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COMMENTARY

Critical considerations for communicating environmental DNA science

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Abstract

The economic and methodological efficiencies of environmental DNA (eDNA) based survey approaches provide an unprecedented opportunity to assess and monitor aquatic environments. However, instances of inadequate communication from the scientific community about confidence levels, knowledge gaps, reliability, and appropriate parameters of eDNA-based methods have hindered their uptake in environmental monitoring programs and, in some cases, has created misperceptions or doubts in the management community. To help remedy this situation, scientists convened a session at the Second National Marine eDNA Workshop to discuss strategies for improving communications with managers. These include articulating the readiness of different eDNA applications, highlighting the strengths and limitations of eDNA tools for various applications or use cases, communicating uncertainties associated with specified uses transparently, and avoiding the exaggeration of exploratory and preliminary findings. Several key messages regarding implementation, limitations, and relationship to existing methods were prioritized. To be inclusive of the diverse managers, practitioners, and researchers, we and the other workshop participants propose the development of communication workflow plans, using RACI (Responsible, Accountable, Consulted, Informed) charts to clarify the roles of all pertinent individuals and parties and to minimize the chance for miscommunications. We also propose developing decision support tools such as Structured Decision-Making (SDM) to help balance the benefits of eDNA sampling with the inherent uncertainty, and developing an eDNA readiness scale to articulate the technological readiness of eDNA approaches for specific applications. These strategies will increase clarity and consistency regarding our understanding of the utility of eDNA-based methods, improve transparency, foster a common vision for confidently applying eDNA approaches, and enhance their benefit to the monitoring and assessment community.

KEYWORDS
communication workflow, decision support tools, eDNA, implementation readiness, RACI charts, transition to management, transparency

1 | THE CHALLENGE WITH COMMUNICATING EDNA-BASED RESULTS

Agencies regulating, managing, restoring, and protecting water resources must be able to monitor and assess the ecological function or condition of aquatic ecosystems. Aquatic ecosystems are subject to multiple stressors and chronic changes associated with shifting climatic patterns and changing water resource demand (Häder et al., 2020). Ecosystem conditions including stress are commonly measured by assessing biological community composition, biodiversity, or dynamics of key ecological functional groups. These findings guide management responses and discern the effectiveness of management interventions. Conventional biomonitoring tasks are often constrained to small spatial scales and short temporal windows, and many, if not most, methods are selective in surveyed species or habitats (Birk et al., 2012; Friberg et al., 2011). Improving monitoring methods by expanding measures across space, time, and environments is labor-intensive and financially challenging. New methods capable of rapid and economic data delivery can support and complement conventional monitoring and aid evidence-based management of global aquatic ecosystems and water resources.

The economic and methodological efficiency of environmental DNA (eDNA) based methods can reduce monitoring constraints by increasing existing monitoring programs' spatial, temporal, and taxonomic resolutions (Thompson & Thielen, 2023). Including single-species (e.g., PCR, qPCR, and ddPCR) or multi-species (e.g., metabarcoding) eDNA approaches in a monitoring toolbox is a cost-effective mechanism to broaden biomonitoring, examine compositional turnover across scales, and uncover patterns and responses to changing ecological conditions (Pawlowski et al., 2020). Deploying eDNA methods has proven effective for aquatic biodiversity monitoring and species surveillance (McElroy et al., 2020; Sepulveda, Nelson, et al., 2020) by improving the assessment of target taxa at low population densities (Adams et al., 2019; Schenekar, 2023; Wilcox et al., 2016).

Implementation of eDNA-based methods for suitable applications has been hampered in part by inadequate communication regarding result uncertainties (i.e., Type 1/Type 2 errors; confidence estimates for detection probabilities), performance consistency, and the fact that the state of the science varies depending on the eDNA application, with some applications needing more research and development than others. Differences between laboratory scientists, ecologists, managers, and other practitioners in understanding and speaking about molecular assay performance can exacerbate data quality issues and lead to misinterpretation of results (Mosher et al., 2020). Communication deficiencies around using eDNA data have contributed to implementation delays in monitoring and assessment programs. They can lead to skepticism or distrust by some in the management community, particularly if communicated results fail to differentiate between a lack of species detection and an assumption of absence. Shortcomings in eDNA science communication detailed in previous reviews include: 1. Miscommunication of valid eDNA results in a high-profile, incipient invasion of the Laurentian Great Lakes by bigheaded carps (Jerde, 2021); 2. Misrepresentation of uncertainties associated with monitoring results (Darling et al., 2021); 3. Inflated claims of applications before confirmatory evidence is broadly available (Sepulveda, Nelson, et al., 2020); 4. Inappropriate extrapolation of preliminary results (Darling & Mahon, 2011); and 5. Insufficient explanation and guidance on different eDNA approaches resulting in assessments being viewed as a generalized "black box" (Morisette et al., 2021). Hence clear, consistent, and accurate communication about eDNA approaches that is accessible to a non-specialist audience is urgently needed.

