THIRD NATIONAL WORKSHOP ON MARINE eDNA

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JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

NATIONAL MUSEUM of NATURAL HISTORY
Smithsonian

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Keynote speakers and APL organizers *(from left: Sarah Herman, Peter Thielen, Jane Lubchenco, Hayley DeHart, Katy Carneal, and Andrew Merkle)*

CONTENTS

OVERVIEW OF ENVIRONMENTAL DNA (eDNA)

Conservation of global aquatic biodiversity requires a detailed understanding of where species live and how they are distributed within their habitats. This knowledge is traditionally captured through direct human observation and requires specialists to identify species ranging from microscopic organisms to marine mammals. With its noninvasive and easy collection, eDNA—the genetic material that organisms shed into their environment—could revolutionize how aquatic life is detected, protected, and managed, while also supporting national environmental priorities. Using just water samples, researchers can detect and monitor the populations and movements of aquatic species while simultaneously empowering communities to learn about—and participate in—the preservation of critical waterways. This unique tool has potential to scale and meet the demands of large-scale biological surveys, serving as a global biological monitoring capability.

eDNA ADVANTAGES

- Biodiversity monitoring
- Fisheries assessments
- Ocean exploration
- Detection of invasive or endangered species
- Identification of harmful algae and other microbes
- Improved detection of rare and hard to find (cryptic) species
- Evaluation of environmental impacts and restoration
- Ease of sampling with minimal environmental impact
- Cost-effective, large-scale biomonitoring
- Automated sample collections

eDNA technology is becoming more affordable as approaches for its analysis mature. It can offer a window into the lives of organisms that have not been well documented, detecting a wide variety of marine life. eDNA has an important role to play in the ability to explore and understand life in the ocean and establishing robust metrics for aquatic health across the nation and beyond.

> ***"Much the way the pandemic underscored the importance of using genomic sequencing data as a crucial surveillance tool for public health decision-making, we envision marine and aquatic eDNA as an essential capability to enable large-scale environmental observation. Imagine the effect that incorporating these data into our decision-making could have on protecting our vital, diverse ecosystems around the world."***
>
> **Andrew Merkle**
> Research and Exploratory Development Mission Area Executive

While eDNA is already being employed across several federal agencies, academic institutions, industry entities, and philanthropic organizations, differences in sampling methods, data analysis approaches, and reporting of results has limited efficient data sharing and use for policy and management applications. There is additional work to be done across the community to advance the capacity of eDNA to characterize aquatic life and enable science-based decision making and realize the full potential of the technology.

WORKSHOP DESIGN

The biennial National Workshop on Marine eDNA serves as a mechanism to bring together researchers, practitioners, and policymakers to discuss eDNA technologies and accelerate the incorporation of eDNA science into environmental management applications. The two prior workshops, held in 2018 and 2022, both injected significant momentum into eDNA science. Recommendations from the second workshop included development of an overarching eDNA strategy to coordinate on methodologies and develop infrastructure support, given the large demand signal from across the community to begin diverse implementation activities.

In June 2024, the third National Workshop on Marine eDNA was hosted at the Johns Hopkins Applied Physics Laboratory (APL) and the Smithsonian Institution. Building on the firm foundation and ambitious aspirations laid by the previous eDNA workshops, this event sought to catalyze implementation and effective adoption of eDNA as a powerful tool for everything from scientific research to resource management and problem solving. Researchers, practitioners, and policymakers from government, academia, industry, and nonprofits brought together a tremendous range of expertise areas, application priorities, and technical approaches.

The workshop included an interdisciplinary roster of interested parties from government, Indigenous organizations, industry, academia, and nonprofits. Key organizations in attendance included the Bureau of Ocean Energy Management, Defense Advanced Research Projects Agency, Department of Energy, APL, Lindblad Expeditions, Monterey Bay Aquarium Research Institute, NASA, National Geographic Society, New England Biolabs, National Oceanic and Atmospheric Administration, Oceankind, OceanX, Office of Naval Research, Oxford Nanopore Technologies, Smithsonian, US Department of the Interior, and US Geological Survey.

STEERING COMMITTEE

- **Peter Thielen,** Johns Hopkins APL
- **Hayley DeHart,** Johns Hopkins APL
- **Chris Meyer**, Smithsonian Institution
- **Niamh Redmond,** Smithsonian Institution
- **Michael Weise,** Office of Naval Research
- **Kelly Goodwin,** National Oceanic and Atmospheric Administration
- **Elif Demir-Hilton,** Oceankind
- **Kevan Yamahara,** Monterey Bay Aquarium Research Institute
- **Susanna Theroux,** Southern California Coastal Water Research Project
- **Margaret Hunter,** United States Geological Survey
- **Kim Parsons,** National Oceanic and Atmospheric Administration
- **Vincent Pieribone,** OceanX

This workshop marked a turning point with the announcement of the **National Aquatic Environmental DNA Strategy**. The new 28-page document provides both a roadmap to expedite the implementation of eDNA monitoring and guidance on developing common practices, policies, and standards. The workshop's subsequent discussions and presentations provided potential directions to put that strategy into action. The workshop included a series of sessions that addressed both immediate translational goals and long-term vision for eDNA applications.

The strategy release and workshop occurred at a critical time, as the world faces increasing environmental challenges, representing a pivotal juncture for protecting earth systems. Fully realizing the potential of eDNA technology through thoughtful, coordinated implementation can provide the community with the information and resources needed to ensure the sustainability and security of our global natural resources.

> ***"Today, we take one step closer to converting the possibility of eDNA into routine reality—not just an idea, not just things that we have tested and are using, but at scale," said Jane Lubchenco, who announced the new strategy. "We are really on the precipice of being able to do some amazing things."***
>
> **The Honorable Jane Lubchenco**
> Deputy Director for Climate and Environment at the White House Office of Science and Technology Policy

The national strategy makes the case that eDNA should no longer be considered an experimental methodology but rather an integral tool for sustained exploration, mapping, and monitoring of aquatic life. It highlights the need for federal agency coordination as well as partnership with state, local, tribal, and territorial governments; academic institutions; industry; and others to develop common guidelines, policies, and standards for how eDNA should be collected and used in decision-making, to bring eDNA from a research concept to sustained operation.

Successful strategy implementation will increase public confidence in eDNA findings and help ensure delivery of reliable, accurate eDNA information to make educated investments, evaluate management actions, and ensure compliance with environmental regulations. Implementation of eDNA monitoring is also central to the success of the nation's broader biodiversity, bioeconomy, biosecurity, and bioconservation goals, and is part of a larger set of efforts including the National Strategy for a Sustainable Ocean Economy and the National Ocean Biodiversity Strategy.

The national strategy consists of three goals with multiple sub-objectives as shown below. The workshop agenda and workshop topics were specifically oriented around these objectives to provide relevant context from multiple perspectives (researchers, technology developers, policymakers, and end users) to stimulate thoughtful discussion on how to move into the implementation phase of this strategy.

NATIONAL AQUATIC ENVIRONMENTAL DNA STRATEGY

GOAL 1

Coordinate Across Sectors to Facilitate Integration of Aquatic eDNA into Decision Making

Objective 1.1:

Coordinate Across Agencies to Align the National Aquatic eDNA Community

Objective 1.2:

Promote Aquatic eDNA Standards and Best Practices

Objective 1.3:

Disseminate Unified Messaging to Advance Technical Insights

GOAL 2

Build the Human Capacity, Infrastructure, and Research Enterprise Needed to Employ eDNA Technology at Large-Scales

Objective 2.1:

Build Human Capacity via Education and Training

Objective 2.2:

Enhance Infrastructure to Meet Technical Demands

Objective 2.3:

Support Continued Research and Development to Address Priority Science and Technology Needs

GOAL 3

Advance Coordinated Aquatic eDNA Observations to Aid Comprehensive Assessments in U.S. Waters

Objective 3.1:

Identify Priority Sites and Applications for Aquatic eDNA Sampling

Objective 3.2:

Implement Technological Advances to Build Operational Capacity

Objective 3.3:

Operationalize Biological Resource Data for Societal Benefit

*From the **National Aquatic Environmental DNA Strategy***

WORKSHOP KEY THEMES

Through technical presentations, panel discussions, and breakout sessions, the following themes emerged as crucial to successful implementation of the national strategy.

LARGE DEMAND SIGNAL FOR eDNA

At the local level, there is an increasing need for more sensitive, efficient, and effective testing techniques to detect invasive species earlier, assess local biodiversity changes over time, monitor pathogens, or identify rare/near-extinction species that may be impractical to detect using traditional methods, which include visual detection, electrofishing, traps, and similar approaches. More sensitive and comprehensive biodiversity information will improve decision-making on habitat restoration, species reintroduction, local eradication policies, and more.

At the national level, biodiversity data are increasingly needed in policy initiatives and large-scale programs. A significant amount of biodiversity data has been collected to date, but it lacks the uniformity and broad distribution needed to show large-scale status and assess progress on a national scale. The few general assessments that have been done at the national level are dated, the last in 1999. To help address this gap, the Biden administration has issued several executive orders directing the federal government to carry out assessments to measure and monitor US progress toward conservation and restoration. National strategies and programs in need of these biodiversity data are as follows:

- National Nature Assessment
- America the Beautiful (30x30)
- National Ocean Biodiversity Strategy
- National Strategy for a Sustainable Ocean Economy
- National Ocean Mapping, Exploration, and Characterization Council Strategic Priorities
- National Strategy for the Arctic Region

eDNA has the opportunity to serve as a ubiquitous tool for biodiversity monitoring and analysis, but challenges associated with adoption of these technologies remain. The workshop sought to outline solutions to these challenges, including technology choices, standardization, and data confidence.

A PATH TO WIDESPREAD ADOPTION

Implementation of eDNA as a tool to measure biodiversity has been successfully deployed in pockets across the nation. Given the diversity of eDNA applications, uptake across government and private sectors has yet to incentivize large-scale, coordinated efforts that represent national-level programs. Innovative grassroots efforts have been driven initially by researchers and technology developers for their primary user communities, often siloing technical expertise into a few regional communities. This process has limited the ability to evaluate the large-scale feasibility of eDNA technologies alongside traditional biomonitoring approaches.

To enable full nationwide implementation and utilization of eDNA monitoring, the following challenges need to be addressed.

MANY TOOLS TO CHOOSE FROM

Several industry and academic organizations have created technology solutions for eDNA sampling, analysis, data processing, and even autonomous platform solutions. With so many options available, and combinations thereof, determining which elements to implement can result in decision paralysis for users. Not only is choosing a solution challenging, but there is no "one size fits all" sampler or eDNA sensor capable of answering all questions for all use cases, nor is there one analytical platform. As collection hardware and analytical methodologies mature, it is imperative that mature eDNA-based monitoring solutions are defined by minimum requirements. These minimum requirements provide a floor from which innovation can improve and should include sample collection, laboratory protocols, methods for analyzing and interpreting data, and identification of methodological limitations.

