boating) for supporting the research team's work, and intense pressure to keep the CAWS fully open. The research team came under direct attack from the same industries, which overstated the uncertainties in our results, which was exacerbated when some environmental groups understated the same uncertainties.

Some of these tensions were reduced by: the 2009 capture of the Bighead Carp described above; two expert reviews of the research commissioned by federal agencies (2009, 2010); our publication of the work (Jerde et al., 2011); and turning over the routine eDNA surveillance program to USACE in 2010 (Table 1). Before the expert reviews, the research team was in a very difficult and isolating situation, both cooperating with and under attack by different parts of USACE (Table 1). Given that Chadderton (in New Zealand) and I (in the United States) had previous experience working with management agencies, we were not naïve about the potential difficulties at the science-management interface. Yet we had no idea how intense would be the tensions described above, the public attention, and the learning opportunities during 2009–2010.

3 | BRINGING THE STORY UP TO DATE

In 2010, when we transferred to USACE the eDNA methods and protocols we had developed, USACE took over the surveillance and monitoring program (Table 1). By 2013, the eDNA surveillance program was largely transferred from USACE to the USFWS. It now includes about 10,000 water samples annually in Great Lakes tributaries including the CAWS (US Fish & Wildlife Service, 2022). Many of our specific materials and technical protocols have been improved by USFWS, but not in ways that cause any major reconsideration of our early results. Currently the sampling by USFWS is a cooperative effort with other federal agencies and the Great Lakes states, with the ICRCC, especially its Monitoring and Response Work Group, co-chaired by the Great Lakes Commission and the Illinois Department of Natural Resources, playing important coordinating roles.

The eDNA sampling has informed many additional management steps in the CAWS during the last decade (Table 1). USACE built and began operation of additional electric barriers at the same site as the original barrier (Figure 1), and has plans to study and/or install additional technologies (e.g., barriers consisting of sounds, bubbles, or carbon dioxide) to further slow dispersal of invasive species in both directions (Invasive Carp Regional Coordinating Committee, 2023). More effective physical barriers have been and will be installed at other sites where the Great Lakes watershed and the Mississippi River watershed are sometimes connected by floods (Invasive Carp Regional Coordinating Committee, 2023). Other state and federal agencies have instituted control measures including on-going harvest of bigheaded carps in the Illinois River to lower the probability of further upstream dispersal toward Lake Michigan (Invasive Carp Regional Coordinating Committee, 2023). Expenditures that are currently underway or planned amount to almost $100 million (Invasive Carp Regional Coordinating Committee, 2023).

Also during the past 15 years, the scientific community has published hundreds of eDNA-related papers, with an accelerating annual rate (Pawlowski et al., 2020). Many of those papers compare eDNA results to traditional capture methods in a spirit of validation of eDNA and calibration against known methods. eDNA has repeatedly proved to be a faster and more sensitive tool than capture methods for the detection of target species and comprehensive biodiversity surveys (McElroy et al., 2020). Thus when eDNA studies are conducted with appropriate contamination controls, in appropriately designed laboratories (Bruce et al., 2021; Goldberg et al., 2016), and with appropriate protocols including negative controls at every step, results should no longer be doubted or require validation against a less sensitive traditional tool. As with any other tool, results also must be interpreted within a rigorous decision support process that, for example, considers alternative explanations for DNA being present. Such a careful approach prevents expensive and unnecessary management overreactions, for example, to a single potentially misleading eDNA detection on a single date (Sepulveda et al., 2020; Tucker et al., 2016).

Some Great Lakes states and federal agencies within the ICRCC are using eDNA surveillance as an early warning system. A typical current practice is to deploy intensive electrofishing and netting efforts in any location where multiple recent water samples and/or individual water samples on multiple occasions have detected eDNA from bigheaded carps (Invasive Carp Regional Coordinating Committee, 2023; Kahler et al., 2020; US Fish & Wildlife Service, 2022). It is often unclear from government statements and documents whether the rationale behind these intensive efforts is to remove the fish(es) detected (reflecting confidence that eDNA detections indicate one or more live fishes) or to confirm eDNA detections (reflecting skepticism about the meaning of the eDNA detections). In recent years, whether a fish is caught or not, typically no other management actions are taken.

The current management actions sometimes seem to be a bit like trying to use an external physical examination to confirm an early-stage human cancer diagnosis derived from sophisticated imaging, or like rejecting a forensic genetic analysis that finds DNA from a suspect at a crime scene because the suspect was not captured at the crime scene. It is not surprising that such efforts to confirm eDNA rarely capture fish, because electrofishing, netting, and other traditional fish capture tools are well documented to be less sensitive than eDNA. They are therefore much less likely to detect a species that is present than is eDNA (Jerde, 2021).