To provide the improved communication needed to remedy skepticism, scientists must build trust with end-user communities by understanding and embracing their needs (Aylagas et al., 2020; Hall et al., 2021). Scientists need to communicate both the limitations and advantages of emerging technologies and assessment approaches for management applications. Goldstein et al. (2020) suggested that science communication can be improved by embracing strategies of storytelling, being strategic about responses we hope to elicit, knowing the audience and capturing their attention, tailoring a clear message in plain language, cultivating trust, and initiating a dialogue instead of a monologue. McGreavy et al. (2022) assert that in areas where miscommunication around eDNA is widespread among the public and the management community, plain language and clear articulation of the methodologies and uncertainties are essential. But communication and relationships must improve not only in the delivery of results but throughout all activities. Innovative, inclusive, and transdisciplinary collaborations can enhance communication among scientists, management communities, and the practitioners they interact with, to understand eDNA and its applications. This is particularly needed in the case of eDNA approaches because the concept that determines appropriate (or inappropriate) uses may not always be readily intuitive; therefore, consistent participatory communication is critical to producing trust and fair valuation in the questions asked, the approach taken, and the answers provided.

This paper outlines communication precepts that scientists can use to increase clarity and consistency when engaging with the broader community of scientists, managers, stakeholders, community practitioners, and the public. The intent is to establish best practices that build trust, partnership, and confidence around integrating eDNA approaches into monitoring and assessment programs. First, key messages should be provided about the appropriateness of questions of interest, the approach for the targeted environment, and resulting data confidence levels. Second, methodological transparency should be improved to foster confidence and enhance the communication of results across a broad range of audiences. Finally, clear and directed communication strategies should be realized to express the benefits and opportunities of eDNA analysis to monitoring and assessment communities.

2 | KEY COMMUNICATION MESSAGES

The field of eDNA application has rapidly evolved by building on foundational studies that supported natural resource management actions through large surveys (Shelton et al., 2022), the detection of invasive species (Ficetola et al., 2008; Jerde et al., 2011) and rare, elusive (Goldberg et al., 2011), threatened, or endangered species (Thomsen et al., 2012). By building on these foundational studies and by addressing many of the critical considerations highlighted in earlier reviews (Goldberg et al., 2016), the field has grown and led to the Executive Summary of the 1st National Marine eDNA Workshop (USA) to conclude, “eDNA works. Get going.” (Ausubel et al., 2019). Upon the accumulation of scientific evidence from repeated studies, there is growing consensus in the following statements:

Many eDNA methods are ready for implementation in biomonitoring and bioassessment programs. There is a growing list of eDNA methods that have survived scientific and legal scrutiny to inform important resource management decisions (Kelly et al., 2023). In this sense, eDNA approaches represent a mature science, already adopted in challenging management and policy contexts. However, eDNA methods are incredibly diverse, and the level of readiness varies based on the intended application (e.g., species surveillance vs. compliance monitoring) and the biological and environmental context. For example, targeted eDNA detection approaches may represent the best available technology for inferring the occurrence of rare species where detection by other non-eDNA methods is prohibitively costly or lacks sensitivity, or there may be a need for non-invasive sampling of sensitive species or habitats. For other applications, eDNA sampling may be most appropriately used in concert with existing methods to provide initial screening or to support a weight-of-evidence approach (Jerde, 2021). This is the case for bioassessment programs, where eDNA sampling offers a way to expand monitoring efforts spatially and temporally due to the ability to collect and analyze samples easily and rapidly. In some cases, eDNA provides information where traditional tools have limitations; for example, oceans include large areas of unsampled habitats, resulting in immense data gaps on biodiversity, including fish and protected species. Yet, decisions must be made in those areas with little or no information available. eDNA methods can help fill such gaps by providing initial estimates of species composition at previously unmonitored locations (Maiello et al., 2022) while assays and models may require extensive calibration and validation in new habitats to produce high accuracy estimates.

