National Aquatic Environmental DNA Strategy

A Report by the

eDNA TASK TEAM *of the*

INTERAGENCY WORKING GROUP ON BIODIVERSITY *of the*

SUBCOMMITTEE ON OCEAN SCIENCE AND TECHNOLOGY

COMMITTEE ON ENVIRONMENT

of the

NATIONAL SCIENCE & TECHNOLOGY COUNCIL

June 2024

About the National Science and Technology Council

The National Science and Technology Council (NSTC) is the principal means by which the Executive Branch coordinates science and technology policy across the diverse entities that make up the federal research and development enterprise. A primary objective of the NSTC is to ensure science and technology policy decisions and programs are consistent with the President's stated goals. The NSTC prepares research and development strategies that are coordinated across federal agencies aimed at accomplishing multiple national goals. The work of the NSTC is organized under committees that oversee subcommittees and working groups focused on different aspects of science and technology. More information is available at http://www.whitehouse.gov/ostp/nstc.

About the Office of Science and Technology Policy

The Office of Science and Technology Policy (OSTP) was established by the National Science and Technology Policy, Organization, and Priorities Act of 1976 to provide the President and others within the Executive Office of the President with advice on the scientific, engineering, and technological aspects of the economy, national security, homeland security, health, foreign relations, the environment, and the technological recovery and use of resources, among other topics. OSTP leads interagency science and technology policy coordination efforts, assists the Office of Management and Budget with an annual review and analysis of federal research and development in budgets, and serves as a source of scientific and technological analysis and judgment for the President with respect to major policies, plans, and programs of the federal government. More information is available at http://www.whitehouse.gov/ostp.

About the Subcommittee on Ocean Science and Technology

The purpose of the Subcommittee on Ocean Science and Technology (SOST) is to advise and assist on national issues of ocean science and technology. The SOST contributes to the goals for federal ocean science and technology, including developing coordinated interagency strategies and fostering national ocean science and technology priorities. The SOST reports to both the NSTC Committee on Environment and the Ocean Policy Committee.

About the Interagency Working Group on Biodiversity

The SOST Biodiversity Interagency Working Group (IWG) was established to enhance coordination of ocean biodiversity research and monitoring to inform federal agency mandated activities (e.g., management, protection, regulation) and to understand, assess, and manage climate and environmental impacts on ocean life and habitats.

About the eDNA Task Team

The eDNA Task Team sits under the National Science and Technology Council (NSTC) Subcommittee on Ocean Science and Technology (SOST) Biodiversity Interagency Working Group (IWG). The team's goal is to accelerate adoption of aquatic environmental DNA (eDNA) analysis to inform environmental research and operational monitoring efforts to address mission objectives and management needs at local, regional, and national scales.

About this Document

The National Aquatic eDNA Strategy is a call to action to clarify sectors where federal involvement in aquatic 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. The application of an eDNA toolkit has the potential to increase efficiencies, reduce costs, harmonize protocols, and deliver improved, enhanced information across numerous agency missions and mandates. As such, the National Aquatic eDNA Strategy will serve as a pillar of implementation to large-scale efforts such as the National Nature Assessment, National Strategy for a Sustainable Ocean Economy, and the National Ocean Biodiversity Strategy. Any future Federal activities will be considered in the broader context of Administration priorities and available resources.

Disclaimers

Reference in this report to any product, service, enterprise, or individual, including any written works (i.e., books, articles, papers), is not an endorsement and does not imply official government sanction or endorsement of those entities or their views. Links to non-U.S. government websites do not constitute or imply official U.S. government or OSTP endorsement of or responsibility for the opinions, ideas, data, or products presented at those locations, or guarantee the validity of the information provided.

Copyright Information

NATIONAL SCIENCE & TECHNOLOGY COUNCIL

Chair

Arati Prabhakar, Assistant to the President for Science and Technology; Director, OSTP

Executive Director (Acting)

