Trends in Ecology & Evolution

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Opinion

Are Environmental DNA Methods Ready for Aquatic Invasive Species Management?

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Multiple studies have demonstrated environmental (e)DNA detections of rare and invasive species. However, invasive species managers struggle with using eDNA results because detections might not indicate species presence. We evaluated whether eDNA methods have matured to a point where they can be widely applied to aquatic invasive species management. We have found that eDNA methods meet legal standards for being admissible as evidence in most courts, suggesting eDNA method reliability is not the problem. Rather, we suggest the interface between results and management needs attention since there are few tools for integrating uncertainty into decision-making. Solutions include decision-support trees based on molecular best practices that integrate the temporal and spatial trends in eDNA positives relative to human risk tolerance.

Highlights

We consider whether eDNA methods have matured to a point where they can go from research to widespread application and be incorporated into aquatic invasive species management.

Under the Daubert standard of scientific evidence, eDNA is arguably a sufficiently mature and reliable technique.

However, invasive species managers struggle with using eDNA since it is uncertain if detections indicate species presence and the costs of acting can be high.

eDNA based, decision support tools for invasive species management are lacking.

Manuals on best practices, decision support trees for the interpretation of results, education and training of managers and stakeholders, and communication protocols are necessary outputs before widespread incorporation of eDNA into invasive species management.

Many of these outputs are coming into place, which will allow eDNA to better support invasive species management.

The Potential of eDNA Surveillance

eDNA comprises intra- and extra-cellular forms of DNA released by an organism into the water, soil, or air [1]. The idea of using eDNA and molecular analysis to infer organism presence has repeatedly and independently occurred across aquatic and terrestrial environments. Even before publication of the initial aquatic eDNA paper on invasive American bullfrogs (*Lithobates catesbeianus*) [2], scientists engaged in natural resource policy and management saw the potential of a molecular revolution for early detection of invasive species [3].

An amazing wave of eDNA research has followed, as demonstrated by reviews summarizing hundreds of studies from across the globe [1,4,5], best practice guidance documents [6], special journal issues [7,8], a textbook [9], and creation of a new journal named *Environmental DNA* (John Wiley & Sons). Nevertheless, managers struggle with how to use eDNA results in confident decision-making and management applications for invasive species.

eDNA detections often precede visual detections of invasive species [7,10]. Delaying management actions until the invader is abundant enough to be detected by nonmolecular approaches can compound negative impacts and increase costly control measures. Furthermore, the economic impacts of invasive species can be staggering, as demonstrated by a recent cost estimate of a zebra mussel (*Dreissena polymorpha*) invasion in Montana, USA (Box 1). This makes it timely and urgent to consider if eDNA methods have matured to a point where they can be incorporated into natural resource management with direct connections to policy, decision-making, and enforcement of statutes. In fact, multiple eDNA working groups and advisory panels composed of scientists and managers have convened to deliberate on this topic (Box 2).

Here, we focus our assessment on eDNA targeted and multitaxa approaches in freshwater environments, which have been the dominant applications of eDNA technology for invasive species surveillance [1]. Targeted approaches include those that amplify DNA molecules of a single

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Box 1. Invasive Species Cost Billions of Dollars Annually

Invasive species cause annual economic losses totaling many billions of US dollars per country since these species can harm agriculture, forestry, fisheries, power production, property values, and international trade [55]. For example, the estimated costs per year (economic losses and/or control) of invasive species exceed US$9 billion in Australia, US$13 billion across Europe, US$14 billion in China, US$26 billion in Canada, and US$120 billion in the US [55–57].

To characterize the breadth and magnitude of economic costs of a single invasive species, we provide a cost estimate of a zebra mussel (*Dreissena polymorpha*) invasion in Montana (USA). Zebra mussels have become an invasive species in North America and Europe where they cause ecological and economic damage in the millions of dollars annually and threaten imperiled bivalve species. In Montana, invasive mussels were detected for the first and only time in 2016 [40]. Nelson [39] estimated the potential economic damages arising from invasive mussels should they become established in Montana at US$234 million annually in mitigation costs and lost revenue as outlined next.