eDNA sampling has limitations, like every biological sampling method. Fitness for purpose is the driving force in determining which eDNA methods are appropriate to adopt for any new application. The World Organization for Animal Health (WOAH) instructs that “the first step in method development is to define the purpose of the method because this guides all subsequent steps in the validation process”. Just like a Phillips-head screwdriver only works on a specific type of screw, eDNA approaches can only answer certain types of ecological questions. For example, eDNA surveys can provide insight into the upstream extent of fish presence in a river (Penaluna et al., 2021) but cannot precisely determine how far downstream the eDNA signal persists, because eDNA is transported by river currents (Roussel et al., 2015) and has complex fate and transport dynamics (Shogren et al., 2017). Ongoing research is improving our ability to understand eDNA fate and transport, such as employing the EDITH model in rivers (Carraro et al., 2021), but it is currently not possible to generalize across multiple ecosystems and settings.

Correlations can provide quantitative estimates of organism abundance (Shelton et al., 2022); however, the precise relationship between eDNA concentration and organismal abundance currently lacks the accuracy required for many applications (Spear et al., 2021) and may need to be calibrated to the location sampled. Environmental DNA analysis can also describe biodiversity (community richness, evenness, composition, and functions), but the resolution varies based on the assay, environmental conditions of the sampled system, and the sampling intensity (Mächler et al., 2019; Pont et al., 2018; Ruiz-Ramos et al., 2023; Zhang et al., 2020). Therefore, the choice of assays and sampling design should be validated based on the management objective. Nonetheless, when eDNA sampling complements traditional tools, a more complete and cost-effective ecological picture across spatiotemporal scales can be achieved

(Andres et al., 2023). Clear communication regarding what eDNA surveys can and cannot do will shepherd its use as an effective component of a comprehensive management plan.

eDNA applications can yield different results than conventional approaches. Different monitoring tools provide different lenses to identify or enumerate organisms, and none offer a complete or error-free description of the actual biosphere of a system. Most approaches to biodiversity assessment seek to begin with the same question: "What organisms are present at the site at the time of sampling?" However, each approach aims to answer that question differently, with advantages and disadvantages. Most make inferences about what is actually present based on the data generated because platforms are lacking that enable data integration and method comparison. For instance, most conventional monitoring methods attempt to survey biodiversity by assessing what organisms can be physically captured and morphologically identified in a sample using long-standing validated standard methods and sampling effort. This has the advantage of providing high confidence in determining the presence of specific target taxa. It also has the distinct disadvantage of biasing diversity estimates toward taxa that are easily captured and identified, potentially missing significant components of overall diversity and/or critical target taxa. Environmental DNA applications, in contrast, attempt to answer the question by determining what genetic material is present in a sample and inferring the likely presence of the organisms that shed that material. Environmental DNA science has shown that the presence of an organism's genetic material and the presence of the organism itself are often the same; thus, complications arise when there is a mismatch. For example, stream electrofishing estimates are based on those fish that are trapped between block nets specific to one point in time and space, whereas eDNA is not contained by block nets and can be representative of larger spatiotemporal scales (Sepulveda et al., 2021). Conventional approaches can be difficult, expensive, time-consuming, and biased toward species able to be captured, but results are determinate. On the other hand, eDNA approaches are somewhat indeterminate in space and time because they detect traces of the organism(s). However, they can recover DNA from species present, including those that are difficult to see or capture and can provide a more complete representation of the community. Thus, eDNA analyses and conventional approaches like electrofishing can be complementary methods that answer complementary questions.

Environmental DNA methods do not directly capture target organisms, but rather provide forensics-type evidence. In management contexts, this means that the value of a positive eDNA detection will always be different from the value of a detection by direct capture. A decision-maker would usually prefer a high-quality visual observation to a similarly high-quality positive eDNA detection, but this should not be a barrier to adopting eDNA monitoring. When direct capture of targets is prohibitively expensive, eDNA detections can provide management-relevant information where previously there was none. As per-sample costs of eDNA approaches are relatively low and continue to decrease, and as more Essential Biodiversity Variables (Pereira et al., 2013) are made freely available to support eDNA machine learning and predictive modeling (Lin et al., 2021), feasibility increases to provide insight into underlying population distributions and biotic interactions across time and space for a fraction of the cost of direct capture. The relative ease of eDNA measures can also increase monitoring efficiency by allowing for broader spatial coverage to inform target locations for direct capture methods. In these cases, the lower value of an individual eDNA detection compared to direct observation is dramatically offset by the overall value of the monitoring effort.