Kei Koizumi, OSTP

COMMITTEE ON ENVIRONMENT

Co-Chairs

Chris Frey, EPA

Jane Lubchenco, OSTP

Richard Spinrad, DOC/NOAA

SUBCOMMITTEE ON OCEAN SCIENCE AND TECHNOLOGY

Co-Chairs

Tom Drake, ONR

Danielle Farelli, OSTP

Alexandra Isern, NSF

Steven Thur, DOC/NOAA

Executive Secretary

Raquel Gilliland, DOC/NOAA

Victoria Moreno, DOC/NOAA

Elaine Shen, NSF

INTERAGENCY WORKING GROUP ON BIODIVERSITY

Co-Chairs

Gabrielle Canonico, NOAA

James Price, BOEM

Woody Turner, NASA

Executive Secretary

Katie Fillingham, UCAR

eDNA TASK TEAM

Co-Chairs

***Kelly Goodwin,** NOAA

***Chris Meyer**, Smithsonian NMNH

***Mike Weise,** ONR

Executive Secretary

Masha Edmonson, UCAR

Katie Fillingham, UCAR

Members

Dee Allen, MMC

Alicia Amerson, DOE

*__Meredith Bartron__, USFWS

Abby Benson, USGS

Gabrielle Canonico, DOC/NOAA

***Karen Clark,** NIH/NLM

***John Darling,** EPA

***Amelia-Juliette Demery,** NSF

***Meredith Everett,** DOC/NOAA

Colette Fletcher-Hoppe, DOE

***Zachary Gold,** DOC/NOAA

***Jennifer Gumm**, USFWS

***Margaret Hunter**, USGS

Nina Joffe, DOE

***Richard Lance**, USACE

***Alyse Larkin**, DOC/NOAA

***Ricardo Letelier,** NSF

Christine Lipsky, NPS

Dana McCoskey, DOE

***Cheryl Morrison,** USGS

***Krista Nichols,** DOC/NOAA

***Kim Parsons**, DOC/NOAA

James Price, BOEM

Kimberly Puglise, DOC/NOAA

Katie Scholl, DOS

***Mike Schwartz,** USFS

***Adam Sepulveda**, USGS

Janet Shannon, DOS

Woody Turner, NASA

Timothy White, BOEM

**Indicates Strategy Writing Team Member*

Acknowledgements

We thank the over 100 subject matter experts and agency leaders who contributed thoughtful and constructive reviews to draft versions of this report. We are grateful to the many individuals who responded to a Request for Information that resulted in 27 submissions containing nearly 500 individual public comments that helped shape this document and will inform subsequent implementation plans. Public comments were received from the private sector, academia, nonprofit organizations, and federal agencies. Comments fell under the following themes: coordination, communication, inclusiveness, partnerships, infrastructure, exploration and characterization, technical needs, and capacity building. We thank the Biodiversity IWG, SOST, and OSTP for their input and support of this work product.

Table of Contents

Abbreviations and Acronyms

BOEM	Bureau of Ocean Energy Management
CARE	Collective Benefit, Authority to Control, Responsibility, and Ethics
DNA	Deoxyribonucleic Acid
DOE	U.S. Department of Energy
DOS	U.S. Department of State
eDNA	Environmental DNA
EDRR	National Early Detection Rapid Response
EEZ	Exclusive Economic Zone
EPA	Environmental Protection Agency
ESA	Endangered Species Act
eRNA	Environmental RNA
FAIR	Findability, Accessibility, Interoperability, and Reusable
IWG	Interagency Working Group
MBON	Marine Biodiversity Observing Network
MMC	Marine Mammal Commission
NASA	National Aeronautics and Space Administration
NCBI	National Center for Biotechnology Information
NIH	National Institutes of Health
NMNH	National Museum of Natural History
NOAA	National Oceanic and Atmospheric Administration
NPS	National Park Service
NSF	National Science Foundation
NSTC	National Science and Technology Council
ONR	Office of Naval Research
OSTP	Office of Science and Technology Policy
PCR	Polymerase Chain Reaction
RNA	Ribonucleic Acid
SOST	Subcommittee on Ocean Science and Technology
UCAR	University Corporation for Atmospheric Research
UN	United Nations
USACE	United States Army Corp of Engineers

USGS	United States Geological Survey
USFWS	United States Fish and Wildlife Service
USFS	United States Forest Service

Executive Summary

Aquatic life is the engine of many ecosystems and economies. The United States is home to estuaries, lakes, rivers, streams, and one of the largest exclusive economic zones in the world. In environments ranging from freshwater to marine, aquatic biodiversity underpins the health, culture, and opportunities of people and supports economic decision making in communities across the country. Recognizing this value, President Biden has set a goal to conserve, connect, and restore at least 30 percent of our lands and waters by 2030 to support and sustain our nation. National prosperity depends on the ability to evaluate nature's status, trends, and future projections, and this requires timely and trusted information about the condition of aquatic biodiversity on a vast scale.

Now, technological advancements offer the potential for faster and more effective assessments to understand aquatic life. Scientists are uncovering the story of these ecosystems by studying biomolecules—the DNA, RNA, and proteins—that reveal the biological foundations of healthy ecosystems, food production, and water safety for drinking and swimming. It is simple, non-invasive, and scalable to collect water that contains these primary signatures of aquatic life.

This strategy focuses specifically on environmental DNA (eDNA) analysis, a key tool that enables critical insights into the nation's aquatic biodiversity. Samples of lake, stream, estuary, and ocean water all contain biomolecules from the organisms that live there, and the identities of those organisms can be revealed by genetic sequencing. This technology has been developed over the last decade and is now deemed sufficiently robust, accessible, and reliable to provide biodiversity data fit for a variety of routine applications. Recent decreases in costs of genetic sequencing, the relative ease of collecting water samples compared to other biological survey methods such as animal capture, and improved understanding of the reliability of eDNA measurement have resulted in the emergence of a powerful aid to traditional biological surveys.

Many state and federal agencies already employ eDNA detection in a variety of mission applications, including protecting human health and ecosystem services as well as monitoring biological conservation and environmental remediation efforts. Several federal agencies are independently developing eDNA technologies. However, their sampling, analyzing, and reporting methodologies vary considerably, reducing the efficacy of data sharing, reporting, and use for policy and management.

Shared technical knowledge is critical in order to produce reliable and credible data. The National Aquatic eDNA Strategy provides a pathway for federal agencies to build a coordinated and effective national eDNA enterprise through collaborative efforts that unite scientific inquiry, entrepreneurial enterprise, philanthropic endeavors, and public and private investments. This strategy can guide both federal and non-federal partners to widely adopt eDNA standards and characterize aquatic life at large scales to support responsible use of biological resources. This strategy also guides value creation through support for research and development of U.S. technology, growth in related economic sectors, investment in new markets, biodiversity monitoring, sustainable development, and global leadership in science and technology.

This document is organized under three main goals:

Goal 1: Coordinate Across Sectors to Facilitate Integration of Aquatic eDNA into Decision Making by engaging cooperative mechanisms aligning and promoting standards and best practices for eDNA workflows across sectors, contributing technical readiness recommendations for priority applications and locales, and unifying communication strategies to enhance scientific literacy and data interpretation across all sectors.