- **Recreation**. Fewer tourists and angling trips and additional boat maintenance sum to US$122 million per year in mussel-induced impacts.
- **Agriculture.** Invasive mussels infest canals and pipelines, clog irrigation pumps, and increase maintenance costs. The direct impact to agricultural production could amount to US$61 million per year.
- **Infrastructure.** Water intake and distribution structures associated with hydro- and thermo-electric power, industrial production, water treatment plants, mining, and domestic water use will all be susceptible to mussels (Figure I). Pipes and screens can become constricted and impede operations. Mitigation costs to these facilities could approach US $47 million per year.
- **Government Revenue.** Local governments rely predominantly on property taxes. With the advent of mussel establishment, property taxes could decrease by up to US$4 million annually from property values declining in association with decreased lake aesthetics.

With the imminent threat of additional invasive mussel introductions, the estimation of potential costs can inform decisions about risk tolerance (see Figure 1 in main text) and the level of funding for prevention. In 2018, Montana appropriated US $6.5 million for its aquatic invasive species prevention program, which is roughly three percent of potential annual costs. Prevention, early detection, and rapid response are considered the most cost-efficient approaches to minimizing the economic damages of invasive mussels. Once established, adult invasive mussels cannot be eradicated, leaving damage mitigation and control as the only feasible and more costly policy responses.

Figure I. Dreissenid Mussels Fouling Intake Structures, Penstocks, and Cooling Water Systems of Hydropower Facilities. Photo courtesy of US Bureau of Reclamation.

Box 2. Key Findings from eDNA Science Advisory Panels

In response to controversial eDNA detections of invasive species, multiple workshops, working groups, and advisory panels comprised of expert researchers and resource managers have been convened to evaluate the reliability of eDNA methods, identify research gaps, and guide the direction of applied eDNA use. Examples include (i) a 2011 Independent External Peer Review panel of eDNA monitoring of Asian carp in the Great Lakes region of the USA; (ii) workshops to explore the application and limitations of eDNA for conservation in New York (USA) in 2017 and British Columbia and Ontario (Canada) in 2018 [30]; (iii) a 2018 panel to review and discuss controversial eDNA results of dreissenid mussels in Montana (USA); and (iv) ongoing DNA working groups and annual conferences in the UK to link researchers and end users of molecular tools (http://www.ukeof.org.uk/our-work/ukdna). Here, we summarize key challenges and recommendations from several of these advisory panels.

Challenges

- Lack of standardized protocols for field collection, laboratory analysis, and communication of eDNA results to managers.
- Lack of analytical framework for evaluating the costs of false negatives or false positives relative to risk tolerance.
- Difficulty communicating what a positive eDNA sample means to managers.
- Understanding alternative sources of eDNA and the transport and fate of eDNA.

Recommendations

- Develop, evaluate and adopt standardized protocols using an approach similar to the Asian Carp QAPP [27] and the UK national surveillance scheme for great crested newts [28]. Protocols should include quality control assurances and be disseminated among multiple parties/partners/entities.
- Validate and test eDNA assays and workflows to ensure specificity, sensitivity and efficiency under different environmental conditions.
- Develop consistent language and procedures for reporting results.
- Develop a communication plan between managers and laboratories that clearly defines the steps to be taken following a detection.
- Identify risk tolerance for false negatives and positives and map management actions for detection scenarios.
- Develop and utilize a decision tree that incorporates multimethod surveillance results with risk tolerance. Examples include Figure 1 and [54].

taxa, while multitaxa approaches use high-throughput sequencing to identify entire species' communities. However, our conclusions should be of interest to those implementing indirect detection methods across systems (e.g., marine) and taxa since the apparent disconnect between scientific results and management utility is not limited to the realm of eDNA, and the question of how management might deal with uncertainty is ever-present.

Is eDNA Analysis a Mature Science?

There are many philosophical ways to assess the maturity of a science or technique, but we adopt a pragmatic approach motivated by law. The Daubert standard, born out of assessing the reliability of scientific evidence in US Federal Courts, uses five factors to determine if the science or technique is admissible evidence [11]. The Daubert standard is not applied evenly across the US nor is it applied internationally, though multiple countries have adopted its use or have comparable criteria for scientific admissibility of evidence [12]. Thus, the Daubert standard provides an initial means to consider the legal reliability of eDNA results across broad jurisdictions. Here, we briefly review the state of eDNA analyses relative to each of the five Daubert standard factors.

Has the Technique Been Tested in Actual Field Conditions (and Not Just in a Laboratory)?

eDNA analyses have been extensively tested in field conditions spanning from freshwater [4] and marine habitats [13] to terrestrial soils [14], lake sediments [15], air [16], and snow [17]. These approaches were born in field experiments [2] and then later calibrated using controlled mesocosm approaches with manipulated species communities and environmental conditions [18–20]. In general, single and multispecies eDNA analyses have proven to be a highly efficient and sensitive means for making inferences about the occurrence of rare organisms in natural environments [8].