Of course, it is possible that an imaging analysis is incorrect, that the DNA of a person could have been planted at a crime scene without the person ever being present, and that the eDNA of a fish could have arrived in a waterway via sewage effluent from human consumption of bigheaded carp, or in the egesta of a piscivorous bird. That's why thoughtful decision support tools, including careful evaluation of alternative explanations in medicine, forensics, and use of eDNA, are also an essential part of decision-making (Sepulveda et al., 2020). However, without a highly probable alternative explanation for the presence of eDNA, it would be illogical to conclude with confidence that no fish is present on the grounds that a less sensitive tool did not capture an organism (Darling, 2019).

The fact that captures have sometimes followed eDNA detections should give confidence to taking management actions based on repeated positive eDNA results. Three out of the four live bigheaded carps captured upstream of the Lockport Lock and Dam in the last 15 years have been in Lake Calumet or nearby in the Little Calumet River (Figure 1). Since 2015 (when the USFWS last changed their eDNA methods), at least one sample from Lake Calumet has tested positive for bigheaded carps in five out the eight sampled years, with multiple samples testing positive in two of those years (2019 and 2022; USFWS Whitney Biological Laboratory dashboard, https://fws.maps.arcgis.com/apps/dashboards/52b22abe9c4d4575adfe851a946f444d). The most recent capture of a live fish was in August 2022, when a Silver Carp was captured in Lake Calumet after water samples had tested positive for Silver Carp eDNA in Lake Calumet in the same year. In 2023, one eDNA sample from Lake Calumet tested positive. It is very unreasonable to believe that the captured fish have been the only individuals present in Lake Calumet or in the upper CAWS.

As a threat to the Great Lakes, these captures and detections are significant because any fish in Lake Calumet has unfettered access to Lake Michigan and only a short distance (11 river km) to traverse. As reported by the ICRCC (https://invasivecarp.us/News/silver-carp-calumet-analysis.html), chemical analysis of an otolith from the Silver Carp captured in 2022 revealed that it was at least 4 years old, and had only recently arrived in the upper CAWS, with isotopic signatures consistent with earlier residence in the Illinois River system (Greg Whitledge, Southern Illinois University, personal communication). These data are consistent with the fish swimming from the Illinois River to Lake Calumet.

Nevertheless, the ICRCC (2023) continues to report for both Silver Carp and Bighead Carp that “The population front has remained unchanged for over 10 years.” It is not clear that this conclusion is incorrect, but it is also not clear what evidence would lead the ICRCC to reject or modify this assertion. In my view, a more nuanced interpretation would be appropriate given the less than 100% effectiveness of electric barriers and other management interventions (Davis et al., 2017), the low sensitivity for species detection of electrofishing and netting, repeated eDNA detections in the CAWS, and multiple fish captures. I think it more likely, for example, that multiple bigheaded carps have traversed (and may be traversing) the electric barriers (Figure 1) and gaining access to Lake Michigan. It also remains possible, of course, that the fish are escaping or being transported by humans from other local sources https://invasivecarp.us/Documents/BigheadCarpinIllinoisUrbanFishingPonds.pdf.

Even if I am correct about upstream migration of bigheaded carp into the upper CAWS, it remains possible that the management goal, which is to prevent Silver Carp and Bighead Carp from establishing self-sustaining populations in the Great Lakes, remains achievable if the number of fishes has decreased because of the ramped up management actions described above. I certainly hope so, because the stakes are high: The potential negative impacts of bigheaded carps on Great Lakes ecosystems and fisheries are large (Rutherford et al., 2021).

4 | LESSONS LEARNED

Here, I summarize some of the lessons we learned from the on-going experience described above—lessons that are relevant to our experience with eDNA in the CAWS, and have been reinforced for me in many other kinds of projects at the nexus of science, management, and policy. They apply as strongly to many other applications of science as they do to eDNA. Some lessons have been written about by other authors (Darling, 2019; Jerde, 2021), but they warrant consideration here because they remain too infrequently practiced.

With respect to eDNA, these lessons are particularly timely. There are many meetings and reports including university-based researchers, government-based researchers, government natural resource managers, policy makers, and those in nascent eDNA-based industries, calling for more rapid adoption of eDNA in ways that maximize its utility and minimize its limitations (Bunce & Freeth, 2022; Darling, 2019; Kelly et al., 2023; Lee et al., 2023; Lodge, 2022; Stein et al., 2023).

Some of the lessons listed below are more applicable to those involved in applying their research, some more relevant to natural resource managers and policy makers, and some relevant to both. By “researchers,” I mean scientists whose primary role is research, whether they are working in a government agency or a university. By “managers and policy makers,” I mean practitioners whose primary responsibilities are to create or execute management plans and/or the policies authorizing them. Many of these practitioners may be trained as scientists, but research is not their primary role.

4.1 | Lessons for eDNA researchers

1. *Do not engage with managers unless you are willing to leave your comfort zone*. To be useful to managers and policy makers, a researcher must have strong motivation to provide actionable information and be willing to spend the time to think and act far beyond the narrow confines of their academic discipline.