MAINTAINING FLEXIBILITY WHILE ENSURING DATA QUALITY

There is an ever-increasing amount of eDNA data being generated by groups across the nation. Because of the breadth of eDNA applications, establishing strict standard practices is impractical, as studies often use different methods for collection, processing, and analysis based on the specific needs or expertise of the individuals doing the testing. The community has yet to arrive at an approach for standardization that can address the diverse technical assays, monitoring needs, or data analysis practices. Nevertheless, identification of common workflow elements and descriptive metadata around those aspects can enable cross-comparison of eDNA data and improve trust and reliability of eDNA methods. The diversity of eDNA analysis approaches will continue to evolve, but standardized, process-oriented metadata tags can facilitate cross-comparison more broadly than the initial data use case.

BUILDING PUBLIC TRUST THROUGH TRANSPARENCY

While detecting an organism using eDNA is conceptually simple, the scientific details involved in interpreting the data can be challenging for practitioners and the general public to understand. Even those in the targeted user communities who have been performing environmental assessments for years using traditional biomonitoring methods have had difficulty getting on board with an eDNA solution, especially if molecular-based analysis is not their field of expertise. In addition, the variation in results due to using different tools and methodologies, and the often highly technical way data are shared, have made it difficult to engender public trust. Broad, impactful, and unified communications to share technical expertise throughout the community will advance eDNA as an acceptable tool that enables decision-making, and these communication improvements will also drive future research and technology development priorities.

A PATH TO NATIONAL IMPLEMENTATION

Over the course of the workshop, subject-matter experts from across government, industry, academia, and philanthropic organizations shared their various test case experiences and lessons learned for implementation at local, regional, and national scales. An overall theme throughout the event was collaboration—not only across the community to lower the barrier of entry, share best practices, develop standards, and share data for broader biomonitoring goals, but also to inspire the broader public to trust eDNA data and use such data in decision-making and planning across the broad variety of impactful end applications. The key is to make eDNA information easily accessible.

The COVID-19 pandemic showed the world the importance of using genomic sequencing data as a critical surveillance tool for public health decision-making. The sequencing community had to quickly determine the best way to gather as many samples as possible, analyze the results, and communicate those results broadly, in a way that was digestible, actionable, and accurate. Various sensing modalities were used across the globe, from public at-home test kits to wastewater assessment. These data were then incorporated into a publicly accessible database that provided the reliable, actionable data needed to inform decision-makers as well as the public.

Biodiversity monitoring could be handled in much the same way. Marine and aquatic eDNA monitoring can become an essential capability to enable large-scale environmental observation that can then be incorporated into decision-making for protecting Earth's vital, diverse ecosystems. The key to the COVID-19 sequencing and tracking efforts was that it provided utility for assessing implications as the pandemic emerged; everyone had the ability to test, provide data, and use the data in their daily lives. By making eDNA information more broadly accessible, the community can introduce people to eDNA and empower them to use it. The ability to achieve the potential of the technology hinges on our ability to communicate the applicability to decision-making goals and overarching conservation and restoration objectives.

The key considerations discussed for overcoming the adoption challenges to advance eDNA research and application, ensuring it contributes effectively to local, national, and global biodiversity goals, are summarized below.

FROM RESEARCH LAB TO OPERATIONAL CAPABILITY

Biodiversity monitoring has been done in different ways in many different places, to varying degrees of success, for a long time. To show the true power of eDNA and all that it can be used for, fully developed use cases will inspire implementation, communicating the variety of impactful uses and how to go about using eDNA for those end applications. At various points during the workshop breakout sessions, the concept of "sandboxes" was discussed. These sandboxes would represent fully developed pilot studies, acting as safe places to experiment before a broader eDNA monitoring rollout. These sandboxes would allow users to try out eDNA monitoring in practical settings, in an operational environment instead of a lab, helping them understand the data that need to be collected, and in what format, to answer critical questions specific to the targeted application. There are already several national locations that could be leveraged for sandbox exercises, and networking across various interest groups will be required for execution of an event.

APPROACHABLE COLLECTION TOOLS

Impactful eDNA information can come from large government assessments of entire oceans or from a local stream next to a neighborhood school. To capitalize on all the opportunities available for test sites, there is a need for accurate high- and low-tech sampling methods. Each user group will have different needs and best practices. Smaller communities will need a larger focus on low technology, easy, inexpensive solutions. The more approachable the tools become, the more users there will be inclined to participate, resulting in more actionable data being gathered. Logistically challenging or remote sites will require easy-to-deploy high-tech solutions that automate sample collection and preservation.

ESTABLISH CLEAR DEFINITIONS

There is a need for standardized eDNA terminology across the community to ensure that the results of collection are accurate and actionable across a wide variety of application spaces. To make progress toward that goal, agreement on well-defined, consistent language is key to enabling community buy-in and communication. As an example, terms such as "regulation," "guideline," and "standard" hold different meanings within and between communities. When driving consistent practices across a larger user base, it is important for practitioners to define these terms to minimize misunderstanding. More precise language can reduce ambiguity while providing sufficient guidance on multiple approaches that may be acceptable, along with achievable performance criteria that can allow for consistency and quality.

VALIDATE INSTRUMENTATION AND LABS

With so many genomics labs and so much sampling instrumentation available for everything from water extraction to data analysis, it is important to understand and establish what requirements are truly needed to ensure valid results as opposed to strictly regimenting methods or options that can be flexible and produce comparable results. Validation protocols and proficiency tests need to be created to set lab and tool performance baselines, evaluate consistency, and identify the pain points that can only be overcome with more explicit requirements.

PROVIDING ENDORSED BEST PRACTICES AND OTHER RESOURCES

Setting up an eDNA implementation program: Agencies are interested in using eDNA, and may have the funding to implement a program, but are uncertain where to start without deep technical expertise. They will need guidance on the development of sampling plans, qualified labs and instrumentation, endorsed primers for targeted assays and metabarcoding applications, databases for bioinformatics, and how to interpret the results.

Ensuring quality control: Best practices and protocols for testing and quality checks can be endorsed, ensuring agreement on acceptable technical assays, monitoring, data practices, and data quality. To create minimum standards and best practices, federal, state, and tribal governments; nongovernmental organizations; academic institutions; regulators; industry; the American National Standards Institute; and other countries that have successfully implemented eDNA monitoring should be included. Once standards are established, ensure publication, initiate outreach to employ them, and include reporting standards as a requirement for funding.

Educating the workforce: Develop key reference materials for users to get started in the field, including information on the existing test site infrastructure, available technologies, how to collect data, where to share the data, certification programs, and more. Partner with national community college organizations, online publishing companies, working groups, and more to develop a training resource repository.

IMPROVE REFERENCE DATABASES AND ESTABLISH BIOREPOSITORIES

Almost all eDNA community studies demonstrate the opportunity to improve genetic reference libraries. Moreover, incomplete characterization of intraspecific diversity or closely related species can impact the level of false negatives or false positives in targeted assay applications. Trusted, voucher-based DNA reference libraries can be improved to reduce the unknowns in amplicon profiles and to improve detection confidence in resulting analyses. Priority should be given to managed, imperiled, or problematic species. Existing eDNA sampling programs can be evaluated to determine which geographic regions or habitats are less well characterized to better guide expeditionary or targeted sampling efforts. Additionally, existing eDNA samples should be strategically archived for future use. These samples represent entire communities in space and time and are rarely analyzed using a comprehensive panel of markers. Moreover, we cannot predict what future questions researchers may envision but would benefit from if they had these mini time machines.

IMPACTFUL INTERFACES AND COMMUNICATION

Different users have different data needs depending on the end application. Similar to the COVID-19 dashboard, there need to be best practices around eDNA interfaces and reporting mechanisms that make the results informative and actionable. Instead of simply providing the output from tools, eDNA implementers and repositories should include key analysis, metrics, and environmental indicators. To ensure successful communications, communities should train scientists to be good storytellers, working with creative designers and effective science communicators. The eDNA community could also engage the Centers for Disease Control and Prevention and state public health officials involved in pathogen outbreak communication for lessons learned and best practices. To enable broader public engagement, there should be creation of interactive storyboards with compelling visualizations to communicate the type of information being collected and why, the outcomes of the information provided, and the power of eDNA to transform biodiversity knowledge and subsequent actions. Meaningful engagement should involve and inform local communities, engendering trust in the process, and empowering them as shareholders in the data.

INCENTIVIZE IMPLEMENTATION AND FEEDBACK

For implementation to be widely successful, key strategies should include providing initiatives and incentives for harmonization, research, innovation, implementation, and partnerships. To make the most of eDNA, people need to not only use it but also provide feedback to interested parties such as technology developers or policymakers. Incentives for lab and tool developers are likely to take the form of coauthorship on publications, acknowledgments of primary data generators in reports, or financial compensation for those offering their time or materials for evaluation studies. Further, primary data generators are in need of a location to store various eDNA data types and clear guidance on when data should be shared with the broader community. For example, funding agencies could mandate data submissions to public repositories on predefined timelines, such as the National Center for Biotechnology Information Sequence Read Archive, when projects generate eDNA sequence data.

INCORPORATE eDNA INTO EXISTING, STANDARDIZED MONITORING PROGRAMS

In areas with ongoing biodiversity monitoring programs, eDNA monitoring can be deployed in concert to compare results and augment census taking in order to gather critical feedback and optimize methodologies and data interpretation, accelerating future integration into standard practice. eDNA can be used to surveil communities more frequently and with greater spatial resolution than those methods currently used that are too expensive or too destructive to sample at such resolution. The resulting data can be compared to determine whether increased spatial and temporal resolution changes the interpretation or decisions based on existing methods.

DETERMINE PRIORITY REGIONS

Priority regions can be determined based on existing capacities or predicted change. Climate models can suggest what regions are most likely to experience dramatic shifts that would drive community change. Proposed or planned future use (e.g., wind areas, establishment of protected areas, land management changes) can be used to prioritize eDNA sampling regimes to track before-and-after effects. Sites with existing investment (e.g., field stations, LTER, MBON, NEON sites) and ongoing monitoring programs should be prioritized to reduce additional costs to contextualize the results. Ongoing research, existing infrastructure, and concerned communities are a good combination to build interdisciplinary, invested cohorts to work together and ensure impact.