Goal 2: Build Capacity, Infrastructure, and the Research Enterprise Needed to Employ Aquatic eDNA Technology at Scale by improving human capacity with training and education, meeting technical demands through infrastructure development — ranging from national sample repositories to interoperable data management structures, and supporting research and development to bolster and transition eDNA science into sustained operations.

Goal 3: Advance Coordinated Aquatic eDNA Observations to Aid Assessments in U.S. Waters by harmonizing the extensive collection and delivery of eDNA data needed for robust and trustworthy metrics about aquatic health across the nation, resulting in an eDNA network to support national priorities and actions and to inform decisions that promote aquatic life and resilient ecosystems.

Introduction

The diversity of life found in marine, coastal, and inland waters (hereafter aquatic[1]) is astonishing and dynamic, but much of it has yet to be discovered, mapped, or understood. This biodiversity helps maintain the complex system that supports life on our planet and underpins local communities and economies nationwide. This includes various industries (e.g., fishing, tourism) and ecosystem services (e.g., coastal resilience). The U.S. ocean economy grew almost twice as fast as the rest of the economy in 2019,[2] contributing $397 billion to the U.S. gross domestic product. Federal agencies survey, monitor, manage, and steward marine and freshwater ecosystems and their living resources to protect food security and imperiled species, combat invasive and harmful organisms, assess and address ecosystem effects from human activities, and characterize underexplored ecosystems. In light of the rapid changes in many ecosystems and their importance to the nation, improved biological survey tools are urgently needed to meet the scale, scope, management, and policy needs of these applications.

The ability to detect and catalog aquatic life efficiently and comprehensively is vital for the sustainable use and protection of the nation's biological resources and ecosystems. However, many biological survey tools in use today only partly meet the needs of the agencies responsible for managing ecosystem resources. Biomolecules (e.g., DNA, RNA, proteins, metabolites) infuse every aspect of the environment and offer an effective lens by which to survey biodiversity. Biomolecules are detected by 'omics techniques[3] such as DNA sequencing to provide exploration, mechanistic understanding, and comprehensive assessments of aquatic life. Environmental DNA (eDNA) (**Box 1**) offers a powerful tool to discover, map, monitor, and manage living resources by leveraging methods developed in the forensic and genetic sciences.

Although the National Aquatic eDNA Strategy outlined here focuses on marine, coastal, and inland waters, many of the goals and objectives may be applied to strategies for eDNA from other environments such as soils, sediments, or aerosols. Subsequent expansion into those domains would require broader consideration of partner and practitioner interests.

[1] For the purposes of this document, "aquatic" refers to bodies of water that support life on our planet, ranging from freshwater through marine environments.

[2] National Oceanic and Atmospheric Administration. 2023. New Blue Economy. www.noaa.gov/blue-economy

[3] National Oceanic and Atmospheric Administration. NOAA 'Omics Strategic Plan. 2021. doi.org/10.25923/1c27-w345 ; National Oceanic and Atmospheric Administration. 2020. NOAA 'Omics White Paper: Informing the NOAA 'Omics Strategy and Implementation Plan. doi.org/10.25923/bd7z-zb37

BOX 1: What is eDNA?

Environmental DNA (eDNA) is genetic material found in the environment. Biodiversity can be examined through traces of eDNA found in environmental samples. For example, marine and freshwater samples contain eDNA from many types of organisms – ranging from the smallest microbes to the largest mammals.

Aquatic applications are many, including:

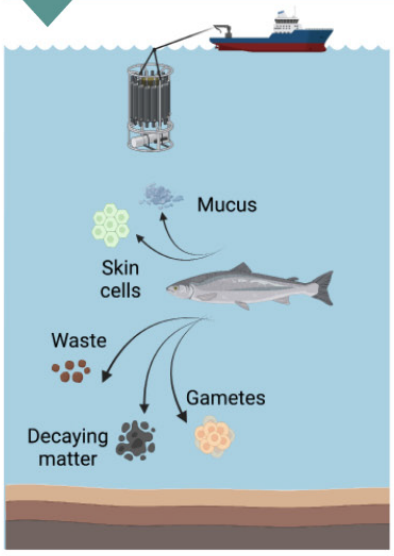
- Detection of invasive or endangered species;
- Surveillance of harmful algae and other microbes;
- Evaluation of environmental impacts and restoration efficacy;
- Fisheries assessments;
- Biodiversity monitoring;
- Ocean exploration.

Strengths of aquatic eDNA biomonitoring:

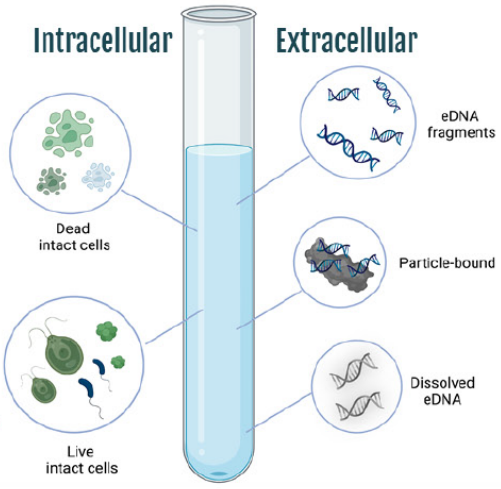
- Ease of sampling with minimal environmental impact and ability to collect samples remotely.
- Detection of broad diversity of species from a single environmental sample - "microbes to mammals" approach.
- Improved detection of rare and hard-to-identify (cryptic) species.
- Standardized taxonomic analyses minimize bias and increase data comparability.
- Cost-effective way to execute large scale observations for an increasing number of applications.