   As examples, and in addition to the events listed in Table 1, one or more members of the research team participated in many public and private briefings of state, regional, and national public officials; public hearings; congressional hearings; briefings to civil society and non-governmental organizations; and national and international media interviews for print, radio, and TV, as well as documentary films.

   The training that I had received a few years earlier in the Aldo Leopold Leadership Program gave me some of the communications tools needed. While such training for graduate students and postdocs has increased in recent years, more early career opportunities are needed for professional development in communications and working with non-academic organizations, if the research-management divide is to be more frequently and successfully traversed.
2. *Practice humility: science should inform, not drive, policy*. Natural resource managers have a very difficult job. Do not make their job harder by acting like you fully understand their goals, opportunities, and constraints. Recognize that scientific information is important for management decisions, but so are lots of other inputs, including the limits of the legal authority possessed by an agency, and what the public wants them to do. In the spirit of humility, embrace co-creation and co-execution of research with relevant agencies and other actors. It takes lots of time, but the information you then provide will be far more relevant and likely to be adopted (Newcomb et al., 2021). Ultimately the managers appointed by elected officials are the decision makers.

   While our research team tried to insist that the scientific inferences drawn by practitioners were consistent with the data, we recognized that the management decisions were much more complex than a faithful treatment of our data and were not ours to make.
3. *Communicate clearly both the strengths and limitations of your methods and results, with transparency about the basis of your inferences* (Darling, 2019). Help the managers distinguish between research methods that are not yet supported by scientific consensus, and management-ready applications. If you are not willing to draw that distinction, then managers may understandably throw the operations-ready baby out with the research bath water and stick with well-known but inferior traditional methods.

   In the example of bigheaded carps and eDNA described above, the research team was in a weak position to do this because we were applying a novel combination of existing limnological and genetic tools to measure a suspended substance the ecology of which we did not understand well (Barnes & Turner, 2016). Although each of the component limnological field sampling methods and the genetic laboratory methods we used had a long history of use and was supported by scientific consensus—facts that were important to the USACE decision to support the work—the combination of techniques was new and being put to a new purpose. We proceeded into this fraught space because USACE wanted answers on an urgent and important problem, and, as a research team, it was an opportunity to innovate.

Regardless of how well research is executed and communicated, expect public criticism from all angles. The more important the information you provide, the more criticism—credible or otherwise—you can expect. Natural resource managers are used to this.

4. *Be prepared to move fast without breaking things*. If you want to have real-world impact, you must move as fast as the pace of the management decisions you wish to inform. Once we began providing results to USACE under the cooperative agreement, USACE urged us to quickly expand our sampling and quickly report results, which we agreed to do, to inform management decisions that they and other federal and state agencies were making in real time. This led us to act contrary to ordinary academic practice, which is to subject results and inferences to peer review and publication before public release.

   USACE and we quickly came under enormous public pressure and criticism for this. The title of a story in a Chicago news outlet exemplified this: "Chicago River businesses to Corps of Engineers … Show us the carp!" The content of the story included a quotation from a local business leader referring to the scientific team's efforts as "a glorified science fair project," while a leader of the Illinois Chamber of Commerce was quoted as saying "because the Corps is such a distinguished institution, this test [eDNA results] has by association been given great credence. And it just needs to stop." (Dahlman, 2010).

   To communicate well (previous lesson) and to move fast without breaking things, more expertise than is available to many researchers is required, including that of dedicated administrators, project managers, and individuals with expertise in institutional relationship management and communication. In our bigheaded carps eDNA work, our initial research team had many of the necessary skill sets, including Chadderton's previous invasive species management experience, as well as his boundary-spanning role at The Nature Conservancy; Andrew Mahon's genetics expertise; Christopher Jerde's quantitative expertise in designing and evaluating sampling designs, sources of errors, and statistics; Mark Renshaw's expert and highly efficient management of the laboratory work; and Joanna McNulty's highly competent, nimble management of fast-changing cooperative agreements. When we first started, however, we had insufficient support on the communications, legal, and government relations fronts. The appointment in November 2010 of journalist Peter Annin as Managing Director at Notre Dame's Environmental Change Initiative dramatically improved our relationship management and communications with government agencies and the public.

   If the necessary resources are not sufficient for the needs of work at the research–management interface, do not attempt to do it on the cheap because it will end unhappily for you, the managers that you were attempting to inform, and for the reputation of science as a reliable source of information. In later projects, other funding agencies, especially NOAA, were willing to financially support communications and collaborations structures (Newcomb et al., 2021).

5. *Seek opportunities to make your practices of quality control and quality assurance available to anyone*. Do not be defensive in the face of questions about exactly what you are doing; if you want to be trusted, welcome verification of your practices. Our QA/QC statements were necessary but insufficient to provide confidence. USACE requested an expedited peer review, which we welcomed. A 2009 expert review was conducted by USEPA, and a 2010 expert review was conducted by Batelle under contract from USACE. Both reviews endorsed our methods and results (Table 1).