Environmental DNA approaches will change. Sampling methods are constantly improving. Fritts et al. (2017) document the long-term monitoring of Illinois River fish surveys evolving from fixed to stratified random sampling and shifting from AC to pulsed DC electrofishing. The motivation was to improve fish surveys with the experimental design and the equipment used to conduct the survey. eDNA assays and sampling efforts will similarly change with refinement. The "readiness" of the current method can be communicated along with all associated results (see discussion of the development of a readiness scale below). Nevertheless, embracing the change of ongoing development and building flexible implementation strategies is important, particularly if they are demonstrably more robust. One promising method is using CRISPR-based technology for eDNA biomonitoring of ecologically and economically important species (Williams et al., 2023, 2019) and the potential to detect nuisance or harmful species (Durán-Vinet et al., 2021). Tools such as this can help expand eDNA usage by creating inexpensive, field-friendly, rapid, sensitive assays, that do not require extensive molecular expertise to implement. Artificial Intelligence tools and the incorporation of eDNA into Earth System models that can better describe environmental complexity (Yamasaki et al., 2017) will also play important roles in detecting trends and patterns that fill knowledge gaps and guide optimization of eDNA sampling and assays. Concurrent development and implementation of new tools are anticipated and encouraged but must occur alongside clear communication about advantages, limitations, and relationships to existing tools. It is important to constantly revisit and revise expectations based on evolving science to ensure the messaging about the appropriate uses of eDNA reflects the most current science and readiness evaluations (Takahashi et al., 2023).

3 | COMMUNICATION STRATEGIES, APPROACHES, AND TOOLS

We suggest the concept of ensuring "*no surprises*" as a cornerstone of effective communication about eDNA for promoting sound management implementation because it allows for adequate preparation and fosters collaboration, trust, and candor among experts, decision-makers, and stakeholders. For example, the surprise of the initial invasive carp eDNA detections in the midwestern United States contributed to distrust of eDNA approaches by managers they were largely unaware of eDNA being used as survey method at that time (a surprise of new surveillance), and there was no plan to enable

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appropriate interpretation of eDNA results nor were there plans for how to translate results to action (Darling, 2019). Subsequent applications have improved communication practices that fostered broader acceptance (Welsh et al., 2020a, 2020b). Environmental DNA workflows that conscientiously include communication plans, results reporting, and results interpretation (Abbott et al., 2021) will further advance a no surprises approach, increasing the likelihood of eDNA data being used successfully to inform natural resource management. The following strategies can improve transparency and reduce the potential for surprises or misperceptions.

Developing a communication workflow plan that transmits information with clear communication of uncertainty and appropriate data uses can ensure no surprises in applying eDNA-based methods. These plans ensure that information is transmitted transparently and meets the end user's need, allowing for timely, evidence-based decision-making (Abbott et al., 2021). Communication workflow plans identify how, when, and what information is exchanged and communicated to the public and are jointly developed by scientists, decision-makers, and stakeholders before initiating eDNA sampling. Components of a communication workflow plan include charts, decision trees, data visualizations, fact sheets, and criteria for describing the next steps following negative or positive detections (Figure 1). Plans define critical terms, such as those defined by Mosher et al., 2020), and what constitutes a negative, positive, or inconclusive eDNA result based on specified risk tolerances of the decision-maker(s). Plans may also consider the spatial or temporal detection patterns that would trigger a decision point for additional action. Multiple examples of eDNA detection decision trees are available (Abbott et al., 2021; Sepulveda, Nelson, et al., 2020; Welsh et al., 2020a). A RACI (Responsible, Accountable, Consulted, Informed) chart (See Box 1 for an example) or checklist can be used to clarify the roles of all pertinent individuals and parties, to ensure that there is an agreement on how to proceed before eDNA data are already in hand, and to minimize the chance for miscommunications (Figure 2).

The development of decision support tools can help balance the benefits of eDNA sampling with the inherent uncertainty to help gauge when inferences are correct against the potential costs and burdens when inferences are misleading. Structured Decision-Making (SDM) has become a common tool in natural resource decision-making but has rarely been applied to eDNA-informed inventory and monitoring programs. Structured decision-making (SDM) is a decision-support framework for guiding natural resource decisions in complex socio-ecological systems characterized by uncertainty and competing objectives (Runge et al., 2020). The SDM framework engages decision-makers, stakeholders, and experts in dialogue and analyses to produce transparent, defensible, and auditable decisions most likely to achieve objectives. SDM acts as an effective communication tool for leadership and stakeholders since it clearly articulates the decision and why it was made. Sepulveda et al. (2022) used an SDM approach to evaluate state-agency management action responses to hypothetical eDNA detections of various invasive dreissenid mussels (*Dreissena* spp.) in a western US reservoir. They found that the optimal response was first to use non-molecular methods (e.g., nets) to corroborate the eDNA detection for approximately 4 weeks, and then to institute containment actions to prevent invasive mussels from spreading to other waterbodies regardless of corroboration. An SDM process can require days to months to implement since adequate time must be invested in discussions with decision-makers and stakeholders to identify objectives, values, and alternatives. Researchers must invest time to develop statistical models that account for uncertainty to ensure that SDMs are based on the most complete information possible.