Image Credits: Susanna Theroux. Images created with biorender.com; https://www.sccwrp.org/about/research-areas/bioassessment/dna-barcoding/edna-101/

Genetic material (DNA) from aquatic life can be found in all environments, including fresh and saltwater.



Typical eDNA workflows involve sample collection, filtration and preservation, DNA extraction, and analysis for species identification or quantification.



eDNA can persist for hours to weeks, depending on environmental processes and its state.

eDNA Science to Support National Priorities

Through eDNA analysis, the simple act of collecting water can lead to critical insights into the nation's aquatic biodiversity—from microbes to whales. In addition to organism identification, genetic properties can help predict species and ecosystem resilience via biological adaptation. Monitoring eDNA provides a means to establish environmental baselines and metrics to evaluate the impact of nature-based solutions,[4] management actions, and development projects. Therefore, aquatic eDNA analysis can serve as a fundamental tool to advance national endeavors such as the National Nature Assessment,[5] America the Beautiful (30x30),[6] the National Ocean Biodiversity Strategy,[7] the National Strategy for a Sustainable Ocean Economy,[8] National Ocean Mapping, Exploration, and Characterization Council Strategic Priorities in Ocean Exploration and Characterization,[9] the National Strategy for the Arctic Region,[10] the Cooperative Science Monitoring Initiative),[11] the United Nations (UN) Decade of Ocean Science for Sustainable Development,[12] and the Ocean Justice Strategy.[13] For example, biomolecular observatories are beginning to emerge through coordinated federal activities[14] that complement larger efforts consistent with the vision of the UN Ocean Biomolecular Observing Network,[15] which calls for the acceleration of *informed decision making to restore the health of our oceans using the universal signatures of life on Earth—biomolecules*. The demand for affordable, large-scale biological observations is reflected in such cooperative eDNA monitoring efforts.

Across the federal government, multiple agency efforts to utilize eDNA are underway, and monitoring microbiological endpoints using DNA extracted from water samples has been a standard approach for many years. For example, recreational water quality assessments conducted by local entities rely on federally promulgated biomolecular methods[16] to detect genetic indicators of pathogens, as well as the

---

[4] White House Council on Environmental Quality, White House Office of Science and Technology Policy, White House Domestic Climate Policy Office, 2022. Opportunities for Accelerating Nature-Based Solutions: A Roadmap for Climate Progress, Thriving Nature, Equity, and Prosperity. Report to the National Climate Task Force. Washington, D.C. www.whitehouse.gov/wp-content/uploads/2022/11/Nature-Based-Solutions-Roadmap.pdf

[5] See "National Nature Assessment". U.S. Global Change Research Program. www.globalchange.gov/our-work/national-nature-assessment

[6] See "Year One Report America the Beautiful". December 2021. www.whitehouse.gov/wp-content/uploads/2021/12/AtB-Year-One-Report_.pdf

[7] The Ocean Policy Committee. National Strategy for Ocean Biodiversity. www.federalregister.gov/documents/2023/11/09/2023-24839/request-for-information-national-ocean-biodiversity-strategy

[8] The Ocean Policy Committee. National Strategy for a Sustainable Ocean Economy. www.federalregister.gov/documents/2023/06/29/2023-13839/request-for-information-national-strategy-for-a-sustainable-ocean-economy

[9] The Ocean Policy Committee. 2023. Strategic Priorities for Ocean Exploration and Characterization of the United States Exclusive Economic Zone. www.whitehouse.gov/wp-content/uploads/2022/10/NOMEC_OEC_Priorities_Report.pdf

[10] The Ocean Policy Committee. 2022. National Strategy for the Arctic Region. www.whitehouse.gov/wp-content/uploads/2022/10/National-Strategy-for-the-Arctic-Region.pdf

[11] U.S. Environmental Protection Agency. 2024. Cooperative Science and Monitoring Initiative. www.epa.gov/great-lakes-monitoring/cooperative-science-and-monitoring-initiative-csmi

[12] UNESCO. 2024. UN Decade of Ocean Science for Sustainable Development. oceandecade.org/

[13] The Ocean Policy Committee. 2023. Ocean Justice Strategy. www.whitehouse.gov/wp-content/uploads/2023/12/Ocean-Justice-Strategy.pdf?cb=1701982354

[14] Marine Biodiversity Observation Network. 2024. marinebon.org/

[15] UNESCO. 2024. Ocean Biomolecular Observing Network. oceandecade.org/actions/ocean-biomolecular-observing-network-obon/.

[16] U.S. Environmental Protection Agency. 2023. Development and validation of same-day monitoring methods for recreational water. www.epa.gov/water-research/development-and-validation-same-day-monitoring-methods-recreational-water

sources of such contamination. The National Wastewater Surveillance System demonstrated how partners quickly built the nation's capacity to track the presence and forecast the prevalence of SARS-CoV-2 coronavirus in communities. The application of eDNA for monitoring aquatic organisms has recently been expanding.[17] For instance, the cross-agency National Early Detection Rapid Response (EDRR) Framework[18] aims to use eDNA surveillance in combination with traditional inland water sampling to provide timely warning of potential biological invasions. These warnings can reduce downstream economic and environmental impacts. In the marine realm, federal agencies support research and routine collection of eDNA during ocean exploration,[19] ocean observing,[20] and annual fisheries surveys to aid environmental monitoring and management evaluations (**Box 2**).

BOX 2: eDNA for Evaluating Management Actions

Challenge:

Significant resources are invested in environmental conservation and restoration, but measuring success in complex and dynamic environmental systems can be difficult. This uncertainty can inhibit further investment for protection and restoration endeavors.