Has the Technique Been Subject to Peer Review and Publication?

Since 2008, over 1500 peer-reviewed papers (*ISI Web of Science*, keyword 'environmental DNA') have mentioned eDNA, with at least 550 papers on macrobial eDNA from water samples. Journals like *Molecular Ecology* and *Ecological Applications* have served as flagships for novel eDNA insights and research applications. The surge of eDNA research has motivated a focused journal and a textbook [9].

What Is the Known or Potential Rate of Error?

Mechanistic underpinnings of error have been a central focus of eDNA research since its inception [10]. Quantification of detection error has come from numerous assay controls [21], controlled experiments with known species' densities [19,22], comparisons of concurrent eDNA and traditional capture surveys [23], with error models and statistical inference [24]. Additionally, research has motivated approaches to justify sampling efforts needed to minimize false negatives [25] and PCR inhibition [26]. While many factors affect the error rates of an eDNA assay, the methods to reduce and quantify errors are now established.

Do Standards Exist for Control of the Technique's Operation?

General standards and best practices for eDNA collection and processing have become robust and well documented, but they are often species and site specific. For example, surveillance for the Asian Carps (*Hypophthalmichthys nobils* and *Hypophthalmichthys molitrix)* in the Great Lakes region (USA and Canada), was an early eDNA application and has a regularly updated Quality Assurance Project Plan [27]. Protocols for eDNA field sampling and laboratory analyses also exist for the native great crested newt (*Triturus cristatus*) in the UK. These protocols were first approved by Natural England in 2014 and, since 2017, Natural England only accepts eDNA results from laboratories that participate in a proficiency testing scheme of blind negative and positive samples [28]. Other examples of government and industry standards include reports on eDNA standardization needs in Canada [29,30]. The EU and countries therein (e.g., Denmark) have standardizations in development that largely focus on metabarcoding approaches [31]. Private and academic eDNA laboratories in many countries are also pursuing accreditation by the International Organization for Standardization (e.g., ISO 9001 and 17025; https://www.iso.org/popular-standards.html).

Has the Technique Been Generally Accepted within the Relevant Scientific Community?

eDNA has now been applied by researchers on nearly every continent and across a wide range of taxa and environments (aquatic plants [18] to forest carnivores [17]; the Arctic [13] to the tropics [22]). We are now observing a transition towards testing ecological theories [32] and measuring the effectiveness of management actions [33,34]. Maybe the most compelling evaluation of eDNA methodology was stated in the executive summary of the 1st US National Conference on Marine Environmental DNA (eDNA), 'eDNA works. Get going.' [35].

Our argument that eDNA methods meet the Daubert standard is not simply hypothetical. In 2010, eDNA data came up for review in a USA court and was deemed admissible under the Daubert standard [36]. The rigor and credibility of eDNA methods have improved greatly since 2010.

Challenges of Integrating eDNA Surveillance into Invasive Species Management

Despite the maturity of eDNA methods, decision-makers have been reluctant to apply eDNA positive results as stand-alone evidence (i.e., absence of evidence of presence from nonmolecular methods) for new invasions [7]. Their principle criticisms are the inherent uncertainty of eDNA detections and the lack of interface to help managers integrate this uncertainty into decisions of how and when to act [7]. eDNA detections are uncertain because multiple sources of underlying error can give rise to false or misleading positives (i.e., detecting DNA of a target species when

that species is not present) and less sensitive, traditional methods with a higher false-negative rate cannot be used for corroboration [7,10]. Thus, managers are put into an untenable position of having uncertain eDNA evidence for invader presence, a low probability of capturing the invader when rare, and high economic, social, and political costs of acting without being able to demonstrate evidence of effectiveness.

This dilemma is similar to that discussed by Finnoff *et al.* [37], in which managers are more likely to allocate resources to control than to prevention since results of control actions are more certain. This dilemma has been exacerbated by a lack of coordination and communication between eDNA scientists and managers [38], who are frequently on opposite ends of the argument. Scientists view managers as not following the precautionary principle and unwilling to adopt an approach that can allow for early detection. Managers view scientists as not providing a complete tool with decision-support structure, and thus question the method.