The greatest benefits of SDM are likely to be reaped when it is used as a tabletop exercise and included in operations and communication plans before initiating eDNA sampling. Tabletop exercises are activities inclusive of the participants in the communication workflow plan, and decision support efforts work through simulated situations to better understand the process and responsibilities. Such an approach is a cornerstone of the USEPA Causal Analysis/Diagnosis Decision Information System (CADDIS; https://www.epa.gov/caddis), which uses an inclusive process to create scenarios of potential causal pathways of "impaired" aquatic ecosystems. Tabletop efforts would ensure decision-maker, stakeholder, and public trust in the decision process and its transparency. Finally, the SDM approach can be adapted and updated based on accumulated experience to ensure

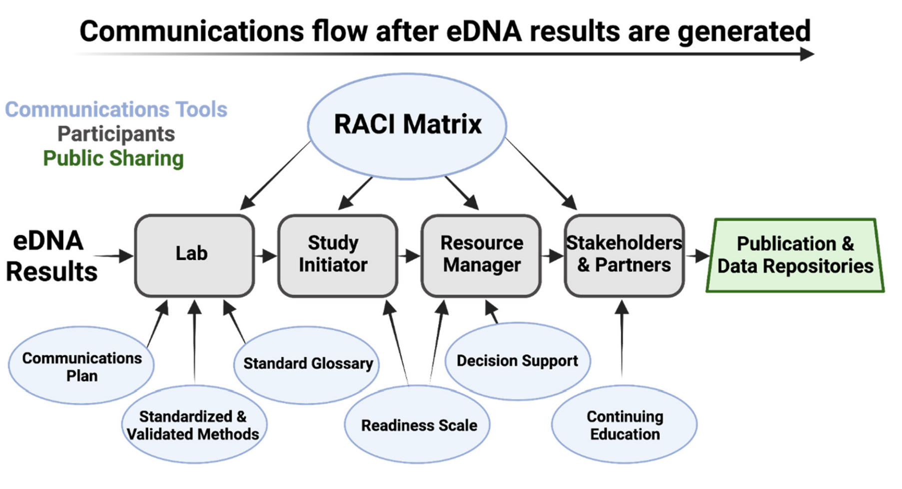

FIGURE 1 Communication workflow diagram showing key points of communication and associated communication strategies. Workflows are ideally developed jointly by scientists, managers, and other end-users and communication may be iterative between each step of the process.

BOX 1 Communication of dreissenid mussels in the United States.

Problem

Invasive dreissenid mussels (*Dreissena polymorpha* and *D. bugensis*) are not widely distributed in western North America and present a difficult management challenge due to the magnitude of their impacts (Higgins & Zanden, 2010). News of new dreissenid detections can result in strong reactions from politicians, managers, and the public. For example, following the first visual detection of dreissenid larvae in this region in 2016, agencies reallocated tens of millions of dollars (USD) to dreissenid management in the northwest United States even though no additional dreissenid mussels have been observed to date. Monitoring could be supplemented with eDNA assays, but the risk of false-positive detections causes concern. A carefully constructed and explained strategy of how positive detections would be confirmed is needed to address hesitancy.

Hesitation in using eDNA

Managers have been cautious about using eDNA sampling for dreissenid early detection because decisions made on a false-positive could result in needless costs and inconvenience. Positive detections could trigger expensive investments in water delivery infrastructure to mitigate mussel fouling and mandatory watercraft inspections to limit dreissenid spread. False positive rates are unknown but could be plausibly caused by contamination or by mussel DNA entering a waterbody without a living mussel ever being present (e.g., dead mussel or residue on a contaminated boat) (Merkes et al., 2014). Non-molecular survey approaches could follow a positive detection lead, such as plankton tows that target the mussel's larval life stage, as they provide definitive invasion evidence despite having other shortcomings. From a natural resource management perspective, false negatives can be problematic when undersampling and/or low eDNA availability may lead to the erroneous belief of species absence. Ideally, researchers will communicate the sampling density needed in other studies to develop models of sampling sufficiency and mapping species occurrence. Because first-time eDNA projects for trials and pilot studies are usually small in budget and sampling effort, false-negative risk is a necessary consideration for the project design. Environmental DNA-based detections, just like non-molecular species observations, is presence-only data; robust determination of negative/absence ranges usually requires analysis of presence-only data in site occupancy models or species distribution models (Beery et al., 2021).