Solution:

eDNA methods are available to assess return on conservation and investment dollars by documenting species and biodiversity baselines and changes associated with management intervention. Depending on the management goal, eDNA methods may be complementary to current techniques or may serve as a more affordable alternative. The ability to deliver affordable and accurate ecological evaluation metrics can unlock future investments in the U.S. bioeconomy.

Photo Credits: Zachary Gold

eDNA surveys successfully tracked fish species inside and outside Marine Protected Areas in southern California.¥ Such data can document management outcomes and guide future investment.

¥ Gold et al. 2021, http://doi.org/10.1371/journal.pone.0238557

Realizing the full potential of eDNA applications will require committed support and broad community involvement to continue gaining scientific and technological advances. Sectors working to advance eDNA science and to develop the technical standards and best practices that underlie trusted environmental observations and metrics include federal agencies, academia, industry, philanthropy,

[17] Holst, M.M., et al. 2022. Rapid Implementation of High-Frequency Wastewater Surveillance of SARS-CoV-2. *ACS EST Water.* doi.org/10.1021/acsestwater.2c00094

[18] U.S. Department of Interior. 2020. Early Detection and Rapid Response. www.doi.gov/invasivespecies/early-detection-and-rapid-response

[19] National Oceanic and Atmospheric Administration. 2023. Environmental DNA. oceanexplorer.noaa.gov/technology/edna/edna.html

[20] See Bio-GO-SHIP: https://biogoship.org/; EXport Processes in the Ocean from Remote Sensing (EXPORTS): oceanexports.org/index.html

and other interested parties. Active areas of research and technological development include the estimation of species abundance,[21] implementation of autonomous eDNA technology to increase sampling efforts,[22] and integration of eDNA products with other types of observations across space and time scales ranging from traditional *in-situ* organismal surveys to satellite remote sensing. Other advances include environmental RNA (eRNA) analytics to detect certain viruses, biochemical responses (e.g., toxin production, stress indicators), organism life stages, and confirm the presence of living taxa to aid applications such as invasive species detection. The applications that can be served by biomolecular observations will continue to expand as eDNA and related science advances.

Depending on the application, eDNA analysis can complement current tools or replace conventional observing methods. For example, eDNA sampling is less destructive and invasive than tools involving animal capture, providing a key advantage for protected species monitoring and making assessments within sensitive habitats. It can be more cost-effective because water samples can be substituted for more time-consuming, labor-intensive, and costly traditional approaches that require collecting and identifying organisms through close inspection of each individual. Sampling can be participatory and community-based, not only democratizing the collection process, but also the opportunity for knowledge sharing and application. Water collection can also be automated, providing a solution to monitoring the nation's living resources at the scale and frequency needed for management under rapid environmental change. Therefore, eDNA analysis can provide robust detection of species at the large geographic scales demanded by survey operations. The development of autonomous eDNA collection instrumentation is a key component of these approaches, and progress is being made to develop this observing capacity (**Box 3**).

[21] Shelton et al. 2022. Environmental DNA provides quantitative estimates of Pacific hake abundance and distribution in the open ocean. *Proc. R. Soc. B.* doi.org/10.1098/rspb.2021.2613

[22] Preston et al. 2023. Autonomous eDNA collection using an uncrewed surface vessel over a 4200-km transect of the eastern Pacific Ocean. *Environmental DNA.* doi.org/10.1002/edn3.468

BOX 3: Autonomous eDNA Sampling

Challenge:

Shifts in biodiversity in some areas are occurring too rapidly for traditional programs to adequately monitor, and operational and financial constraints restrict the ability to increase sampling.

Solution:

eDNA is amenable to integration into autonomous platforms. With remote sampling, changes in biodiversity, including harmful and invasive species, can be monitored with reduced need for expensive ship and personnel time. A distributed set of autonomous eDNA platforms can enable biological observing akin to present day weather observations and forecasting. The United States can realize this goal by capitalizing on public and private investments. The use of autonomous platforms is consistent with NOAA's Uncrewed Systems and 'Omics Strategic Plan, the Department of the Navy's Strategic Roadmap for Unmanned Systems, the USGS Next Generation Water Observation Systems, and the DOI National EDRR framework (see **Additional Resources**).

Autonomous vehicles collecting eDNA samples in complement with a traditional survey vessel in the open ocean (top)¥ and for harmful algal bloom applications in the Great Lakes (bottom).§

Photo Credits: NOAA

¥ https://www.aoml.noaa.gov/major-step-forward-in-monitoring-ocean-health/

§ https://www.aoml.noaa.gov/developing-autonomous-vehicle-to-advance-omics-research/

The Need for a National Aquatic eDNA Strategy

Through a vibrant research enterprise, the United States continues to demonstrate scientific accomplishment in the field of biomolecular observing. The field of eDNA analytics is at an exciting point in which federal coordination can promote continued advancement and accelerate meeting the mission requirements of various agencies. This opportunity can catalyze the next stage of technology uptake and delivery of vetted data. The resulting harmonized and trusted analytics can help clarify opportunities for investors and serve as a stimulant for public-private partnerships, fostering job creation in a growing industry of eDNA-related goods and services.

Surveying aquatic species is a standard activity for many agencies, but it is a non-trivial matter that can have substantial policy implications that affect local communities and their economies. Internationally,

a number of countries have published strategy and guidance documents to guide implementation of aquatic eDNA monitoring (see **Additional Resources**), and the United States is now in a position to guide aquatic eDNA analysis to assist the nation. If efforts can be strategically coordinated, eDNA analysis can serve the protection and use of living resources, analogous to the benefits remote sensing has provided to the understanding and prediction of weather and climate. Although fit-for-purpose eDNA methodologies would continue to be developed in the absence of federal coordination, piecemeal technology uptake is inefficient and threatens effective interpretation and communication of results, potentially undermining public confidence in assessment efforts. By building human, infrastructure, and research capacity, measurements of eDNA can be employed at a large scale to increase confidence in environmental assessments and trust in actions that reduce risk to biological resources.