Invasive dreissenid mussel (*Dreissena* spp.) management challenges in Western North America exemplify why managers have been hesitant to incorporate eDNA into decision-making. Dreissenid mussels are an invasive species in North America and Europe, where they have caused extensive ecological and economic damage [39]. Consequently, detections can cause strong reactions in politicians, managers, and the public. For example, dreissenid larvae were initially detected in Montana (USA) in 2016, but no additional mussels have been observed to date [40]. Regardless, greater than US$13 million has been reallocated to mussel prevention and early detection efforts in this region.

Transitioning from Research to Application

Examples from Other Molecular Fields

The adoption of PCR-based molecular tools into diagnostic or operational settings has challenged many disciplines, such as the medical field, where results can have major repercussions yet cannot be confirmed with nonmolecular methods [41]. Nevertheless, many of these disciplines have moved forward by ensuring that scientific validation to minimize uncertainty precedes implementation. The adaptation of DNA analysis (DNA fingerprinting) into forensic science decision-making provides a useful roadmap for further improving the rigor of eDNA methods (Box 3).

DNA analysis was first introduced as a human forensics tool (1980s) to identify the origin of biological samples from crime scenes [42] and then as a fisheries and wildlife forensics tool [43]. DNA as evidence was controversial and spurred scientific and legal challenges that ultimately led to it becoming admissible evidence in courts, and the gold-standard of forensic inference [44]. Much of this transition was steered by international committees (e.g., DNA Commission of the International Society of Forensic Genetics) that standardized and strengthened protocols.

In DNA forensics, there is a clear distinction between data for research purposes and the generation of evidence destined for courts. For the latter, each stage of the DNA forensic workflow must be assessed and validated via peer review prior to use by law enforcement or courts. This vetting ensures repeatable and reproducible results, determines the conditions under which results can be obtained, and defines limitations [45]. Consequently, there can be a lengthy lag time between development and application of a new method. Once forensics methods are validated, sample analysis is restricted to accredited laboratories that meet auditable standards. Results are commonly presented as simple likelihood ratios that describe the difference between contrasting hypotheses (e.g., prosecution vs defense [46]). This roadmap ensures that DNA forensic analyses produce unequivocal and unbiased results with the highest degree of certainty

Box 3. History of Ancient DNA and Noninvasive Genotyping, and Their Contributions to eDNA Studies

eDNA research and monitoring benefits from early studies of ancient DNA (aDNA) and noninvasive (NI) genotyping that solved many technical and conceptual challenges faced by eDNA projects [59]. Here, we describe how aDNA and NI-DNA studies set the foundation for eDNA and solved problems helpful to advance eDNA applications.

aDNA

The first aDNA study was conducted in 1984, when DNA was sequenced from a 150-year-old museum specimen [59]. Similar to eDNA, a key aDNA challenge was that target DNA in fossils is often degraded, rare, and associated with contaminating DNA. Consequently, PCR of target DNA had a high risk of false positives. Indeed, the first report of dinosaur DNA recovery in 1995 was later concluded to have been human DNA contamination [60].

By 2004, the field of aDNA had identified best practices to address this challenge and ensure reliable aDNA recovery, including phylogenetic (species) verification and repeatable sampling, and laboratory analyses using PCR and sequencing [61]. Scientific journals started requiring reporting of precautions taken such as independent replication and use of blank samples with no DNA in extractions and PCRs to monitor for contamination and false positives. Best practices in aDNA are still evolving today, including communications between researchers and end-users to improve research and applications [38,62,63].

NI Genotyping

The first NI-genotyping studies were in 1992, where researchers genotyped brown bear (*Ursus arctos*) feces and hair without capturing or observing the target animal [64]. NI genotyping suffered challenges such as high genotyping error rates and cross-contamination between samples for mitochondrial DNA, microsatellite, and SNP analyses [65]. Solutions included validation of field and laboratory methods, blind testing to ensure species specificity of PCR, replication of DNA analyses >2–8 times to ensure low genotyping errors, and monitoring with blank samples from field and laboratory work to detect potential false-positive amplification [66]. Managers have used NI genotyping to detect presence of endangered species in many habitats (e.g., blunt-nosed leopard lizard *Gambelia sila* in the desert [67]), and to manage species and diseases in taxa ranging from bears (*U. arctos*) in Eurasia [68] to *Chlamydia* disease in koalas (*Phascolarctos cinerus*) in Australia [69].