So what?

Failure to rapidly act on eDNA results that truly indicate mussel presence or delayed detections resulting from reliance on non-molecular alternatives could allow an incipient population to become established and spread, prevent any practical control efforts, and increase the magnitude of ecological and socio-economic impacts (Lodge et al., 2006).

Solutions

Managers recognize that conventional tools are unlikely to detect incipient mussel invasions and that eDNA sampling can play a key role (Counihan et al., 2023). For managers to maximize the usefulness of eDNA results, their deliberate engagement is required throughout the entirety of the eDNA workflow, from study goal development through result dissemination (Mosher et al., 2020), so their concerns are adequately addressed. Many tools exist to facilitate partner engagement (Reed et al., 2009), but we highlight RACI matrices (Figure 2) since they are simple and adaptable (Hirmer et al., 2021). A RACI matrix is an accountable way to ensure managers and other relevant parties have been engaged, the eDNA sampling appropriately accomplishes their management goal (s), field and lab best practices are used, and the communication chain is established and respected so that results do not come as a surprise.

Benefits

With appropriate communication workflow plans and the use of tools like RACI matrices, eDNA can be a game-changing tool for invasive species management and result in positive experiences (i.e., "bright spots"; Cvitanovic & Hobday, 2018) that can be shared with colleagues. Ultimately, the real-world experience by managers or those in their social network will shift attitudes toward increasing acceptance of eDNA methods, not solely the dissemination of yet more information about eDNA (Toomey, 2023).

it includes lessons from past implementation successes and failures to build a transparent and effective decision-making process.

Developing a readiness scale to articulate the technological readiness of eDNA approaches for specific applications will also improve the trust and adoption of eDNA techniques. Several readiness scales can be used as a model to enhance communication and can be adapted for use with eDNA. Good readiness scale models have been produced by NASA (https://www.nasa.gov/sites/default/files/trl.png), NOAA (https://orta.research.noaa.gov/readiness-levels/) as well as the NIH National Library of Medicine Technology Readiness Levels (TRLs; https://www.ncbi.nlm.nih.gov/books/NBK201356/). These are designed to guide the transition of new technology to management applications. TRLs provide a common understanding of technology status, support risk management associated with

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FIGURE 2 A RACI (Responsible, Accountable, Consulted, Informed) chart showing who is responsible for various communication aspects along the entire eDNA workflow. JA is jurisdictional authority.

RACI Matrix

Tasks	Client	Lab	JA	Partners	Accountable signature & date
Determine jurisdictional authority (JA)	RA	C	C	C	
Discuss eDNA sampling with JA	RA	I	C	I	
Flow of eDNA results: who can talk to who and when	R	C	A	I	
Sampling goals & objectives	RA	C	C	I	
eDNA assay readiness level	C	RA	C	I	
eDNA detection criteria	R	RA	C	C	
Field sampling methods	RA	C	C	I	
Lab analysis methods	C	RA	C	I	
QA/QC methods	C	RA	C	I	
Results to client	C	RA	I		
Results to JA	RA	C	C		
Results to partners	I	I	RA	I	
Draft media release	RA	C	C	I	
Results to public database	C	RA	C	I	
Point of contact					
Signature & date					

Definitions				
R	Responsible		C	Consulted
A	Accountable		I	Informed

adopting new tools, and guide decisions concerning the transition of technology to implementation. They can aid in communicating the readiness of eDNA for specific applications. For example, the TRL approach developed for the Finnish eDNA implementation plan (Norros et al., 2022) recognizes different levels of readiness based on whether a method has been validated in a relevant environment, demonstrated in a relevant environment, demonstrated in an operational environment, or is complete, qualified, and proven in an operational environment. Thalinger et al. (2021) developed a validation scale to determine the readiness of a qPCR eDNA method for applied use in biomonitoring programs. This approach can help reduce miscommunication and confusion among researchers developing new methods and the practitioners implementing them. Readiness is dynamic because science continues to evolve, and tools improve as knowledge gained from early implementation is used to improve the approach, so readiness assessments must be continuously updated.