   These endorsements increased the confidence of managers in multiple agencies and decreased the credibility of those casting doubt on the reliability of our work. Additional standardization of protocols for management applications, as well as performance standards, and perhaps laboratory certification, are essential to increase future adoption of eDNA by other agencies and for other applications (Goldberg et al., 2016; Kelly et al., 2023; Thalinger et al., 2021), and are being created by many countries, including Canada (National Standards of Canada, 2021).

4.2 | Lessons for natural resource managers and policy makers

6. *Do not expect researchers to act like commercial contractors*. If you engage researchers in a cooperative agreement (not a contract), welcome their questions and opinions, be patient, and embrace co-creation (Darling, 2019). Recognize that researchers may have management-relevant ideas, and that research typically moves very slowly, with time measured in months and years, and temper your expectations. If the circumstances do not allow leeway on time, then be prepared to provide the resources necessary for the researchers to speed up effectively or use a commercial contractor instead of a research group. In our case, USACE did provide additional resources over time, but the time lags of administrative review of modifications to our cooperative agreement meant our capacity was often lagging USACE's desire to sample, analyze and report quickly.
7. *Establish processes to accept improvements in technology along the way*. Researchers will be an appropriate vehicle to inform management goals only if managers want innovation, and researchers are allowed to discover and implement better ways to accomplish co-created goals. For policymakers, a longer-term imperative is to avoid lock-in of inferior technologies in a fast-developing technological tool like eDNA. Natural resource management should not get stuck with the eDNA technological equivalent of the QWERTY keyboard, which became the standard typewriter (and

computer) keyboard despite its ergonomically inefficient order of letters (Lee et al., 2023).

In our work with bigheaded carps eDNA, we started out using gel electrophoresis to visualize results, but within months moved to more sophisticated and precise approaches, especially qPCR, which were welcomed by USACE. The current field and laboratory protocols used by the USFWS in the on-going surveillance eDNA surveillance program for bigheaded carps have also changed over time (e.g., https://invasivecarp.us/ecals.html). More generally, new policies need to enable best available technologies, and periodic approval of improved technology (Laschever et al., 2023).

8. *Use eDNA as a basis for decisions without "confirmation" from less sensitive traditional tools*. A less sensitive tool cannot be a gold standard against which to compare more sensitive methods. For some applications (and with the qualifications described earlier), eDNA is the most sensitive tool available and is management ready. For some applications, it is not merely complementary to traditional tools, but better, faster, and cheaper (Andres et al., 2023; Kelly et al., 2023).

4.3 | Lessons for both parties

9. *Build trust*. When the goal is to inform important management decisions, interactions at the science–management–policy interface are likely to go awry without a foundation of trust on both sides (Sepulveda et al., 2020). If the managers or policy makers undermine the research because they do not trust the scientists, then societal acceptance will be low, and management will be ineffective. If researchers undermine the manager's discretion, the opportunities to inform decisions will diminish. Setting aside time and situations conducive to informal conversation, brainstorming, and co-creation in project planning is essential. This was not done in the work described in this paper. The final three lessons below are additional mechanisms to build and maintain trust.
10. *Agree on any technical standards, lab certifications, and other aspects of QA/QC that are required*. Identify the conditions under which changes during the work would be acceptable. In the experience described in this paper, the research team and USACE successfully navigated this, but with some difficulty.
11. *Agree on written internal and external communications guidelines*. Avoid surprises in both directions (Stein et al., 2023). Written agreements should include the timelines by which data must be provided to managers, and whether joint approval is needed on public statements by the managers about the presentation and interpretation of the data provided by researchers. The recommendations made by Stein et al. (2023) to jointly adopt a Responsible, Accountable, Consulted, Informed (RACI) approach will align expectations and prevent surprises and misunderstandings.

    This was not done in the work described in this paper. Under tight time constraints, we relied instead on on-the-fly verbal agreements, which turned out to be woefully inadequate. It is too late to talk about communications protocols after data emerge that require urgent and difficult decisions to be made by managers. In 2009, in one of the earliest public statements made by USACE about surprising eDNA results that we provided, a verbal agreement on how to present and interpret the data was ignored by the USACE spokesperson, with the effect of minimizing the eDNA evidence. Along with later similar interactions, this led to declining trust on both sides.

    One very tangible manifestation of that lack of trust was a 2010 email sent by a USACE lawyer to EPA recommending that EPA cancel awards that EPA had recently made to ND for additional eDNA and related invasive species risk assessment projects (Table 1). EPA and other Great Lakes Restoration Initiative funders did not heed USACE and welcomed the collaborative development of communications protocols with multiple federal and state agencies that worked very effectively in subsequent years (Newcomb et al., 2021).
12. *Co-produce decision support tools*. If researchers and managers work together on decision support tools, everyone understands how scientific data will be used in decision making, and which kinds of scientific input will be most relevant. Examples for eDNA include Sepulveda et al. (2020) for Western US waterways, and an on-going effort by the Great Lakes Fisheries Commission (http://www.glfc.org/science-transfer-toolkit.php). The recommendation by Stein et al. (2023) to approach this through Structured Decision-Making will increase the likelihood of efficient use of scientific input in a way that researchers will expect and understand.