Given the rapid pace of eDNA research and development and the wide range of applications, a unified national strategy is critically needed. Many operators in the private sector (i.e., coastal and climate resilience, ocean renewable energy, etc.) look to federal agencies to provide defensible, robust guidelines and standards for eDNA applications that can facilitate adoption and help establish eDNA approaches as a primary tool for biological monitoring. Furthermore, this national strategy outlines the federal role in accelerating eDNA research and development, motivating innovation and maintaining flexibility to take advantage of continuous improvements. An immediate task under the National Aquatic eDNA Strategy is to develop a set of implementation plans to guide the achievement of the goals and objectives listed herein.

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,[23] 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,[24] 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 (**Box 2**).

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,

[23] Stein et al. 2023. Critical considerations for communicating environmental DNA science. *Environmental DNA*. doi.org/10.1002/edn3.472

[24] See "Invasive Carp Regional Coordinating Committee" invasivecarp.us/eDNA.html

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.

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,[25] and reproduction of publicly available data will be considered throughout (e.g., Findability, Accessibility, Interoperability, and Reusable (FAIR) principles;[26] Collective Benefit, Authority to Control, Responsibility, and Ethics (CARE) guidelines for Indigenous Data Governance[27]). 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.

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 (see text boxes). 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

[25] National Oceanic and Atmospheric Administration. 2024. Public Access to Research Results (PARR). www.ngdc.noaa.gov/parr.html

[26] Wilkinson et al. 2016. The FAIR Guiding Principles for scientific data management and stewardship. *Sci.* doi.org/10.1038/sdata.2016.18

[27] Carroll et al. 2020. The CARE Principles for Indigenous Data Governance. *Data Science Journal*. doi.org/10.5334/dsj-2020-043

environmental justice[28] 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.

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.[29] 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.

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 biorepositories 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

[28] White House Council on Environmental Quality. 2023. Strategic Planning to Advance Environmental Justice. www.whitehouse.gov/wp-content/uploads/2023/11/Strategic-Planning-to-Advance-Environmental-Justice_final-Oct.-2023.pdf

[29] Collins, A., & Meyer, C. 2023. Environmental Samples across the National Landscape: the Scale and Scope of Environmental Sample Collection to Support US-based Research and Monitoring. doi.org/10.5281/zenodo.10304229

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,[30] 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.

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 (**Box 3**). 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 (**Box 4, Box 5**).

[30] See United States Department of Agriculture's Aquatic eDNAtlas Project: www.fs.usda.gov/rm/boise/AWAE/projects/the-aquatic-eDNAtlas-project.html

BOX 4: National Environmental Policy Act (NEPA) Compliance

Challenge:

Under NEPA, agencies are legally required to consider the environmental impacts of their actions and decisions. Offshore projects can benefit natural resources, recreation, national security, and economic vitality at local, regional, and national scales. Post-authorization monitoring requirements to verify effects of an action under the Marine Mammal Protection Act and the Endangered Species Act are within the bounds of permits and can incur considerable cost and time. For example, construction and operation of wind farms, wave energy converters, and certain sonar activities can require biological monitoring using the 'best available science'[§] as part of an environmental analysis.

Solution:

Some agencies have begun using eDNA to provide nimble environmental monitoring capability. Tracking species in time and space can support multiple regulatory requirements and strategic goals. Trusted baseline information can be supplied to resource managers and partners to assess potential changes in biodiversity. Adherence to best practices can allow project proponents, such as wind farm investors, to better understand and mitigate development risks. Harmonized best practices, protocols and data standards, benchmarking, and intercalibration exercises can be established in a coordinated and cross-agency fashion.

§ https:// www.federalregister.gov/documents/2022/04/20/2022-08288/national-environmental-policy-act-implementing-regulations-revisions

eDNA monitoring could benefit mandated assessments.

Left Photo Credit: Open Source, Creative Commons. Right Photo Credit: Greg Schorr, NMFS.

Increased federal coordination will enable identification of strategic research priorities across the federal enterprise and coordinate funding opportunities to support eDNA approaches to meet individual and cross-agency needs. Through contract and grant mechanisms, including those focused on small business and innovation, federal agencies can support the development and adoption of eDNA technologies and applications. As research and development advances, crosscutting budgets and/or other funding coordination can be leveraged to achieve cost and operational efficiency of federal investments and desired social and environmental outcomes at the scale required via public-private partnerships.

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 (see Introduction). 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).

BOX 5: Commercial Fisheries Applications

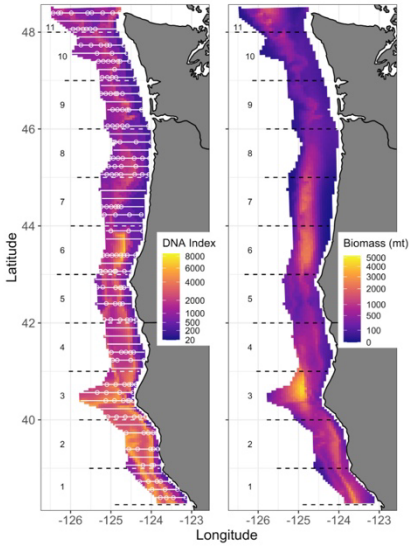
Challenge:

The Magnuson-Stevens Act requires information about fish and fisheries on a vast spatial scale. However, survey vessels are expensive to operate, and current methods struggle to capture broad biodiversity and are often invasive. These limitations hinder routine stock assessments and the ability to respond to emergent events within the more than 4.3 million square miles of the U.S. exclusive economic zone.