4 | BENEFITS AND OPPORTUNITIES OF ENHANCED EDNA COMMUNICATION

Consistent, clear, and transparent communication has benefits beyond increasing the likelihood of incorporating eDNA sampling into routine monitoring and assessment programs. It can also reveal opportunities to seize upon other novel characteristics of eDNA methods (such as the potential for sample and sequence data archiving), diversify the natural resource management workforce, motivate broader professional training in molecular and data sciences, improve communication in the natural resource management community at large, and support commercialization of routine biomonitoring using eDNA approaches.

Communicating data archiving actions and protocols in proposals, reports, presentations, and peer-reviewed publications will enhance the use of eDNA for future studies. Genetic data is digital information and thus can be archived without the same limitations as environmental samples themselves (e.g., air, water, and soil), for which long-term storage presents physical capacity and longevity barriers. Metabarcoding or metagenomic data have longevity, and can be continuously re-probed for signals, so communication to set data usage and benefit sharing permissions should be especially considerate of unexpected discoveries. For example, by improving reference databases and informatics, an eDNA sample could be found to contain a new record of an invasive species in an area, so it is important to make the ideal communication workflow known on how that should be reported to a state or local agency (see Darling et al., 2020 on why caution is also needed). In another example, an unexpected threatened species could be detected in a sample upon first analysis or later re-analysis, when permission to sample from that species' habitat was never explicitly sought because it was not considered. This result could have negative legal repercussions for the research team because they did not acquire permits to sample in the threatened species' occupied area. Public knowledge of that species sighting may also increase vulnerability of that species to poaching. Most policies around opportunistic discovery are not written to accommodate the dynamic results of eDNA surveys. This is especially important to consider when eDNA data gets generated from passive monitoring stations and sentinel sites that are reanalyzed over time.

The opportunities and benefits of future uses will only be realized if we build the digital infrastructure that facilitates access and responsible raw data sharing and curates reliable, searchable, and accessible databases, where eDNA data can be cataloged, stored, and shared. Cataloging and storing eDNA data in any International Nucleotide Sequence Database Collaboration (INSDC) bank such as NCBI cannot have usage restrictions and should hold metadata details on how to ethically handle discoveries from the physical samples or data. The INSDC is a hallmark example of the global open data movement that led to the development of the FAIR guiding principles. The FAIR principles for scientific data management and stewardship make data Findable, Accessible, Interoperable, and Reusable (https://www.force11.org/group/fairgroup/fairprinciples). However, there is growing visibility of the need for databases that help regulate access to information and utilization of the data that meets more complex permissions and metadata details. For instance, the Global Biodiversity Information Facility (gbif.org) intakes eDNA amplicon sequence variants (ASVs) in addition to taxonomic results with the expectation that they will be re-analyzed in the future and employs measures to protect sensitive species' data and extend metadata to track usage permissions assigned to the physical sample the data came from. Indigenous groups rallied for and developed the CARE principles for Indigenous data governance that provide for Collective Benefit, Authority to Control, Responsibility, and Ethics (Carroll et al., 2021). The past decades have also seen a global movement to increase equitable benefit sharing facilitates usage rights of biological samples and digital sequence information (The Nagoya Protocol; see Adler-Miserendino et al., 2022). Data repositories following CARE principles are now alternatives to unregulated INSDC repositories where eDNA data can be deposited. A recent example is arthropod eDNA operational taxonomic units (OTUs) being deposited in the Native BioData Consortium (NBDC) that were collected from Kānaka ʻŌiwi (Native Hawaiian) agroecosystems (Hutchins et al., 2023). Early discussions across the research team, end users, and those who gave permission to collect the samples are essential to ensure appropriate and inclusive data use.

Detailed metadata must also be accessible and shareable, and conform to specifications consistent with ecological metadata language (EML; Jones et al., 2019), minimum field, lab, and informatic metadata standards for the genetics community (e.g., Darwin Core; Wieczorek et al., 2012), and conform with relevant federal or regulatory agency requirements. Respecting boundaries and permissions specified in metadata is also essential to building a culture of responsible information sharing. Principles of transparency, no surprises, and clear documentation of uncertainty already discussed must also apply to any future uses of eDNA data to maintain trust in the application of eDNA approaches and have that extend to digitally archived samples. Communication plans and consent documents need to include terms on how physical or digital samples will be used and attributed so appropriate repositories can be identified.