ESTABLISH A COORDINATING BODY

Coordination among numerous parties (practitioners, policymakers, managers) is needed to identify priorities and facilitate high-level harmonization of common guidelines and policies. To ensure all perspectives are accounted for in coordination body formation, federal and non-federal entities need to be included in discussions. For the federal portion, include a bioethicist, a coordinator with the public, and international representation to learn what others have already established (look to New Zealand, Australia, and Europe). As an indicator of success, leveraging a metric of communications for activities such as announcements, websites, meeting notes, pamphlets, and social media posts should be completed to ensure the general public and other organizations know what progress is being made and what resources are available.

CONCLUSION

It is evident that eDNA technologies, and opportunities for their application, are accelerating at a rapid pace. Following the workshop, Jane Lubchenco led a panel discussion at Capitol Hill Ocean Week, in which she reflected that "eDNA is a very powerful tool whose time has come." The workshop has made clear that the overall community is primed to address significant conservation and management challenges, furthering local, national, and international goals.

To realize the transformative potential of eDNA technologies, significant coordination will be required between groups that may not routinely work together. Establishing standard practices for eDNA data reporting will require flexibility in definitions, and frameworks for reporting will require improvements to remove technological or communications barriers. Widespread adoption of eDNA for scalable aquatic biomonitoring is within reach, and the grassroots community that came together for the National Workshop displayed both the vision and momentum to make implementation possible.

ACKNOWLEDGMENTS

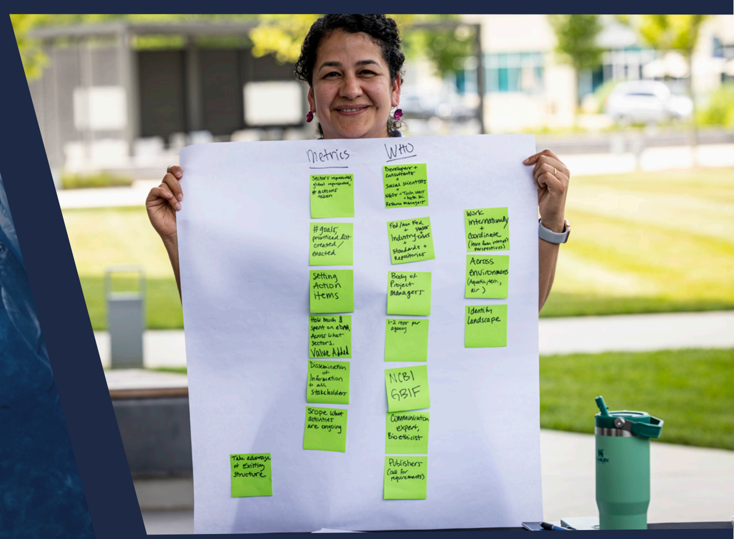
The authors would like to express their appreciation to the Third National Workshop on Marine eDNA participants who provided valuable presentations, discussions, and feedback.


Metrics
WHO
Setting Action Items
Body of Project Managers
Identify Landscape
Value Added


Introduction to the Exercise
Hayley DeHart
Johns Hopkins APL
Strategy → Implementation
Strategy is the... WHAT
Characterize Aquatic Life in U.S. Waters
Implementation is the... HOW

APPENDIX A

- BREAKOUT ACTIVITY 1: IMPLEMENTATION ACTIONS
- BREAKOUT ACTIVITY 2: GAP ANALYSIS AND PRIORITIZATION



FROM STRATEGY TO IMPLEMENTATION: OVERVIEW

The National Aquatic eDNA Strategy is a call to action to clarify sectors where federal involvement in aquatic environmental DNA (eDNA) research can accelerate research and development for biological monitoring, improve information content, encourage partnerships, and help foster job creation in a growing industry of related goods and services. Major goals and objectives of the Strategy are captured on page 2.

The biennial National Workshop on Marine eDNA brings together researchers, practitioners, and policymakers to discuss eDNA technologies, newly released national strategies, and implementation priorities. In June of 2024, the third national workshop was hosted at the Johns Hopkins University Applied Physics Laboratory and the Smithsonian National Museum of Natural History. This appendix contains a summary of the impactful discussions held on the second day of the workshop on June 4th 2024.

GENERAL APPLICATION AREAS

- Biodiversity monitoring
- Fisheries assessments
- Ocean exploration
- Detection of invasive or endangered species
- Identification of harmful algae and other microbes
- Improved detection of rare and hard to find (cryptic) species
- Evaluation of environmental impacts and restoration
- Ease of sampling with minimal environmental impact
- Cost-effective large-scale biomonitoring
- Automated sample collections

NATIONAL AQUATIC ENVIRONMENTAL DNA STRATEGY

GOAL 1

Coordinate Across Sectors to Facilitate Integration of Aquatic eDNA into Decision Making

Objective 1.1:
Coordinate Across Agencies to Align the National Aquatic eDNA Community

Objective 1.2:
Promote Aquatic eDNA Standards and Best Practices

Objective 1.3:
Disseminate Unified Messaging to Advance Technical Insights

GOAL 2

Build the Human Capacity, Infrastructure, and Research Enterprise Needed to Employ eDNA Technology at Large-Scales

Objective 2.1:
Build Human Capacity via Education and Training

Objective 2.2:
Enhance Infrastructure to Meet Technical Demands

Objective 2.3:
Support Continued Research and Development to Address Priority Science and Technology Needs

GOAL 3

Advance Coordinated Aquatic eDNA Observations to Aid Comprehensive Assessments in U.S. Waters

Objective 3.1:
Identify Priority Sites and Applications for Aquatic eDNA Sampling

Objective 3.2:
Implement Technological Advances to Build Operational Capacity

Objective 3.3:
Operationalize Biological Resource Data for Societal Benefit

BREAKOUT ACTIVITY 1: IMPLEMENTATION ACTIONS

As part of the workshop, key stakeholders from Government, Industry, Academia, and Non-Profit organizations met to identify and assess the milestones needed to implement the objectives of the national strategy, leveraging the depth and breadth of expertise from across the community.

Goal 1: Coordinate Across Sectors to Facilitate Integration of Aquatic eDNA into Decision Making

Multiple federal agencies rely on biological monitoring data to make informed decisions regarding environmental protection, restoration, and resource allocation. eDNA surveys are repeatable, scalable, and provide information that complements existing survey methods to meet mandates to manage natural resources. Effective communication is critical for the effective application of eDNA technology, and it facilitates the exchange of expertise and knowledge across partners, agencies, Tribal Nations, and Indigenous communities. Interagency coordination, such as that exhibited by the Great Lakes invasive carp eDNA monitoring program, can help deliver comparable, trusted eDNA data to discern the biological consequences of environmental stress and to inform management choices. Public confidence, investment decisions, and understanding of uncertainty and risk can be improved by proper integration of aquatic eDNA applications into decision making efforts and evaluation of management actions.

Objective 1.1: Coordinate Across Agencies to Align the National Aquatic eDNA Community

Coordination is needed to identify priorities and facilitate high-level harmonization of common guidelines and policies. This will promote the use of best-available science, align efforts with international and multilateral organizations, and collaborate with experts and interested parties from state and local agencies, academic institutions, private sectors, nonprofits, Indigenous communities, and Tribal Nations. In addition, it is critical to co-design implementation plans tailored for mission applications through interagency cooperation that addresses national priorities, statutory requirements, federal agency missions, and a prioritized framework to enable needs. Dedicated resources are needed to support coordination to ensure implementation of all the goals and objectives of the National Aquatic eDNA Strategy.

1.1 Milestone/ Action	Key Stakeholders	Actions Needed	Performance Indicators	Length of Time to Complete
Define clear vision of what outcomes/ objectives a coordinating effort or body is intended to accomplish.	• Need concrete steps/a mechanism to get there. Ensure engagements between feds and non-feds. • Start with a preexisting body and introduce a subcommittee – may want a tiered approach. Does the coordinating body need to be scientists? Maybe we need to add a step to figure out who is the coordinating body. Do a survey of who exists and what's already been done. • Ensure your group/objective is bipartisan by nature so it will withstand a change of administration. • Publishers (to enforce standards requirements).		• Develop tangible outcomes--a concrete goal that you did or didn't meet.	
Determine a mechanism for coordination.	• Technical committee on existing Federal Advisory Committee Act (FACA).			
Establish coordinating body across federal and non-federal partners.	• FACA established by some part of DOD instead of Office of Science and Technology Policy (OSTP); • Include fed and non-feds; • Fed would be eDNA Task Team including a Bioethicist, a Coordinator with public, and international representation to learn from what others have already established (look to New Zealand, Australia, Europe).	• Need for federal investment in infrastructure that will lift everybody up. For example, support for NCBI, GBIF.	• Develop tangible outcomes/concrete goal.	• Needed before a change in administration; • Would require weekly meetings on the fed-side (dependent on time commitment/availability for everyone).
Inventory agency commitments toward eDNA applications to ID opportunities for collaboration, and gaps for R&D and/or applications.	• ROSA—responsible offshore science alliance—having an eDNA equivalent would be very helpful.	• Coordination of data standards at the federal level without a top-down mandate; • Need to incorporate all of US waters.	• Assess what stakeholders are doing and how much are we investing in/spending on eDNA across agencies and evaluate its value. Could have metric of adding/ editing eDNA references in databases overtime; • Dissemination of information from all of these groups, using communication as a metric—an announcement, website, meeting notes, a pamphlet, and social media (outreach). Need to provide an update on the progress and the resources available; • Binding vs non-binding, buy-in vs not - Non allows you continue to innovate as new tech comes along. Did all of the federal agencies on the body actually put money in? • Taking advantage of industry funding could be incredibly helpful. Show them the advantage, incentivize.	

1.1 Milestone/ Action	Key Stakeholders	Actions Needed	Performance Indicators	Length of Time to Complete
Create opportunities for public engagement to provide input into Implementation Plan.				
Review and update Implementation Plan periodically Thereafter.	• Having representation/leadership at the state/non-gov level could be essential in ensuring things continuing moving and carry on. Beneficial to have coordination amongst states.			