Conclusions

Lessons learned from aDNA and NI genotyping have benefited eDNA. Best practices for eDNA described in [6,9] are built from aDNA and NI-genotyping studies [58,61]. Finally, many eDNA researchers have experience conducting aDNA and NI genotyping, which helps ensure quality of eDNA science.

that can be easily understood by decision-makers (e.g., jurors). However, eDNA should not be held to the same standards as DNA forensics since the two disciplines ask different questions and results have different consequences. For example, eDNA is used to infer species presence, whereas forensics asks how likely it is that two matching samples came from different people.

Examples from eDNA Studies

Peer-reviewed studies demonstrating manager use of eDNA methods or results for invasive species are rare [1]. The predominant management application is as a trigger for nonmolecular sampling, as exemplified in the eDNA surveillance program for Asian carp in the Great Lakes region (USA and Canada). Positive eDNA samples that follow the standard operating procedures in [27] prompt intensive molecular and nonmolecular monitoring to locate fish populations.

Managers in Europe [34,47,48] and North America [33,49] have used eDNA to evaluate the success of invasive fish and mussel eradication efforts, where positive detections trigger nonmolecular sampling and can postpone native fish reintroductions. For example, eDNA sampling was used to evaluate if manual removal of the black pygmy mussel (*Xenostrobus securis*) resulted in eradication [48]. Managers have also used positive eDNA detections to delineate where to conduct eradication efforts and construct exclusion barriers to prevent spread, and following eradication, where to conduct nonmolecular sampling [48–51]. For example, eDNA sampling for invasive brook trout (*Salvelinus fontinalis*) was conducted prior to piscicide application in a western USA stream to confirm that connected tributaries were fishless [49]. Many other eDNA studies provide pertinent information about management of invasive species distribution and spread (e.g., American signal crayfish *Pacifastacus leniusculus* and Chinese

mitten crab *Eriocheir sinensis* [52]), however it is unclear how results have been translated into management actions.

A common theme across applications is manager reliance on nonmolecular sampling for corroboration of eDNA positive detections before implementing control actions. When nothing is captured, it provides justification for inaction thereby discounting eDNA results. However, positive eDNA detections without corroboration from traditional methods should be expected when we know direct capture methods have low detection probabilities [7,10]. The reliance on nonmolecular corroboration is contrary to how managers have used molecular sampling for non-invasive species decision-making. For example, water quality managers routinely use molecular methods for detecting *Enterococcus* spp., and use results to inform decisions about waterbody closures [53]. Similarly, eDNA analysis was approved by Natural England in 2014 for determining great crested newt presence. Developers can be prohibited from developing wetlands where there have been positive eDNA detections [28].

Invasive Species Management with eDNA Analyses

Although critical steps are being taken to ensure that validation of eDNA methods precedes implementation, there is still uncertainty regarding whether or not an eDNA detection is indicative of species presence. Like any detection technology (e.g., security airport screenings), inferences based on eDNA detections are susceptible to error. Researchers have implemented methods to reduce this uncertainty, including independent replications of PCR, use of multiple markers, stringent scoring criteria, resampling verification, spatial and temporal trend analyses, and quality assurance measures [21,25]. Researchers are also pursuing new molecular methods to be better indicators of live organism presence, such as concurrent use of environmental RNA with eDNA [20].

Despite these advances, managers will face the dilemma of deciding whether to act or not on positive eDNA detections. Failure to act on a true positive could compound negative impacts and increase already costly control measures. Alternatively, many invaders fail to establish or cause impacts, so failure to act on a true positive may have minimal cost. However, acting on a false positive could result in needless costs and inconvenience. In turn, the use of eDNA as a monitoring tool may come into question, potentially triggering reactions that are politically motivated especially in high profile cases. For example, the adoption of DNA-based monitoring of invasive Asian carp in the Great Lakes region (USA and Canada) has engendered intense criticism by some stakeholders when detections occurred in unexpected locations and gave rise to multiple court cases with repeated motions to close locks and dams critical to commerce [7].

To better navigate the manager's dilemma, we propose a decision-support tree that integrates ecological, socioeconomic, cultural, and/or political measures of risk tolerance (i.e., how much of a loss a manager is prepared to handle; Figure 1). Indeed, the need to discuss tolerance for inferential and management uncertainty prior to study initiation was underscored in [38]. Decision-support trees are frequently used in other disciplines, such as medical decision-making [41]. Our decision-support tree acts as an interface to connect eDNA results to social and political constructs beyond science, such as: can we risk being wrong?