Increasing diversity, equity, and inclusion (DEI) in the eDNA science workforce will improve communication with underrepresented stakeholders. As an emerging technology poised to employ the next generation of scientists, eDNA related fields provide opportunities to actively build a more diverse workforce. With this, there is an opportunity to better democratize biological data collection and increase inclusivity and diversity within the science, management, and end-user communities. Inclusion, in turn, will facilitate successful communication and broad end-user engagement. The ease of eDNA sample collection makes it amenable to the involvement of community-based scientists, including those from traditionally under-represented communities. Through a commitment to DEI principles and adopting FAIR or CARE principles as appropriate, eDNA approaches can open the untapped benefit of communicating results to a more diverse audience by having those presenting the results reflect the racial, social, and cultural diversity of the community vested in the results. This will serve to reduce barriers to adoption that are often encountered by communities with limited resources. To achieve these goals, overall communication of the approach, efforts, results, interpretations, and limitations is critical at all stages of the workflow and sample processing.

New curricula are needed for professional natural resource managers to enable the translation of eDNA results into policy and action in ways that are accessible to the intended end-user community. Many professional programs in natural resource management are adopting communication courses as core curricula, particularly as the stressors that motivated the development of eDNA applications, such as detecting invasive species and biodiversity surveys, drive public calls for action. Further, the interdisciplinary nature of eDNA approaches necessitates expertise in translation across complicated molecular, data science, and engineering concepts. Recent efforts by some agencies (e.g., Great Lakes Fishery Commission; http://www.glfc.org/science-transfer-toolkit.php) have provided pathways for online natural resource continuing education, specifically on eDNA approaches.

Partnering with industry and community organizations on adopting eDNA technology increases the capacity and acceptance of the technology across multiple applications. Numerous companies offer commercial eDNA services and are most successful when commercial partners participate with academic and agency researchers in developing protocols and best practices. These companies often facilitate communication with their client base as part of their marketing efforts, thereby increasing awareness about eDNA applications. Co-development of protocols facilitates technology transfer in a cost-effective manner, helps ensure accurate and effective communication about strengths and limitations, and provides training opportunities. Commercial standardization can also facilitate the transition to community science organizations, which increases understanding of molecular methods and the underlying ecology of the surveyed system. This will be particularly useful in helping to enhance participation by under-represented communities in monitoring and assessing local resources.

5 | CONCLUSIONS AND FUTURE EFFORTS

Roadmaps for the generation and use of eDNA results for management and policy decisions are already being created through several government initiatives, such as the United States National eDNA Strategy (Kelly et al., 2023), European Cooperation in Science and Technology's DNAqua-Net (https://dnaqua.net; Blancher et al., 2022), the Australian National eDNA Reference Centre (https://ecodna.org.au), and Fisheries and Oceans Canada (Abbott et al., 2021). Thus, scientists should convey messages that despite some limitations, eDNA methods are ready for implementation. While eDNA methods may produce different outputs than conventional approaches, this need not be a detraction as eDNA-based outputs are largely complementary to conventional ones. Indeed, it is increasingly becoming accepted that eDNA data can guide evidence-based management and policy decisions when application guidelines are consistent, procedural standards and validated methods are employed, and effective communication between scientists and end-users is prioritized (Abbott et al., 2021; Goldberg et al., 2016; Thalinger et al., 2021).

Ultimately, decision-makers want to feel confident that eDNA results and subsequent interpretations are trustworthy and relevant to their management concerns. Like Murdick (2022), we encourage scientists to hone in on the "So what?" aspect of their eDNA results and communicate their potential impact on generating desired outcomes in real-world applications. This requires insight into management priorities and communication regarding the applicability of eDNA approaches to decision-maker goals, which will build trust in eDNA approaches. Other important elements to fostering trust in eDNA results that require more attention are the quantification and reduction of uncertainty (Mathieu et al., 2020), routine interlaboratory proficiency testing (Sepulveda, Hutchins, et al., 2020; Vasselon et al., 2019), and the accreditation of eDNA testing laboratories by recognized standards organizations (e.g., International Organization for Standardization; Trujillo-González et al., 2021). Broadly recognized frameworks for properly using and interpreting eDNA data in management and policy contexts, including communication plans, will also help increase confidence in interpreting eDNA results and in the decisions they inform (Sepulveda, Nelson, et al., 2020). As we have demonstrated here, developing clear communication workflows and decision support tools will aid in applying eDNA methods to support management decisions, future diverse workforces, and foster new partnerships with industry and community groups.

AUTHOR CONTRIBUTIONS

EDS and CLJ led the writing in consultation with other authors, the majority of whom were speakers and participants in the 2nd National workshop on Marine eDNA, held at the Southern California Coast Water Project Authority in Costa Mesa, California, in September 2022. EAA and AJS led the development of Box 1: Communication of dreissenid mussels in the US in consultation with others.

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