Objective 1.2: Promote Aquatic eDNA Standards and Best Practices

Increased coordination will enable greater transparency, accessibility, and commonality of aquatic eDNA data reporting, with a focus on technical components. Standards, best practices, and technical readiness of approaches that satisfy federal monitoring and management needs and requirements, particularly in terms of actionable data and scientific basis for regulations and decision-making, will be identified and recommended. Efforts will include best practices and continual improvement for the entire eDNA workflow, including sampling design, assay development, lab protocols, recommendations for verification of results, metadata formatting, data production and management, and sample archiving to allow interoperability across space, time, and agency programs. This work will be conducted with communication among appropriate federal agencies, international bodies, academic institutions, user groups, Tribal Nations, and Indigenous communities. Guidelines for the use, sharing, and reproduction of publicly available data will be considered throughout (e.g., Find-ability, Accessibility, Interoperability, and Reusable (FAIR) principles, Collective Benefit, Authority to Control, Responsibility, and Ethics (CARE) guidelines for Indigenous Data Governance). Defining data ownership and privacy issues are key considerations and require early and sustained engagement with affected parties. Although most eDNA methods are unlikely to collect human sequence data with enough resolution to raise privacy concerns, ethical guidelines will explicitly consider those use cases in which unintentional gathering of personally identifiable human sequences might be possible and will ensure alignment with applicable federal, state, and local policies or laws relating to the collection of such data.

1.2 Milestone/Action	Key Stakeholders	Actions Needed	Performance Indicators	Length of Time to Complete
Conduct outreach with users and broader community on the minimum standards and best practices for eDNA applications.	• Include Federal, State, Tribal, NGOs, Academic, Regulators (USACE regulators), Industry, American National Standards Institute (ANSI), and other countries who have done this, Canada; • Decision Makers/ Regulators should be brought in at right moment - not too early, possibly after initial outreach to other stakeholders for feasibility.	• Steering committee and subcommittees - delineation of number and type of specific standards.	• Community consensus/acceptance; • Comment period on formation of committee.	• Depends on the mechanisms of the committee. Target 1 year.

1.2 Milestone/Action	Key Stakeholders	Actions Needed	Performance Indicators	Length of Time to Complete
Develop a process/framework for establishing minimum standards.	• Same as above. • Note: Industry may need to step out of some discussions due to conflicts of interest. However, in Canada, some industry groups were engaged to ensure their participation. Include those who were not included in the public comment period (where each of their comments would need to be addressed).	• Labor, time and money. Comment period for external groups. Public comment; • If different groups can come to consensus, it is a more strongly supported standard.	• Community consensus/acceptance.	• 1 year.
Establish minimum standards for eDNA analysis (i.e. metabarcoding informatics).	• Same as above. • Note: Industry may need to step out of some discussions due to conflicts of interest.	• Publication and outreach.	• Established benchmarks.	• 1 year, ongoing iterative review.
Determine eDNA workflow subdomains/subprocesses for determining minimum standards.	• Same as above. Industry is engaged here as well as sequencing/laboratory service providers and Academics.	• Time, volunteered or otherwise; • Financing of working groups and comment windows. • Understanding and adoption of preexisting eDNA minimum standards documentation.	• Number of standards identified, comprehensiveness of end product(s) and document(s).	• Approximately 18 months, modeled after CSA eDNA standardization efforts.
Cross-agency adoption of existing reporting standards when they exist.	• Same as above.	• Common metadata and end-user formatting guidelines and forms.	• Uptake/adoption of the standard by broader community; • Number of reporting standards generated.	• Within a 3-year timeframe, possibly 2 years with a curated working group.
Develop national data management framework leveraging existing biodiversity, genetic, and environmental data management systems.	• INVOLVED: NCBI, major federal and state agencies, Tribes, Private sector (specifically platforms such as eDNA Explorer); • LEAD: NOAA, Smithsonian (and equivalents), USGS, EPA; • USFWS.	• A centralized decision/enforcement body made of the lead constituents; • Regional jurisdictions; • Data support teams well-versed in ‘Omics bioinformatics’.	• Use metrics– number of users, sequences, and diversity of sequences/ representative taxonomies; • Impact factors/citation metrics.	• Within a 5-year time frame, should be the final “phase” combining standards and decisions made from the above milestones.

Objective 1.3: Disseminate Unified Messaging to Advance Technical Insights

Clear, consistent, and inclusive communication across agencies and with non-technical audiences is critical for successful uptake of eDNA data into decision making. Cross-sectoral awareness of eDNA science can help prepare practitioners and end users to interpret and utilize eDNA data to address an array of environmental and sustainability challenges. Utilizing common messaging among partners can enhance awareness of fit-for-purpose eDNA technologies, mature use cases, emerging capabilities, and applications not suited for eDNA tools. Broadening target audiences to meaningfully engage states, businesses, policymakers, Indigenous communities, and civil society, with outreach to systemically underserved communities, is needed to foster scientific literacy and enhance public trust in science-based decision making. This work will incorporate commitments to environmental justice and Indigenous and local knowledge, as outlined in the Ocean Justice Strategy. Clear communication of successful integration of eDNA data into decision making, particularly at the federal level, could have a catalytic effect on the mobilization of nature assessments, aquatic biodiversity information products, and private technology investment. This positive feedback loop can promote market expansion, technological development, and increased utility to decision makers.

1.3 Milestone/Action	Key Stakeholders	Actions Needed	Performance Indicators	Length of Time to Complete
Establish a workshop or session during an accessible national meeting for community input on best practices.		• Bring in social scientists and story tellers. Train scientists to be story tellers; • Teach scientists to be science communicators. Incentivize /reward science communication so that it is part of performance; • Use Influencers. NatGeo explorer version. • Engage CDC and state public health others involved in pathogen outbreak communication; • Lice outbreak model: communication is enabled by a clear ability to tell people what to do next.		
Regularly update best practices publication/manual.		• Each agency engages with their communication and outreach teams to create interactive storyboards that include compelling visualizations to communicate the type of information that is and is not collected during eDNA sampling and explains outcomes of the information provided (ex. biosecurity surveillance for invasive species). Prioritize federal investment in restoration projects etc.		
Develop use case vignettes for public outreach.	Science communicators, illustrators, and story tellers	• Understand: Why people that make decisions do so: a) Right thing to do. Right tool for job. 2) Avoid negative outcome. 3) Defendable position of the outcomes; • This turns into: Understanding socio-economic mechanisms that drive decision making. Cater messaging to that. Find a way to get science communication. Build rapport; • Use charismatic fauna as ambassadors.		
Active engagement of DEIA communities and produce multi-lingual informational resources for dissemination.		• Engage people locally so that people care. Inform them, collaborate with them, involve them, empower them. Telling people results. Giving them an eDNA kit. Citizen science is key. When communities ask for things, politicians listen.	• Established memorandums of understanding (MOUs) • Co-management plans	Years
Establish clear links between data standards and decision processes that are made available for partners and public.	Data generators, large-scale data users, and social scientists	• Bake in a transparency component. Here is what we are trying to collect *and* here is what we are not collecting. • Find out how people get their info and start there; • Work with creative designers and creative science communicators. • Support full-time personnel that focus on transition of data > knowledge > decisions. • *Incentives* that drive data submissions, accelerate adoption, and define potential data-driven decisions	• Use case studies with codified language • An eDNA society • Surveys that capture quantitative changes in decision making	Some are short term, others indefinite periods

Goal 2: Build the Human Capacity, Infrastructure, and Research Enterprise Needed to Employ eDNA Technology at Large-Scales

There is a cross-sectoral need to address challenges in the use of eDNA for biological monitoring by creating the workforce, infrastructure (field, laboratory, informatics), partnerships, and strategic investments that fuel the research and development enterprise and catalyze innovation. A projected hundredfold increase in infrastructure and organizational capacity is needed to keep pace with the projected growth of eDNA sample processing and help the federal government meet its monitoring and management responsibilities. Fulfilling this potential will require additional strategic commitments in existing infrastructure, improved and automated technologies; workforce development; sample and data storage and management; analytical and modeling capabilities; and refined tools fit for purpose.

Objective 2.1: Build Human Capacity via Education and Training

Science, engineering, and technology hold the key to solving many of humanity's most pressing challenges. Education and training programs, forums, and national workshops can improve the proficiency of practitioners and partners to accurately evaluate eDNA data and make evidence-based decisions. This strategy calls for training and hiring to bolster expertise and to address critical issues of U.S. competitiveness and technical leadership informed by diversity, equity, inclusion, and accessibility principles. Workforce proficiency can be enhanced with the establishment of incubators and accelerators focused on eDNA research. Community science opportunities and competitions can engage the public and learning communities in the development and implementation of a national eDNA enterprise.

Additional note from attendees:

Workforce training and development is important for expanding the eDNA enterprise and ensuring workforce readiness. These efforts should leverage and expand ongoing STEM workforce development efforts instead of reinventing the wheel. There is a need for greater support for molecular biology-specific training and accreditation with an eye towards cross cutting skills and flexibility/adaptability with other key skillsets - data science, AI/machine learning, taxonomy, and natural history. There are few terminal positions in agency and academic science which contribute to a leaky pipeline from high school to undergrad, to graduate, postdoc, and scientist levels. This is less of a problem for industry, which suggests that instead of a training bottleneck, it may actually be a mismatch in job opportunities. At the same time, there is a need to better inform the public and students on agency opportunities and have more coordinated and easy to digest information that is readily available. More efforts towards internships, mentorships, and apprenticeships are needed to enhance training and workforce development. There are also lots of opportunities to enhance outreach, including development of eDNA specific curricula, as well as engaging and expanding community science opportunities.