5 | COLLABORATIVE GOVERNANCE AND FUTURE USE OF eDNA IN MANAGEMENT

As pointed out above, we learned some of these lessons the hard way—by not implementing them. The learning process was painful during the years described, especially for the younger scientists involved, for which this was an unexpected and intense mentoring experience. In hindsight it is not surprising that we had to learn that way. We were engaged in the first large-scale use of eDNA in a high stakes management context and were unprepared for the demands that came at us from many directions. Likewise, USACE could not have been prepared for the results of the work they were supporting.

Because our cooperative agreement with USACE initially focused on invasive species risk assessments not involving eDNA, the rapid focus and acceleration of the use of eDNA meant that both USACE and we were unprepared to collaborate sufficiently on the interpretation and potential use of the results. Because the CAWS withdraws Great Lakes water, its governance already had a long, contentious history, including the city of Chicago, all the Great Lakes states, several US federal agencies, and the government of Canada (Annin, 2018). In 2009, in response to our eDNA results, many of those parties were quickly brought into a collaborative organization, the Asian Carp Rapid Response Workgroup, to respond to the eDNA results, and to mitigate the temporary shutdown of the electric barrier described earlier.

Thus, our experience may have been a worst-case scenario at the research–management interface, exposing more painfully than usual the potential fault lines addressed in the dozen lessons above. I hope that the examples above of the things we did well and the things we did not do, which we should have done, will help current and future researchers and practitioners do better.

Our experience with eDNA and bigheaded carps was a manifestation of the general and well-known difficulty of adopting new technology. Technology adoption is a path-dependent social process, with more potential pathways that result in suboptimal outcomes for society than pathways that lead to optimal or near optimal outcomes (Lee et al., 2023). However, the history reviewed in this paper, and the on-going process of eDNA technology development and adoption in the CAWS and Great Lakes is an imperfect example of the collaborative governance pathway that is recommended by Lee et al. (2023) as the approach most likely to lead to a societally optimal outcome. It brought together three of the four categories of partners viewed by Lee et al. (2023) as key to collaborative governance: resource managers, researchers (both university and government), and policy leadership. The category of partner listed by Lee et al. (2023) that needs to be more strongly and positively engaged is non-governmental users and supporters. In particular, I believe that for-profit companies are a key missing player that could scale new eDNA technologies to increase the availability of eDNA goods and services while driving down the costs.

As I have argued elsewhere (Lodge, 2022), the for-profit private sector needs more certainty of eDNA acceptance in government decision-making before greater private investments will flow. In my view, the best future outcome is that government and university researchers continue to push eDNA technology forward, while private laboratories and environmental consulting firms provide the monitoring services required by government. If it remains unclear what use cases and what specific eDNA approaches (e.g., performance standards) will be accepted by government agencies as the basis of regulatory decisions, then eDNA technology development and application, including monitoring, will remain largely the purview of the research branches of government agencies and universities. Without stronger public–private partnerships, research groups are ill-suited to scale technologies. If those aspects of collaborative governance in the CAWS and in other promising use cases, for example, offshore wind environmental assessment, are strengthened, a virtuous cycle of technology, policy, and management could unleash a potentially fast-growing component of the environmental services economy.