Solution:

Water samples contain eDNA, including genetic traces of fish, mammals, invertebrates, and other species. For some applications, analyzing eDNA can add to high-confidence indices of abundance for fish species, and add value by mapping other species of interest, such as marine birds and mammals, harmful algae, or invasive species.

Graphic Credit: NOAA



A comparison of hake abundance from a NOAA fisheries survey based on eDNA (left) and acoustic profiles (right).

Graphic Credit: Shelton et al. 2022, https://doi.org/10.1098/rspb.2021.2613

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 (**Box 3**) 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.

Objective 3.3: Operationalize Biological Resource Data for Societal Benefit

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 (**Box 6**) and invasive and harmful species monitoring (**Box 7**).

For example, the EDRR Framework[31] 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.[32]

[31] See U.S. Department of Interior's Early Detection and Rapid Response for more information: www.doi.gov/invasivespecies/early-detection-and-rapid-response

[32] See Executive Order 14096 on Revitalizing Our Nation's Commitment to Environmental Justice for All: https://www.whitehouse.gov/briefing-room/presidential-actions/2023/04/21/executive-order-on-revitalizing-our-nations-commitment-to-environmental-justice-for-all/

BOX 6: Endangered Species Act Consultations

Challenge:

The Endangered Species Act (ESA) requires federal consultations to ensure human activities do not jeopardize endangered or threatened species. Meeting this mandate requires up-to-date information on rare species that are often difficult to identify and expensive to survey. Moreover, traditional survey methods, such as trawling and electrofishing, can incidentally harm species already in peril. It can therefore be difficult to adequately forecast the effects of actions, document trends in species abundance, and know if recovery efforts are working - all of which are federally mandated. The complexity and large scale of living resources demands innovative monitoring tools.

Solution:

eDNA surveys offer sensitive, noninvasive tools that can be scaled up to benefit agencies working, for example, under the ESA, Marine Mammal Protection Act, and other statutes. eDNA surveys can provide information otherwise unavailable. For example, the U.S. Forest Service (USFS) garnered insight on the distribution of an ESA-threatened trout from eDNA for water samples collected at 10,000 locations throughout a 128,220 km² distribution of mountainous, topographically complex terrain in the Rocky Mountains.§ This up-to-date distribution information was used to inform ESA Section 7 consultation required to conduct a restoration project involving vegetation treatments, fuel reduction, and road improvements. In this case, eDNA sampling indicated that the target species was most likely absent from the restoration site, providing significant time and cost-savings by eliminating the need for costly ESA Section 7 consultation.

§ https://www.fs.usda.gov/rm/boise/AWAE/projects/BullTrout_eDNA.html

Native Westslope cutthroat trout and bull trout are the focus of many conservation efforts.

Photo Credit: U.S. Geological Survey

BOX 7: Early Detection of Invasive Species

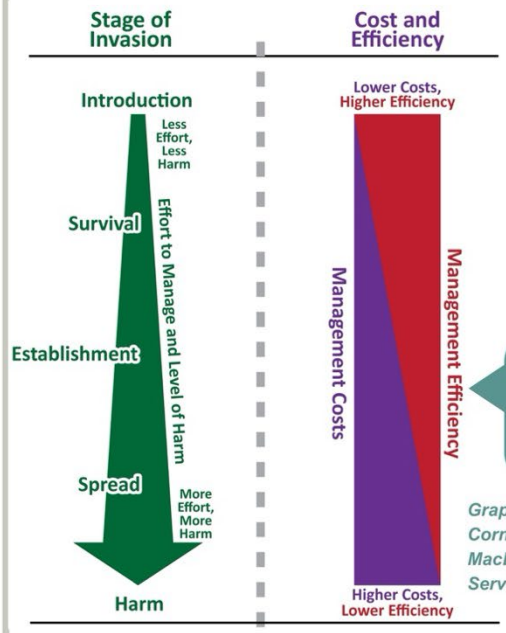
Challenge:

A number of agencies and departments have authority to identify and prevent the introduction of harmful species but lack sufficient tools for applications that include border inspections, testing introduction vectors, and ecosystem monitoring to detect emerging invasions. Improved systems of early detection and rapid response are urgently needed to reduce costs and prevent further threat of invasive species.

Solution:

eDNA can identify the presence of harmful species with sensitivity and accuracy, allowing the detection of incipient invasions. For example, federal agencies cooperate to use eDNA to screen for dreissenid mussels at ports of entry and for invasive carps in the Great Lakes region. Technical standards combined with interagency guidance from policymakers and legal guidance from counsel on how to use eDNA as a line of evidence would promote wider adoption of eDNA tools, helping minimize the risk and economic impact of invasive species. The U.S. Fish and Wildlife Service's Quality Assurance Project Plan[§] details the eDNA monitoring process for bighead and silver carps including methods, quality control, and results communication, and it provides a template for effectively integrating eDNA tools into invasive species surveillance programs.

[§]https://www.fws.gov/media/quality-assurance-project-plan-edna-monitoring-bighead-and-silver-carps



Graphic Credit: David Lodge, Cornell University; Don MacLean, U.S. Fish & Wildlife Service

Time lag in invasion response increases control costs.