2.1 Milestone/Action	Key Stakeholders	Actions Needed	Performance Indicators	Length of Time to Complete
Additional Milestone Proposed: Estimate need for training and retraining for 2025-30; retraining likely to be more important in near term; estimate cost per person (re)trained.	• Interagency task group, contracting with labor economics consultant and with advice from MTC.	• Contracting funds (modest).	• Estimate guides programmatic developments (example, if estimates are far off, programs are poorly sized).	• 6 months from contract start; need to revise every 24 months until 2030.
Identify training needs and audiences to develop targeted training opportunities.	• Interagency task group leads, with advice from MTC (which would set up a panel on training and retraining – includes industry & consultants).	• Contracting funds (modest).	• Number of job descriptions upgraded and jobs filled in eDNA specialties (would need a survey); • Worsening delay in eDNA pipelines, delaying decision support and thwarting adoption.	• 1 year from contract start; need to revise every 24 months until 2030.
Create training resource "repository" or build upon existing tools to connect training opportunities.	• Led by online publishing consortium and national community college organizations, with advice from MTC panel on retraining and interagency working group.	• Implementation may be substantial depending on identified need ($ per person retrained); industry can co-fund.	• Number of users served, who graduate from programs, who earn credentials, or are hired into upgraded jobs.	• 2027; review progress in 2028 to update estimated need (milestones 1 & 2).
Support training webinars, workshops, and courses, prioritizing those that support capacity building in DEIA communities.	• Led by substance experts (e.g., NSTA committee or parallel for community colleges) with advice from end-user panel assembled by MTC and interagency working group.	• Implementation may be substantial depending on identified need ($ per person retrained); industry can co-fund.	• # of graduates from programs, who earn credentials, or are hired into upgraded jobs; • Outreach to underrepresented candidates meets expectation.	• 2027; review progress in 2028 to update estimated need (milestones 1 & 2).
Develop career pathway opportunities to bring graduate students into federal agency molecular science & comms positions.	• Workforce development decision makers • ORISE or NSF programs (and similar internship/post-program opportunities)	• Paid agency internships • Improved education pipelines from high school through doctoral training • Establish a wide workforce – not just PhD level scientists! • Apprenticeship opportunities • Coordination between education offices and federal organizations • Lifelong learning programs / on the job training	• Identified personnel with eDNA expertise • Personnel retention rates • Mentorship connections	• Immediate goals within 5 years, but continuous effort overall
Support training in traditional and molecular taxonomy approaches that are integrated with eDNA applications.	• Ecosystem managers	• Increase number of job openings with taxonomic expertise requirements • Integrate new tech (e.g. AI, ML) into such activities to enable scaling	• National network of taxonomists across domains of life • Bridging of taxonomy and molecular biology expertise • Established best practices documentation	• Immediate goals within 5 years, but continuous effort overall

Identify opportunities for citizen science or engagement in eDNA projects.	• Highschool teachers • Community engagement partners • Top-level government stakeholders • US National Park Service • US Fish and Wildlife, Forest Service	• Connect eDNA with food: practical connections to things like fisheries • Establish an eDNA sampling day; pair with National Parks permit pass? • Teacher trainings that include lesson plans, activities, and projects that translate to action	• Increase in non-scientific descriptions of eDNA observations • Increased uptake of eDNA science into post-secondary education • Annual surveys that are integrated into large-scale observations	• Initiate program within 3y; provide continuous support

Objective 2.2: Enhance Infrastructure to Meet Technical Demands

This strategy highlights that adequate field, laboratory, and informatics infrastructure is needed to efficiently and effectively collect, process, and archive eDNA samples. Reliable, affordable, and rapid devices are needed to enable large-scale collection of samples across diverse aquatic habitats from coastal estuaries to the deep sea. Clean and mechanized laboratory facilities are needed for high-quality, high-throughput data generation. Access to long-term bio-repositories will enable verification and reuse as new assays are developed. Expansion of curated, voucher-verified, open access libraries of DNA reference sequences is essential to ensure that organisms are properly identified during eDNA analytics. Reliable and easy access to computational resources and bioinformatic expertise is critical to manage the massive expansion of sequence data and to document biodiversity change, elucidate mechanisms that confer ecosystem resilience or vulnerability, and help inform strategies against multiple threats (e.g., toxic, invasive, and infectious species). Interagency coordination is needed to ensure that data workflows and databases that emerge within agencies, such as the Aquatic eDNAtlas, can achieve the goal of national integration and are efficiently tethered to existing resources such as the International Nucleotide Sequence Database Collaboration and the Global Biodiversity Information Facility.

2.2 Milestone/Action	Key Stakeholders	Actions Needed	Performance Indicators	Length of Time to Complete
Establish minimum guidelines for eDNA (qPCR) process lab infrastructure	Coordinating body, some debate/contentiousness over implementation/litigation vs. research needs, federal and state agency buy in	Practitioners, state agencies, labs who would be doing it and work with academic labs too, commercial/service companies	Decision tree established, defensible, structured standards	Look to EDRR, lock in risk, Canada, look to see what might be quickly adopted if it exists and palatable elsewhere - extra: instrument drift/good lab practices
Conduct reference library stakeholder meeting to agree on strategy, priorities, data architecture and governance	Smithsonian can lead and coordinate this meeting, those with collections or maintaining lists, users and taxonomists, NCBI for flagging/tagging	Users, taxonomists, list generators, MetaZooGene, Midori, MARES, SILVA, PR2, etc. agencies	Establish a governing body, host the meeting, workflows with subject matter experts, establish minimum viable product that maintains attribution	Meeting should happen within this calendar year
Funding to sustain a trusted, curated national genomic database to ensure credible data	National? Philanthropic? who is working with lists? Regional coverage (e.g. Zack Pac NW, versus domanial (MetaZooGene)	Dedicated personnel to maintain list	Does funding exist? Creation of coverage metrics, capacity to build/employ compliance directives	Unknown - sustained funding likely needed
Development of sustained, curated reference genomes/sequence generation strategy to fill critical national gaps and data strategy	Coordinated body, determined at stakeholder meeting, tiered taxonomically?	WORMS, GBIF, OBIS, ChecklistBank, taxonomists, users	Capacity to build/employ compliance directives, use demonstration sites to show feasibility - not everywhere all at once	Prioritize fishes, existing priority checklists first
Develop guidelines for data storage and management and plan for expansion of interagency computational resources	Coordinating body, Agreed formats, metadata descriptors, NCBI, repositories (practitioners that can gatekeep protocols), NOAA/SI, NMNH guidelines for this, GBIF, OBIS	Data managers within agencies or states, data providers, mobile data manager support, UI / API developers, expertise	Clear data management plans Mapped data workflows	Bespoke operations funneled into common frameworks and interoperable toolkits, harmonization of wildly different agency or practitioner approaches
Coordinate tissue inventories on national scale	Biobank providers, museums, GGBN (Global Genome Biorepository Network), how much tissue?	Tap into EDRR framework, Cheryl's group, type specimens, filed forward strategies	Punch list for missing tissues, utility of the tool - put into the hands where triage happens, query inventory - do we have it/need it? Like GGBN gap list	
Work with ISO/ANSI (or others) to develop eDNA specific protocols that are accredited.	Regulatory boards, labs (public and private), wildlife forensic labs, EDRR, NIST? this is driven within agency or facility	Needs to be made a priority - group determined it's not a priority unless someone says you have to comply	Protocol clearinghouse, BeBOP / OBON, guidelines, protocols, standards	
Develop & support implementation of Quality Management Systems needed for credible eDNA data and that can be achieved outside of ISO 17025.	Need cost/benefit analysis of compliance	mandates		
Develop data interpretation guidelines for qPCR, including reporting	EDRR/USGS protocols			
Develop data interpretation guidelines for metabarcoding, including reporting	Relative abundance, not too prescriptive, guidance for sequence quality, index communities, AI training systems - what is "good"	Interpretation requirements, what is needed? document known biases, fit for purpose guidelines for interpretation	(False?) positives could trigger auxiliary data/actions (invasives, imperiled, etc.)	Data dashboards, TICI like functionality, flags for interpretation (invasives alerts), QA/QC, maximal/minimal parameters
Develop cross-lab proficiency testing and quality standards.	Heard some of this in presentations … less problematic?			

Objective 2.3: Support Continued Research and Development to Address Priority Science and Technology Needs

Federal agencies have the opportunity to lead the research and development trajectory of eDNA applications and facilitate the transition of eDNA science and implementation from basic research through sustained operational observations. Emerging research areas include assessments of species abundance, population structure, and individual animal conditions. Continued development of sampling methodologies, including autonomous eDNA sampling and on-site diagnostics, is needed to improve access to a range of environments (e.g., deep, sensitive, ice-covered) and to accelerate access to rapid and reliable information. Fundamental research is needed to further understanding and communication of uncertainties in the interpretation of eDNA observations, assay development, fate and transport studies, and model development. Applications of machine learning, artificial intelligence, and other advanced statistical and analytical tools to better guide and understand increasingly complex aquatic eDNA biodiversity data may provide novel insights into ecological change. Federal and private support is needed to meaningfully advance each of these frontiers, consistent with the authorizations of the various federal agencies, administration policy priorities, and partner perspectives.

2.3 Milestone/Action	Key Stakeholders	Actions Needed	Performance Indicators	Length of Time to Complete
Develop national priority list for species-specific and community-based eDNA assays	eDNA task team with public input	< $1M	White papers to ID priorities	<1 year (ETA June 2025)
Identify cross-agency research requirements and priorities from basic to applied needs.	eDNA task team with public input	< $1M	White papers to ID priorities	<1 year (ETA June 2025)
Establish regular cross-agency research topic calls (via NOPP or other similar cross-agency funding mechanisms) **highest priority	eDNA task team	< $1M	Annual cross-agency call by 2025	~1yr (ETA Dec 2025)
Identify existing or new funding mechanisms to support research and development (NOAA SBIR, etc.) and coordinate topics across agencies	Combined with above	Combined with above	Combined with above	Combined with above
Establish and support technology transfer opportunities (help to create a market) for autonomous eDNA platforms (and associated technologies)	ONR DARPA + private sector +MBARI+WHOI+NIH+ NASA	$5-10M	1-3 affordable autosamplers community accessible	2030
Develop public-private partnership opportunities (i.e. SBIR) to facilitate technology transition	Low priority	Low priority	Low priority	Low priority
Establish a Sustainable Plan for National eDNA Biorepository	Smithsonian + NIST	$10M upfront $2M/yr.	Sample reuse/requests	1yr= plan development 2yr = funding identified 3yr = submission structure

Goal 3: Advance Coordinated Aquatic eDNA Observations to Aid Comprehensive Assessments in U.S. Waters

A growing number of national initiatives require detailed and comprehensive biodiversity data that demand advancements in observing approach and capacity. However, surveying biological resources has historically been a difficult and labor-intensive challenge. A national eDNA enterprise can deliver robust metrics and unprecedented characterization of aquatic life at all scales. Analysis of eDNA can aid a variety of operations, including environmental and biodiversity assessments, modeling, protected area designations, and place-based management. Creation of a network of sustained eDNA observatories at key sites across inland waters and the U.S. exclusive economic zone (EEZ) would allow more consistent exploration, monitoring, and mapping of aquatic life. As a biodiversity assessment method that can be coordinated to deploy at large scales, eDNA analytics is key to implementing a variety of priority efforts. Built upon the efforts outlined in Goals 1 and 2, aquatic eDNA collections and data can be made accessible to inform decisions that restore and sustain biological resources into the future.

Objective 3.1: Identify Priority Sites and Applications for Aquatic eDNA Sampling

Coordination to implement the National Aquatic eDNA Strategy would enable collaboration with partner agencies across the federal enterprise and national landscape to prioritize current and future U.S. EEZ and inland water sites for inventory, characterization, and/or exploration to understand the extent and state of U.S. living resources and ecosystems. Priority mission objectives must be selected based on the best available science and to identify areas with the greatest potential biological resources, conservation threats, sensitivity to climate and other anthropogenic impacts, and value to existing long-term ecological monitoring efforts. Another consideration is operational efficiency, such as opportunities to use eDNA analysis to replace or complement existing observational modalities. Building integrated monitoring strategies and study designs will require coordination across biological monitoring efforts and synergy with other national strategies, such as those focused on biodiversity and nature assessments. Information from across federal agencies and non-federal partners can be compiled to identify opportunities for collaboration, efficiency, and resource coordination. Efforts will be tailored for mission applications through interagency cooperation and co-design with partners. Interagency and non-federal coordinating bodies can be used to help execute actions as appropriate (e.g., the National Oceanographic Partnership Program, Aquatic Nuisance Species Task Force, National Invasive Species Council, and other similar groups and programs).