ACKNOWLEDGMENTS

Leading up to the work described in this paper, Colonel Vincent Quarles (Retired), then Commander of the Chicago District (USACE), persistently asked about the detection sensitivity of netting and electrofishing for Asian carp in the CAWS—exactly the right question to be asking—and prompted us to undertake the work described in this paper. Colonel Quarles communicated tirelessly with us throughout. Dr. Al Cofrancesco (then of USACE ERDC) and his staff shepherded our cooperative agreements and helped at every step of the work. Kelly Baerwaldt (then USACE fisheries biologist) cooperated effectively with our research team in the field and otherwise throughout the work, as did fisheries biologists from the IL Department of Natural Resources and the USFWS. Two anonymous reviewers provided helpful suggestions on an earlier version of this manuscript. Thanks also to Peter Annin, Lindsay Chadderton, Chris Jerde, Kai Lee, Andy Mahon, and Tammy Newcomb for saving me from several errors in earlier versions of this manuscript, and for suggesting many improvements. I am grateful for the incredible teamwork, often under stressful timelines and circumstances, of the eDNA team based in my laboratory at the University of Notre Dame's Center for Aquatic Conservation (which, during the period described in this paper, was subsumed by the newly created Environmental Change Initiative). The core science team (ND employees unless otherwise specified) was Christopher Jerde (now at UC Santa Barbara), Andrew Mahon (now at Central Michigan University), and Lindsay Chadderton (TNC), supported throughout by spectacular project management by Joanna McNulty, and later, wise, and steady counsel from Peter Annin (now at Northland College), who has vast expertise in Great Lakes governance, communications and government relations. A succession of expert technicians contributed to the field and laboratory, including Michele Budny, Joel Corush, Jill Deines, Erick Elgin, Matt Galaska, Amy Rohly, and Karen Uy, with special thanks to Crysta Gantz and Mark Renshaw, who also provided very significant scientific ideas and guidance. Other graduate students, postdocs, and research assistant professors in the laboratory at the time who contributed to our thinking and/or to related eDNA projects included Matt Barnes, Andrew Deines, Cameron Turner, and Scott Egan. Faculty colleagues who had patiently taught me genetics were Jeff Feder and Mike Pfrender. At Cornell University (where I moved in 2016), Jose Andres, Kara Andres, and Suresh Sethi have been terrific collaborators, and together we have continued to grow the kinds of information that we can derive from eDNA and expanded the management applications with strong support from Cornell Atkinson Center for Sustainability. Many thanks to all.

FUNDING INFORMATION

The field and laboratory work described in this retrospective was supported by agencies including Great Lakes Protection Fund, USACE, USFWS, NOAA, EPA, Indiana Department of Natural Resources, Illinois Department of Natural Resources, and the Great Lakes Fisheries Trust. During the preparation of this manuscript, the author was partially supported by Oceankind.

CONFLICT OF INTEREST STATEMENT

I have no conflict of interest.

DATA AVAILABILITY STATEMENT

No original data were created in preparing this manuscript.

ORCID

David M. Lodge https://orcid.org/0009-0008-1287-2611

REFERENCES

Andres, K. J., Lambert, T. D., Lodge, D. M., Andrés, J., & Jackson, J. R. (2023). Combining sampling gear to optimally inventory species highlights the efficiency of eDNA metabarcoding. *Environmental DNA*, *5*, 146–157. https://doi.org/10.1002/edn3.366

Annin, P. (2018). *The Great Lakes water wars* (p. 384). Island Press.

Barnes, M. A., & Turner, C. R. (2016). The ecology of environmental DNA and implications for conservation genetics. *Conservation Genetics*, *17*, 1–17.

Bruce, K., Blackman, R. C., Bourlat, S. J., Hellström, M., Bakker, J., Bista, I., Bohmann, K., Bouchez, A., Brys, R., Clark, K., Elbrecht, V., Fazi, S., Fonseca, V., Hänfling, B., Leese, F., Mächler, E., Mahon, A. R., Meissner, K., Panksep, K., … Deiner, K. (2021). *A practical guide to DNA-based methods for biodiversity assessment*. Pensoft Advanced Books. https://ab.pensoft.net/article/68634/

Bunce, M., & Freeth, A. (2022). Looking further and deeper into environmental protection, regulation and policy using environmental DNA. *Policy Quarterly*, *18*, 33–39.

Dahlman, S. (2010, March 18). Chicago River businesses to Corps of Engineers … Show us the carp! *Loop North*. https://www.loopnorth.com/news/carp0318.htm

Darling, J. A. (2019). How to learn to stop worrying and love environmental DNA monitoring. *Aquatic Ecosystem Health and Management*, *22*, 440–451.

Davis, J. J., LeRoy, J. Z., Shanks, M. R., Jackson, P. R., Engel, F. L., Murphy, E. A., Baxter, C. L., Trovillion, J. C., McInerney, M. K., & Barkowski, N. A. (2017). Effects of tow transit on the efficacy of the Chicago sanitary and Ship Canal electric dispersal barrier system. *Journal of Great Lakes Research*, *43*, 1119–1131.

Dean, T., Chadderton, L., Grainger, N., & Alliborne, R. (2001). Introduction. In *Proceedings of a workshop hosted by Department of Conservation, 10–12 May 2001*. Hamilton Department of Conservation.

Egan, D. (2018). *The death and life of the Great Lakes* (p. 356+). W. W. Norton & Company.

Egan, S. P., Barnes, M. A., Hwang, C.-T., Mahon, A. R., Feder, J. L., Ruggiero, S. T., Tanner, C. E., & Lodge, D. M. (2013). Rapid invasive species detection by combining environmental DNA with light transmission spectroscopy. *Conservation Letters*, *6*, 402–409.

Ficetola, G. F., Miaud, C., Pompanon, F., & Taberlet, P. (2008). Species detection using environmental DNA from water samples. *Biological Letters*, *4*, 423–425.