The invasive green crab is considered one of the most invasive species in the marine environment, and eDNA has been used for early detection in a multiple lines of evidence approach to support decision making.[¥]

[¥] Keller et al. 2022, https://doi.org/10.1002/eap.2561

Photo Credit: Linda Shaw, NOAA Fisheries

Conclusion

The National Aquatic eDNA Strategy is a call to action to harness the power of eDNA to explore, map, monitor, and better understand aquatic life to sustain and restore freshwater and marine ecosystems and their biological resources into the future. It outlines a pathway to promote robust guidelines for eDNA approaches, technical readiness for priority applications, and unified strategies for data communication to enhance scientific understanding.

Federal coordination can promote partnerships, aquatic eDNA research and development, adoption of eDNA as a basic biological monitoring tool, and a growing industry of eDNA-related goods and services. Enhanced federal coordination and strategic allocation of resources are required to build a national eDNA enterprise to operationalize the collection and delivery of eDNA data to provide robust metrics about aquatic health across the nation. Meeting these challenges will require coordinated action and collaborative efforts that join scientific inquiry, entrepreneurial enterprise, philanthropic endeavor, and public and private investment.

Implementing the National Aquatic eDNA Strategy can ensure that validated eDNA approaches are available to support multiple federal initiatives that require biodiversity data. The goals and objectives outlined herein will allow federal agencies to be more effective and cost-efficient in carrying out their mandates and maintain such improvements into the future. Meeting these goals can increase knowledge and understanding of national aquatic resources, enhance U.S. economic competitiveness, strengthen national security and international leadership, protect the environment, and further apply an environmental justice lens to aquatic research.

Additional Resources

Abbott, C., Coulson, M., Gagné, N., Lacoursière-Roussel, A., Parent, G.J., Bajno, R., Dietrich, C., and MayMcNally, S. (2021). Guidance on the use of targeted environmental DNA (eDNA) analysis for the management of aquatic invasive species and species at risk. Department of Fisheries and Oceans Canada, Sci. Advis. Sec. Res. Doc. 2021/019. iv + 42pp.

De Brauwer, M., Deagle, B., Dunstan, P., and Berry, O. (2023). Integrating environmental DNA science into Australia's marine parks: A roadmap. CSIRO, Hobart.978-1-4863-1917-6. ISBN: 978-1-4863-1917-6

De Brauwer, M., Chariton, A., Clarke, L.J., Cooper, M.K., DiBattista, J., et al. (2022). Environmental DNA test validation guidelines. Canberra, Australia, National eDNA Reference Centre, 33pp. http://dx.doi.org/10.25607/OBP-1886.

Environment Agency. (2016). Using DNA-based methods for environmental monitoring and decision-making. https://assets.publishing.service.gov.uk/media/5a81a57a40f0b62305b90144/Using_DNA-based_methods_for_environmental_monitoring_and_decision-making.pdf.

HELCOM. (2021). Guidelines for the monitoring of target non-indigenous species using molecular methods Helsinki, Finland, HELCOM, 6pp. http://dx.doi.org/10.25607/OBP-1819.

Japan Agency for Marine-Earth Science and Technology. 2017. Application of environmental metagenomic analyses for environmental impact assessments. Version 1, 01 May 2017.

Kanagawa, Japan, Japan Agency for Marine-Earth Science and Technology, 20pp. (SIP Protocol Series No. 1). https://doi.org/10.25607/OBP-1472.

National Oceanic and Atmospheric Administration. 2020. NOAA Uncrewed Systems Strategy. https://doi.org/10.25923/ezpb-6588

National Oceanic and Atmospheric Administration. 2021. NOAA 'Omics Strategic Plan. https://doi.org/10.25923/1c27-w345.

Norros, V., Laamanen, T., Meissner, K., Iso-Touru, T., Kahilainen, A., Lehtinen, S., Lohtander-Buckbee, K., Nygård, H., Pennanen, T., Ruohonen-Lehto, M., Sirkiä, P., Suikkanen, S., Tolkkinen, M., Vainio, E., Velmala, S., Vuorio, K., and Vihervaara, P. 2022. Roadmap for implementing environmental DNA (eDNA) and other molecular monitoring methods in Finland–Vision and action plan for 2022–2025. Reports of the Finnish Environment Institute, 20.

Przeslawski, R. and Foster, S. [eds]. 2020. Field manuals for marine sampling to monitor Australian waters, Version 2. Report to the National Environmental Science Program, Marine Biodiversity Hub. Geoscience Australia and CSIRO. Canberra, Australia, National Environment Science Programme Marine Biodiversity Hub, 327pp.

Santi, I., Casotti, R., Comtet, T., Cunliffe, M., Koulouri, Y., Macheriotou, L., Not, F., Obst, M., Pavloudi, C., Romac, S., Thiebaut, E., Vanaverbeke, J., and Pade, N. 2021. European Marine Omics Biodiversity Observation Network (EMO BON) handbook. (Version 1.0). Paris, France, EMBRC-ERIC, 63pp .http://dx.doi.org/10.25607/OBP-1653.

UNESCO. 2022. Environmental DNA expeditions in UNESCO World Heritage Marine Sites: Field sampling booklet; detailed instruction on how to use the sampling kits. https://unesdoc.unesco.org/ark:/48223/pf0000384014.

United States Department of Defense. 2018. Department of the Navy Strategic Roadmap for Unmanned Systems. https://digital.library.unt.edu/ark:/67531/metadc1982991/.

Unites States Department of the Interior. 2016. Safeguarding America's lands and waters from invasive species: A national framework for early detection and rapid response, Washington D.C., 55p. https://www.doi.gov/sites/doi.gov/files/National%20EDRR%20Framework.pdf.

United States Geological Society. 2021. Next Generation Water Observing System (NGWOS) https://www.usgs.gov/mission-areas/water-resources/science/next-generation-water-observing-system-ngwos#.