3.1 Milestone/Action	Key Stakeholders	Actions Needed	Performance Indicators	Length of Time to Complete
Develop outreach strategy to assess state/tribal needs for eDNA assessments	Suggestion to mine the Strategy RFI respondents for outreach POC. Should be inclusive of State & territory EPAs, federal line offices, watershed org, First Nation and tribal councils.	Would benefit from contracting someone to work on the education pkg & outreach. Suggest a collaborative team that includes social scientists to aid in messaging, interpretation of responses & evaluation of success.	A general recommendation for the development of an education package with example use cases before outreach begins to ensure common language (maybe one freshwater & one marine). Follow-up the distribution of education pkg with a general census to evaluate needs & users (Google Form? User, needs, priorities, economic impact, benefits, scope of work). Success could look like equitable representation across users/groups.	Suggested to view this as an iterative process that can be revisited as the state of knowledge evolves & uptake & use needs change.
Build a risk assessment tool and a decision tool to identify and prioritize sites for long term ecological monitoring efforts.	Guided by eDNA 'coordinating body'. Ensure there is a direct path for knowledge to be shared with communities via this body. Sites could be evaluated on a scale covering both effort & urgency (and value?).	Both financial & long-term investment in identified priority sites. Priorities should be founded on diversity so that sites represent diverse geographic, socioeconomic and ecological/habitat needs/values.		Estimated to take ~1yr with dedicated effort.
Identify currently existing networks & infrastructure where aquatic eDNA sampling can bring added value; Develop partnership opportunities to increase integration between traditional sampling and eDNA sampling for monitoring.	Guided by eDNA 'coordinating body' to leverage existing relationships & networks. How to identify existing projects/networks leverage these trusted relationships? Suggest reach-outs to granting bodies, eDNA slack channel, Omics network, OBIS/GBIF/DNA explorer. Examine current projects using traditional sampling methods that could benefit from eDNA tools.		Could include this (i.e. partnerships) as a criterion for the Risk Assessment tool. Communication, education and trust will be key criteria for success. Success could be evaluated through representation and comparison of current and future projects/systems using eDNA tools.	
Establish guidelines and best practices for integrated monitoring strategies and study designs.	Should be developed by technical subgroup of the eDNA coordinating body with adequate representation across taxa and survey methods. Make use of existing guidelines either published in primary literature or those implemented in other countries. A data management plan will be important. Some discussion is needed to cover issues such as data archiving and data formats.			
Integrate eDNA data with other technological tools to facilitate landscape-level approaches to management.				
Work with existing climate programs (i.e. modelers) to determine regions most likely to experience dramatic shift that would drive community change				

Objective 3.2 Implement Technological Advances to Build Operational Capacity

Applications of eDNA create diverse opportunities for public-private partnerships, including the development of autonomous platforms and low-cost instruments that can be operationalized by leveraging existing federal programs (e.g., Small Business Innovation Research), assets, and operators. Industry can assist with full-scale implementation by developing novel technologies and off-the-shelf products to improve the efficiency, affordability, and effectiveness of the entire workflow, which includes study design, sampling, extraction, data generation, analysis, management, and reporting. The number of steps executed "in-house" versus by commercial partners varies depending on agency needs, creating an array of partnering or contracting opportunities. Strategic deployment of investments across public, private, and academic sectors should increase cost efficiency (e.g., by harnessing the collective bargaining power of the federal government) while simultaneously providing scaling incentives and price certainty for investors and can free nonprofit entities to concentrate on non-routine analyses and novel method development. As innovation and infrastructure grow, implementation of the National Aquatic eDNA Strategy can help the nation take advantage of these opportunities and ensure that advances are continually integrated into the network.

3.2 Milestone/Action	Key Stakeholders	Actions Needed	Performance Indicators	Length of Time to Complete
Identify Federal funding and incentivizing mechanisms; identify how these funds can be used to contribute to supporting technology development and demonstration projects.	• Need larger coordinating body at the federal level, to include all agencies from Department of Commerce, Education, Defense, Energy, Interior, and Transportation; • Leverage funding mandates and use specific use cases to develop actual budget line items (e.g., marine biosecurity); • Connect Federal, Private and Philanthropic organizations to amplify funding.	• Coordinating body larger than NOPP.	• Number of funding calls that support eDNA studies. • Data upload metrics to Global Biodiversity Information Facility (GBIF)/Ocean Biodiversity Information System (OBIS).	• Now (<1 year) with larger projects starting in < 5 years.
Foster public engagement to support development and testing of new technologies.	• Include general public, early education, tech companies, industry.	• K-12 Curriculum and Community Science Programs.	• School or community participation metrics and ocean literacy improvement	• 5 years.
Provide opportunities for non-federal entities to participate in federal funding opportunities - i.e. prize challenge, 'moon shots'	• Involved: Academic, government, commercial / entrepreneurial; global components • Lead: Government (if govt funds, will want oversight); • Integrate into existing programs: Long-term Ecological Research Network (LTER), National	• Non-monetary: Sampling plans; • Extend who sees the results; • Building tools and platforms; • eDNA incubator network • Money: Incentivize public private	• Milestone based; • Annual report (funding summary, progress update, samples in hand, geographic coverage, etc.); • Track new eDNA users. Assess whether funding is	• 1-3 years? 5-10 years? Depended on milestones and stage-gate success (phased approaches); • Takes 2-3 years to get money, 2-3 years to give it away responsibly, and 2-3

3.2 Milestone/Action	Key Stakeholders	Actions Needed	Performance Indicators	Length of Time to Complete
	Ecological Observatory Network (NEON), etc.; • Increase budgets to programs to get sampling now, adding new eDNA specific Programs; • Create the opportunities for commercial companies.	partnerships, SBIRs, Postdoc funding (specific to eDNA strategy), academia in general.	providing useful capacity. (Number of times reference is queried, users leveraging data, completeness of database, quantity and quality) • Assess how to build capacity without repeating errors (Re-use and re-analysis); • Commercially sustainable or globally impactful.	years for them to deliver on it.
Develop tiered, implementable milestones across eDNA workflows, including sampling, sample processing, metanalyses, and decision frameworks	• Involved: All stakeholders (government, academic, industry, etc.), at all levels including boots on ground perspective; • Community feedback – need to determine most impactful way to gather. • Lead: NOAA omics, GBIF, Omics	• Metanalysis of eDNA data for management decisions; • Uniform meta-analysis reporting format; • Funding; • People; • Decision framework for invasive species (qPCR and metabarcoding); • Clear standards for each step of process (including transparency of workflows, especially with commercial companies storing and processing); • How to create milestones in changing dynamic • Sequence data and metadata for long term storage; • How to future-proof? Look to other industries to not repeat mistakes.	• Performance-based proficiency testing; • Benchmarking - sending same samples; • Divide and conquer - have people who are most knowledgeable and capable help coordinate and measure it - keep it transparent and share information (front end: agencies do sampling, share methods and metadata – back-end processing); • From commercial side – bioinformatics and result assessment can get siloed – need to close the loop; • Incentives for data sharing; • Use DOIs and track citations of workflows; • Visible dashboard • Example of GenBank - no way to remove even if error.	• Short term successes (1-3 years for infrastructure): Protocols, data sharing, flexibility, making workflows citable - for tracking, building for future • Long term: Repositories and big data opportunities; build consensus around workflows and then companies will support (need platform and communication to build consensus)

Objective 3.3 Operationalize Biological Resource Data for Societal Benefits

Analysis of eDNA data can provide critical insights into ecosystem status and mechanisms that confer resilience or vulnerability. Combined and cooperative eDNA analysis can map aquatic life at an unprecedented scale and aid predictive modeling of the biological resources that underpin the health and security of the nation. Employing eDNA technology to characterize aquatic life can help address the needs of multiple federal agencies across disparate mission mandates such as listed species management and invasive and harmful species monitoring. For example, the EDRR Framework aims to use the potential sensitivity, speed, and accuracy of eDNA data to provide timely warning of potential invasive events to reduce economic and environmental impacts. Lessons from this effort can benefit other agencies seeking to use eDNA data as a line of evidence in decision making. Enhanced and co-produced biodiversity monitoring activities and data can promote equity and environmental justice. Future emphasis on educational initiatives and meaningful community engagement at the outset of decision making may further support local economies.

3.3 Milestone/Action	Key Stakeholders	Actions Needed	Performance Indicators	Length of Time to Complete
Set standards for all applications requiring monitoring strategies and data usage to be informed by DEIA and environmental justice principles.		• Ethics review board/guidelines; • Incentives for work in underserved areas; • Evaluate likely outcomes for people/communities at project planning stage.	• Defined progress assessments • Local community surveys	• Ongoing; adaptive.
Engage communities for development of rigorous and accountable decision-making processes regarding eDNA data.	• Indigenous communities, relevant communities, and self-selected individuals.	• Best-practices decision tree, connections to projects, and data-sharing agreements • Development of communications materials • Data literacy campaigns	• Project renewals • Ongoing community trust and increased participation. • Shared authorship on reports and publications	• Ongoing / forever.
Develop guidelines for participatory science projects.	• Participants, organizing groups, and scientists with data. • Institutional Review Boards (IRB)	• Learning modules for citizen science decision tree for protocols, and YouTube/etc. outreach.	• Increased participation, increased completion, decreased conflict, and real decisions in real world.	• < 1 year.
Develop and support mobilization of biodiversity monitoring data including the generation of information sharing resources to enable enhanced science communication and science-based decision making.	• Database managers • Portal managers • Federal and local stakeholders	• Ocean/environmental literacy outreach; • Answer the "why". • Gamification; • Personalization. • Protection approaches for sensitive data • Ease of use and automated workflow development	• Rules grounded in best available science. • Citations of eDNA data in federal register / decisions.	
Engage and/or encourage eDNA projects that include a social sciences component to increase fundamental understanding of public perceptions and social implications of eDNA research and monitoring.				
Additional Milestone Proposed: Decrease costs to participate.	• Funding agencies to spur development; • R&D for cost-reduction.	• Leverage existing infrastructure; • Cheap/easy/ reliable tools; • Public/private partnerships; • Ambassadors.	• Lower cost to user.	• 5-10 years.