Goldberg, C. S., Turner, C. R., Deiner, K., Klymus, K. E., Thomsen, P. F., Murphy, M. A., Spear, S. F., McKee, A., Oyler-McCance, S. J., Cornman, R. S., Laramie, M. B., Mahon, A. R., Lance, R. F., Pilliod, D. S., Strickler, K. M., Waits, L. P., Fremier, A. K., Takahara, T., Herder, J. E., & Taberlet, P. (2016). Critical considerations for the application of environmental DNA methods to detect aquatic species. *Methods in Ecology and Evolution*, *7*(11), 1299–1307. https://doi.org/10.1111/2041-210X.12595

Invasive Carp Regional Coordinating Committee. (2023). 2023 Invasive Carp Action Plan. 154 pp. https://invasivecarp.us/Documents/2023-Invasive-Carp-Action-Plan.pdf

Jackson, P. R., & Lageman, J. D. (2014). *Real-time piscicide tracking using Rhodamine WT dye for support of application, transport,and deactivation strategies in riverine environments* (p. 43). U.S. Geological Survey Scientific Investigations Report 2013-5211. https://doi.org/10.3133/sir20135211

Jerde, C. L. (2021). Can we manage fisheries with the inherent uncertainty from eDNA? *Journal of Fish Biology*, *98*, 341–353. https://doi.org/10.1111/jfb.14218

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*, 150–157. https://doi.org/10.1111/j.1755-263X.2010.00158.x

Kahler, J. S., Liu, R. W., Newcomb, T. J., Herbst, S., & Gore, M. L. (2020). Public risk perceptions associated with Asian carp introduction and corresponding response actions. *Management of Biological Invasions*, *11*, 80–95.

Kelly, R. P., Lodge, D. M., Lee, K. N., Theroux, S., Sepulveda, A. J., Scholin, C. A., Craine, J. M., Andruszkiewicz, A. E., Nichols, K. M., Parsons, K. M., Goodwin, K. D., Gold, Z., Chavez, F. P., Noble, R. T., Abbott, C. L., Baerwald, M. R., Naaum, A. M., Thielen, P. M., Simons, A. L., … Weisberg, S. B. (2023). Toward a national eDNA strategy for the United States. *Environmental DNA*. https://doi.org/10.1002/edn3.432

Kolar, C. S., Chapman, D. C., Courtenay, W. R., Jr., Housel, C. M., Williams, J. D., & Jennings, D. P. (2007). *Bigheaded carps: A biological synthesis and environmental risk assessment*. American Fisheries Society Special Publication 33.

Laschever, E., Kelly, R. P., Hoge, M., & Lee, K. N. (2023). The next generation of environmental monitoring: Environmental DNA in agency practice. *Columbia Journal of Environmental Law*, *48*, 260–310.

Lee, K. N., Kelly, R. P., Demir-Hilton, E., Laschever, E., & Allan, E. A. (2023). Adoption of environmental DNA in public agency practice. *Environmental DNA*, *6*, e470. https://doi.org/10.1002/edn3.470

Lodge, D. M. (2022). Policy action needed to unlock eDNA potential. *Frontiers in Ecology and the Environment*, *20*(8), 448–449. https://doi.org/10.1002/fee.2563

Lodge, D. M., Williams, S., MacIsaac, H. J., Hayes, K. R., Leung, B., Reichard, S., Mack, R. N., Moyle, P. B., Smith, M., Andow, D. A., Carlton, J. T., & McMichael, A. (2006). Biological invasions: Recommendations for US policy and management. *Ecological Applications*, *16*(6), 2035–2054.

Mahon, A. M., Barnes, M. A., Senapati, S., Feder, J. L., Darling, J., Chang, H.-C., & Lodge, D. M. (2011). Molecular detection of targeted invasive species in heterogenous mixtures using a microfluidic carbon nanotube platform. *PLoS One*, *6*, e17280.

Mahon, A. M., & Jerde, C. L. (2016). Using environmental DNA for invasive species surveillance and monitoring. In S. Bourlat (Ed.), *Marine genomics. Methods in molecular biology* (Vol. *1452*). Humana Press. https://doi.org/10.1007/978-1-4939-3774-5_8

McElroy, M. E., Dressler, T. L., Titcomb, G. C., Wilson, E. A., Deiner, K., Dudley, T. L., Eliason, E. J., Evans, N. T., Gaines, S. D., Lafferty, K. D., Lamberti, G. A., Li, Y. Y., Lodge, D. M., Love, M. S., Mahon, A. R., Pfrender, M. E., Renshaw, M. A., Selkoe, K. A., & Jerde, C. L. (2020). Calibrating environmental DNA metabarcoding to conventional surveys for measuring fish species richness. *Frontiers in Ecology and Evolution*, *8*, 276. https://doi.org/10.3389/fevo.2020.00276

Morisette, J., Burgiel, S., Brantley, K., Daniel, W. M., Darling, J., Davis, J., Franklin, T., Gaddis, K., Hunter, M., Lance, R., & Leskey, T. (2021). Strategic considerations for invasive species managers in the utilization of environmental DNA (eDNA): Steps for incorporating this powerful surveillance tool. *Management of Biological Invasions*, *12*(3), 747–775.