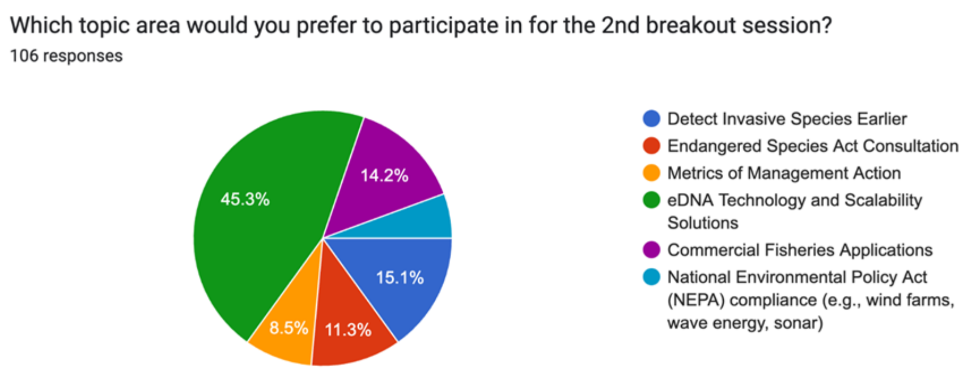
BREAKOUT ACTIVITY 2: GAP ANALYSIS AND PRIORITIZATION

Workshop attendees gathered in several discussion groups to evaluate if the state of eDNA is ready for implementation in key areas, assessed based on coordination, communication, inclusiveness and partnerships, infrastructure, and technical science.

Key Topic Areas

- Detect Invasive Species Earlier
- Metrics of Management Action
- Endangered Species Act Consultation
- eDNA Technology and Scalability Solutions
- Commercial Fisheries Applications

Participants in this activity were allowed to self-assign with Key Topic Areas. The distribution of selections is displayed below:



Defining Categories

- Coordination (multiple entities needed)
- Communication (engagement and outreach to align communities)
- Inclusiveness and partnerships (practices to ensure broad participation and collaboration of all stakeholders)
- Infrastructure (basic organization and structure needed to accomplish goals)
- Technical Science (scientific research and development that focuses on practical application and implementation of the knowledge gained for societal benefit)

Detect Invasive Species Earlier

Overview

Effective management of invasive species in fisheries requires robust communication, coordination, and technological infrastructure. This summary outlines the critical needs and priorities for improving the detection and management of invasive species, with a focus on ballast water management, data infrastructure, and the need for enhanced communication among federal, state, tribal, and private stakeholders.

Participants

James English, Cindy, USACE, Christine Lipsky, John Hagan, Maggie Hunter

Ballast Water Management

Ballast water is a primary vector for invasive species. Key priorities include:

1. **Priority Species List:** Developing a critical list of species of concern to facilitate quick identification and subsequent management.
2. **Marker Design:** Once priority species are identified, designing specific genetic markers for these species is essential.
3. **Testing Framework:** Establishing a comprehensive framework for testing ballast water across the numerous ships that utilize it.

This area is considered lower priority compared to others due to the extensive technological and logistical gaps.

Communication and Coordination

Effective management of invasive species is heavily reliant on strong communication and coordination mechanisms:

1. **Interagency Communication:** There is a significant gap in communication between federal, state, and tribal entities. Establishing regular, inclusive meetings can facilitate better data sharing and collaborative efforts.
2. **Multiway Engagement:** Creating platforms for multi-directional communication, including all relevant stakeholders (terrestrial and aquatic environments, tribal authorities, etc.), is crucial. This could be achieved through regional panels, workshops, or regular network meetings.
3. **Detection of Invasive Species Working Group:** Forming a dedicated working group to focus on the detection and early response to invasive species can help streamline efforts across jurisdictions.

Data Reporting Infrastructure

A robust data reporting infrastructure is vital for the effective management of invasive species:

1. **Baseline Establishment:** Establishing a baseline to detect the presence of invasive species is a high priority, especially with the rapid changes brought about by climate change.

2. **Reference Libraries:** Developing comprehensive reference libraries for invasive species to aid in accurate and quick identification.
3. **Central Clearing House:** Creating a centralized repository where new invasive species detections are reported and accessible to all stakeholders. EDDMaps could serve as a model for terrestrial species but should be expanded to include aquatic species.

Technological and Scientific Needs

There are several technical and scientific needs to enhance the detection and management of invasive species:

1. **Point of Use Tools:** Developing and deploying point-of-use tools for regulation and monitoring at the site of detection.
2. **Automated Monitoring Systems:** High priority should be given to developing automated monitoring systems to provide continuous, real-time data on invasive species presence.
3. **National Standards:** Establishing national standards for data collection and reporting to ensure consistency and reliability across different jurisdictions.

Specific Scientific Challenges

1. **Abundance Estimations:** Managers require accurate abundance estimates of invasive species to make informed decisions. There is a medium priority and gap in this area.
2. **Fate and Transport Studies:** Understanding the pathways and transport mechanisms of invasive species to better target monitoring efforts is another medium priority area.
3. **Data Sharing Agreements:** Creating frameworks for data sharing across regions and watersheds to ensure timely alerts and coordinated responses.

Case Study: Green Crab Invasion

The green crab invasion in the Northwest highlights the critical need for central communication and coordination. Issues arise when user groups are reluctant to communicate. A neutral body, such as the US Geological Survey (USGS), could serve as a coordinator to bridge these gaps.

Prioritization and Action Steps

Given the complexity and urgency of managing invasive species, all outlined priorities can be considered high priority and high gap depending on the context. The following steps are recommended:

1. **Enhance Coordination and Communication:** Establish robust mechanisms for regular, multiway communication among all stakeholders.
2. **Build Partnerships:** Engage social scientists and facilitators to bridge the gap between technology developers and end users.
3. **Strengthen Infrastructure:** Invest in building comprehensive data reporting and reference infrastructure.
4. **Advance Technological Solutions:** Focus on developing and deploying automated and

point-of-use monitoring tools.

5. **Adopt National Standards:** Ensure consistency and reliability in data collection and reporting through national standards.

By addressing these priorities, the management of invasive species in fisheries can become more effective, ensuring better protection of ecosystems and resources.

Endangered Species Act Consultation

Priorities:

1. Data sharing platforms
2. LOD for specific target species and community sharing of validated marker libraries
3. High priority and High gap
4. How to use eDNA for home range analyses and/or range shifts/expansions
5. What does an ESA consultation based solely on eDNA look like?
6. How to formally integrate eDNA and other data streams for ESA consultations
7. What is “proof” of presence (eDNA vs visual observations)?
8. eDNA fate/transport models needed to support data interpretation
9. The use of eDNA as a monitoring tool to address consultation requirements
10. A desire for standards and guidelines so that the community knows how to evaluate eDNA data validity to support an understanding of data quality (re: using ‘best available science’)
11. Workflows/pipelines for designing species-specific, validated assays (What about low-shedding species? Closely related species?)
12. Tribal inclusion is desired to support eDNA adoption as an ESA tool
13. Community adoption of data sharing platforms

Lower Priorities:

1. How do users interpret non-detects? What does ‘proof of absence’ of an ESA listed species look like?
2. Enumeration/biomass estimates from eDNA (lower priority but high gap) - More development is desired here to move into the quantitative space; Training and education needed to support users of eDNA data
3. Communication on how eDNA data can/are being used
4. What does ‘vouchered data’ look like?
5. eDNA adoption as complementary data to support ESA species assessment

Metrics of Management Action

Participants

Susie Theroux, Mike Bunce, Kara Andres, Jordan Angle, and Beverly McClenaghan

Technology Transfer to Managers (field, lab, bioinformatics data, visualization)

- **Key Stakeholders:** EPA, USFW, NOAA, State Agencies, Conservation Groups, Indigenous Groups, BOEM, NPS
- **Metrics of success:**
    - 3 State agencies successfully use eDNA for biodiversity testing
    - Certification of eDNA skillset

Reference Databases

- **Key Stakeholders:** Smithsonian and other repositories, DOE, OBIS/GBIF, NCBI
- **Metrics of success:**
    - Databases are FAIR Compliant
    - Modern taxonomy updates
    - Gap analysis for US aquatics - % closure by 2030

Index Development

- **Key Stakeholders:** EPA, BOEM, Commercial
- **Metrics of success:**
    - CITI index for US aquatic waters and streams
    - Index used for retention and restoration

Baseline Data

- **Key Stakeholders:** EPA, NOAA, USFW, USGS, BOEM
- **Metrics of success:**
    - Aquatic eDNA incorporated into all NRSA sampling
    - Strategy for long-term archiving and storage

Regulatory Acceptance

- **Key Stakeholders:** EPA, NOAA, State Organizations, BOEM, NPS
- **Metrics of success:**
    - Interagency statement on acceptance of eDNA data
    - Environmental Impact Assessment

eDNA Technology and Scalability Solutions

Overview

The group identified several clusters of issues that should be addressed or included in the implementation plan for the National Strategy for Aquatic eDNA.

Participants

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High Gap/High Priority

De-risk eDNA, especially for small businesses. Scaling up an eDNA enterprise will continue to depend upon a wide range of business participants. Small businesses with eDNA services as a major component of their revenue streams (including sampling devices, bioinformatics, environmental consultants) cannot attract investment needed to scale up without an assured market for some period into the future. Direct federal guarantee of purchases for selected services, or indirect federal support such as tax credits for investment are needed. Indirect support makes more sense if the eDNA market is likely to be decentralized, e.g., via state agencies or project proponents complying with environmental impact analysis requirements.

Set system requirements for instrumentation to meet user needs. The MoSCoW exercise (Yamahara presentation) illustrates an essential step in implementation. Federal agencies should convene principal users of eDNA methods among their own programs and their constituencies (e.g., via regional offices) to meet with firms able to supply equipment and services to set minimum system requirements to guide innovation and procurement. These requirements should be reviewed every 3-5 years to avoid lock-in to designs and techniques that are superseded by technological improvements.

Establish certification for laboratories offering eDNA services. The implementation plan should call for work with NIST, existing certification organizations, and expert advisers from leading eDNA laboratories (e.g., SCCWRP) to organize a transparent and credible effort to develop a laboratory certification program, to be administered on a for-profit basis by an existing certification organization.

Moderate Gap/High Priority

Stand up a national eDNA resource center, to be co-funded by industry. The center, an independent nonprofit that might be modeled on the Electric Power Research Institute, would serve a range of industry-wide purposes as the eDNA enterprise scale up:

- Hub for developing and updating system requirements, laboratory certification standards, and training programs and materials development
- Maintain a national registry of certified laboratories
- Work with the Smithsonian on expanding and maintaining biological and digital repositories to support a globally accessible genomic library

- Provide an administrative support platform to assure long-term data storage and advanced computation services, to the extent these are needed for R&D and transitional operations before datasets are archived (there may be lessons learned from similar activities at the National Center for Biotechnology Information)
- Facilitate sharing of expensive and infrequently used equipment. Business firms developing eDNA equipment and services need access to infrequently used assets such as long-range autonomous underwater vehicles.
- Curate a directory of governmental and private sector programs that can benefit small eDNA businesses

Endorse an association of eDNA business firms. Such an organization could be hosted initially by the Marine Technology Society. By including this in the implementation plan, the members of the association would have a legitimate platform to pursue a range of objectives, including providing advice to the interagency work group.

Low Gap/High Priority

Anticipate opposition. A barrier to scaling up the eDNA enterprise is active opposition by groups whose economic or cultural interests are perceived to be harmed by the use of eDNA. An inclusive and transparent approach to developing the enterprise, in communications and in the steps recommended in this document, is an essential starting point.

Deploy eDNA in multiple places with multiple uses and user groups. This makes sense from a practical standpoint, but it also provides a way to find opposition and to address the concerns of opponents, at a tractable scale.

Moderate Gap/Moderate Priority

Reach out to underrepresented populations and communities.
- Work with industry on outreach programs, including internship and apprenticeship programs for workforce development
- Use existing federal programs for curriculum development, summer internships, and other educational opportunities for underrepresented populations
- Offer one-time eDNA surveys of publicly accessible aquatic landscapes used by minority communities, and work with natural history museums to develop interpretive materials to acquaint residents with this view of their landscape

Low Gap/Moderate Priority

Develop metadata requirements working with TDWG (Biodiversity Information Standards), a nonprofit. Minimum standards would facilitate archiving in global databases.

Categories: (A) Communications/Comms (B) Coordination, (C) Infrastructure, (D) Technical Science, (E) Inclusivity and Partners

Rankings: Low priority to high priority (immediate need) VERSUS low gap to high gap (perceived readiness)

1. **COMMUNICATION**

- Need to lower predictive certainty thresholds for future planning (mid to low priority, mid gap)
- Uncertainty because of incomplete reference libraries – either false negatives or mis-annotations (high to mid priority, mid gap)
- Communicate reality (high priority, mid to low gap)
- Develop notification network, alert systems, and/or communications (high to medium priority, medium gap)

2. **COORDINATION**

- Market an easy tool (low priority, mid to low gap)
- Transparency (mid to high priority, lowest gap)
- Define markets, could be communications as well (mid priority, mid to low gap)
- Device systems Integration, hand offs between processing steps (medium priority, medium to high gap)
- Alignment, capacity for harmonized workflows (medium priority, low to medium gap)

3. **INFRASTRUCTURE**

- Data plumbing (medium to high priority, medium gap)
- GBIF/OBIS functionality/support for data management, ASV tracking visualization, consistent taxonomic annotation (highest priority, low to medium gap)
- Environmental Samples Biobank (high to medium priority, low gap – except for cost $$)
- Data Attribution and traceability (medium to high priority, medium to low gap)
- Public Informatics Pipelines – repeatable workflows like MBRAVE, eDNA Explorer, MGNIFY, etc. (medium priority, low to medium gap)
- Reference Libraries (highest priority, medium to low gap)
- Systems to connect users, could be coordination as well (medium to high priority, medium gap)

4. **TECHNICAL SCIENCE**

- Metagenomics (low priority, high to medium gap)
- Onboard AUV sequencing (medium priority, highest gap)
- Rapid Tool Implementation (medium priority, medium to high gap)
- Reproducibility (high priority, medium to high gap)
- Quantitative Metabarcoding, UMIs? (medium to high priority, medium to high gap)
- Extraction (low priority, low gap)
- Primer Development (medium to low priority, medium to low gap)
- Shipboard sequencing (medium priority, lowest gap – it's happening)
- Priority List of Target Organisms, National Priority List (high priority, low gap)
- Ease of Use of Automated Samplers (high priority, medium gap)
- Sampling Gap Analysis (medium to high priority, medium to low gap)
- Connect needs to Sampling (medium to high priority, medium to low gap)

- Room Temperature Storage (high priority, medium to low gap)
- Positive Controls, needs market identity, Zymo-like, for metabarcoding as well (high to medium priority, low to medium gap)
- Synthetic Spike Ins, calibrations, positives (medium to high priority, low to medium gaps)
- Filtration Capacity in various conditions, clogging (medium priority, medium gap)
- Automated Samplers – high capacity=many samples, not high volume, many samples >100 (medium priority, medium to low gap)
- Integrated Sampling Devices – takes not just samples, but also pH, turbidity, salinity, O2, etc. (medium priority, medium gap)

5. INCLUSIVITY AND PARTNERSHIPS

- Ease of Use, comms, partners, protocols, BeBOP, OBON (medium priority, medium gap)
- Responsive INSDC, NCBI, Genbank, getting data public, mitogenomes verified for novel taxa (high priority, medium gap)

Commercial Fisheries Applications

eDNA is ready for commercial fisheries applications, but there are technological and communication barriers for widespread adoption. In particular, eDNA is well suited to provide information that current methods cannot provide such as increased information over space and time and in areas that cannot be surveyed (untrawlable habitat, offshore wind, etc.) as well as data limited fisheries, particularly state fisheries that do not have routine fisheries independent monitoring efforts. To do this, there is a need to improve our ability to derive quantitative information from eDNA, increase trust and reliability through more paired eDNA + traditional survey methods, and to facilitate eDNA sampling on vessels to expand scope and scale of sampling. There is a push within the scientific community to increase the uptake of ecosystem-based fisheries management in which eDNA can provide important and expanded roles on providing prey availability, early life history information, and information on disease - however, existing fisheries management does not frequently incorporate this information although efforts like the Integrated Ecosystem Assessments are a good place to start. Lastly, deriving population genetics from eDNA, particularly from single celled sequencing, would open the door to a suite of fisheries management applications that rely on stock identification.

Overview

eDNA technology is poised for broad application in commercial fisheries, providing data and insights beyond the scope of traditional methods. eDNA excels in offering enhanced spatial and temporal data and can be especially valuable in environments that are challenging to survey, such as untrawlable habitats, offshore wind farms, and data-limited fisheries, including many state-managed fisheries without routine independent monitoring.

Key Benefits and Challenges

eDNA offers several advantages over traditional survey methods:

- **Spatial and Temporal Coverage:** eDNA can cover areas that are difficult to survey with traditional methods and can provide more frequent data collection over time.
- **Untrawlable Habitats:** eDNA can obtain data from regions where trawling is impossible, such as rocky substrates or areas with extensive underwater structures like offshore wind farms.
- **Data-Limited Fisheries:** eDNA is particularly useful for species and regions lacking robust monitoring programs, providing critical data to support management decisions.

However, several barriers need to be addressed for widespread adoption:

- **Quantitative Data:** Enhancing the ability to derive quantitative information from eDNA is crucial. This involves improving the understanding of eDNA shedding and degradation rates.
- **Trust and Reliability:** Increased use of paired eDNA and traditional survey methods can build trust in eDNA data. This involves more comprehensive ground-truthing exercises to calibrate and validate eDNA results.
- **Sampling on Vessels:** Simplifying eDNA sampling processes on commercial fishing vessels can expand the scope and scale of data collection. This might include using

autonomous sampling platforms or integrating eDNA sampling with existing fishing operations.

Integration with Ecosystem-Based Fisheries Management

The scientific community advocates for incorporating eDNA into ecosystem-based fisheries management (EBFM), which includes:

- **Prey Availability:** eDNA can provide detailed information on prey species' presence and abundance, aiding in understanding predator-prey dynamics.
- **Early Life History and Disease:** eDNA can offer insights into the early life stages of fish and the presence of diseases, although current fisheries management practices rarely incorporate this information.
- **Population Genetics:** Advancements in single-cell sequencing from eDNA could revolutionize stock identification and population genetics, essential for managing bycatch and assessing stock structure.

Linking Biodiversity Data and Stock Assessments

eDNA has the potential to enhance stock assessments and ecosystem-based management by:

- **Predicting Recruitment and Population Dynamics:** Integrating eDNA data with traditional demographic data can improve predictions of fish recruitment and population trends.
- **Addressing Data Gaps:** eDNA can fill in data gaps for species and habitats not well-covered by traditional surveys, such as invertebrates and species in untrawlable areas.
- **Quantitative Integration:** Developing integrated models that combine trawl data with eDNA can provide a more comprehensive understanding of fish populations.

Technological and Methodological Innovations

To fully leverage eDNA, several technological and methodological innovations are needed:

- **Autonomous Sampling:** Developing more affordable and efficient autonomous samplers, such as moorings, ASVs, and AUVs, can enhance eDNA data collection.
- **Passive Filters and Long-Line Sampling:** Using passive filters and integrating eDNA sampling with long-line or trawl operations can increase data collection efficiency.
- **Improved Assays:** Creating a library of qPCR assays for the top commercial species can streamline eDNA analysis and ensure consistency across studies.

Stakeholder Engagement and Adoption

Effective stakeholder engagement is critical for the successful integration of eDNA into fisheries management:

- **Communication and Outreach:** Improved communication and outreach with fishermen, regulators, and other stakeholders can build understanding and support for eDNA technologies.
- **eDNA-Literate Managers:** Training and education for fisheries managers on eDNA applications and benefits can facilitate its adoption.
- **Regulatory Inclusion:** Engaging regulators in discussions about incorporating eDNA into fisheries observations and assessments can help integrate new data sources into management frameworks.

Use Cases and Future Directions

eDNA can support a variety of use cases and future directions, such as:

- **Range Expansions and Climate-Driven Changes:** Monitoring species range expansions due to climate change, such as pollock in the Arctic, can provide early warnings and management insights.
- **Impact Assessments:** Using eDNA for monitoring the impacts of offshore wind farms and Marine Protected Areas (MPAs) can provide valuable data for environmental assessments.
- **Bycatch Management:** eDNA can help manage bycatch by providing detailed population structure data and filling gaps left by reduced ship-based surveys.

In conclusion, while eDNA holds significant promise for enhancing commercial fisheries management, achieving its full potential requires overcoming technological and communication barriers, improving quantitative data extraction, and fostering collaboration among stakeholders. Through these efforts, eDNA can provide critical insights and support more sustainable and effective fisheries management practices.