National Standards of Canada. (2021). *Environmental DNA (eDNA) reporting requirements and terminology*. CSA W214:21, CSA Group.

Newcomb, T. J., Simonin, P. W., Martinez, F. A., Chadderton, W. L., Bossenbroek, J. M., Cudmore, B., Hoff, M. H., Keller, R. P., Ridenhour, B. D., Rothlisberger, J. D., Rutherford, E. S., Van Egeren, S., & Lodge,

D. M. (2021). A best practices case study for scientific collaboration between researchers and managers. *Fisheries*, *46*, 131–138.

Pawlowski, J., Apothéloz-Perret-Gentil, L., & Altermatt, F. (2020). Environmental DNA: What's behind the term? Clarifying the terminology and recommendations for its future use in biomonitoring. *Molecular Ecology*, *29*, 4258–4264. https://doi.org/10.1111/mec.15643

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*, 588–592. https://doi.org/10.1016/j.jglr.2011.05.015

Reeves, A. (2019). *Overrun: Dispatches from the Asian carp crisis* (p. 469). ECW Press.

Rutherford, E. S., Zhang, H., Kao, Y., Mason, D. M., Shakoor, A., Bouma-Gregson, K., Breck, J. T., Lodge, D. M., & Chadderton, W. L. (2021). Potential effects of bigheaded carps on four Laurentian Great Lakes food webs. *North American Journal of Fisheries Management*, *41*, 999–1019.

Senapati, S., Mahon, A. M., Gordon, J., Nowak, C., Sengupta, S., Powell, T. H. Q., Feder, J., Chang, H.-C., & Lodge, D. M. (2009). Rapid on-chip genetic detection microfluidic platform for real world applications. *Biomicrofluidics*, *3*(2), 022407.

Sepulveda, A. J., Nelson, N. M., Jerde, C. L., & Luikart, G. (2020). Are environmental DNA methods ready for aquatic invasive species management? *Trends in Ecology and Evolution*, *35*(8), 668–678. https://doi.org/10.1016/j.tree.2020.03.011

Stein, E. D., Jerde, C. L., Allan, E. A., Sepulveda, A. J., Abbott, C. L., Baerwald, M. R., Darling, J., Goodwin, K. D., Meyer, R. S., Timmers, M. A., & Thielen, P. M. (2023). Critical considerations for communicating environmental DNA science. *Environmental DNA*, *6*, e472. https://doi.org/10.1002/edn3.472

Sutherland, W. J., Bardsley, S., Clout, M., Depledge, M. H., Dicks, L. V., Fellman, L., Fleishman, E., Gibbons, D. W., Keim, B., Lickorish, F., Margerison, C., Monk, K. A., Norris, K., Peck, L. S., Prior, S. V., Scharlemann, J. P. W., Spalding, M. D., & Watkinson, A. R. (2013). A horizon scan of global conservation issues for 2013. *Trends in Ecology and Evolution*, *28*, 16–22.

Sutherland, W. J., Bennett, C., Brotherton, P. N. M., Butterworth, H. M., Clout, M. N., Côte, I. M., Dinsdale, J., Esmail, N., Fleishman, E., Gaston, K. J., Herbert-Read, J. E., Hughes, A., Kaartokallio, H., LeRoux, X., Lickorish, F. A., Matcham, W., Noor, N., Palardy, J. E., Pearce-Higgins, J. W., … Thornton, A. (2023). A global biological conservation horizon scan of issues for 2023. *Trends in Ecology and Evolution*, *38*, 97–107.

Thalinger, B., Deiner, K., Harper, L. R., Rees, H. C., Blackman, R. C., Sint, D., Traugott, M., Goldberg, C. S., & Bruce, K. (2021). A validation scale to determine the readiness of environmental DNA assays for routine species monitoring. *Environmental DNA*, *3*, 823–836. https://doi.org/10.1002/edn3.189

Tucker, A. J., Chadderton, W. L., Jerde, C. L., Renshaw, M. A., Uy, K., Gantz, C., Mahon, A. R., Bowen, A., Strakosh, T., Bossenbroek, J. M., Sieracki, J. L., Beletsky, D., Bergner, J., & Lodge, D. M. (2016). A sensitive environmental DNA (eDNA) assay leads to new insights on ruffe (*Gymnocephalus cernua*) spread in North America. *Biological Invasions*, *18*, 3205–3222.

U.S. Fish & Wildlife Service. (2022). *Great Lakes region environmental DNA: 2021 Annual Report* (p. 15+). U.S. Fish & Wildlife Service.

How to cite this article: Lodge, D. M. (2024). Lessons learned from eDNA adoption in the management of bigheaded carps in Chicago IL USA Area Waterways. *Environmental DNA*, *6*, e528. https://doi.org/10.1002/edn3.528