We use risk tolerance as a means to place eDNA results into appropriate context and to guide how quickly a manager should reach a decision point given positive eDNA detections. For instance, high risk tolerance (i.e., prepared to tolerate large losses) might result from a manager's willingness to proceed more cautiously with eDNA detections because of poor matching of potential invaders to a waterbody's environmental conditions. Low risk tolerance (i.e., only willing

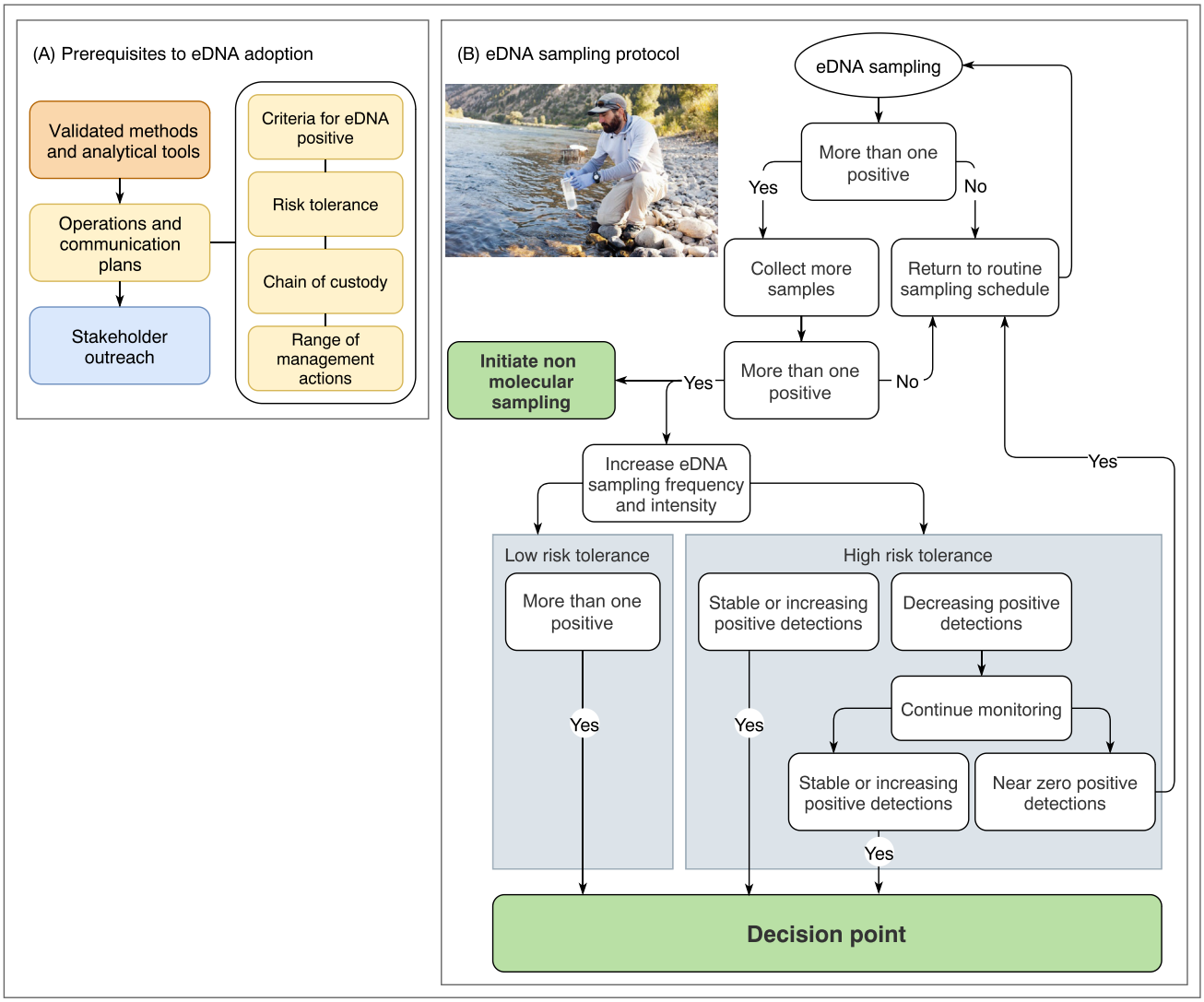

Figure 1. Environmental (e)DNA Decision-Support Tree Schematic. (A) Summary of the necessary elements before commencing an eDNA monitoring program including (i) specific standards and best practices for eDNA collection and processing; (ii) development of operations and communication plans; and (iii) development of a communication strategy for working with various stakeholders and the public. The operations and communication plans should include: criteria for concluding a positive eDNA detection; risk tolerance levels, specific to the areas and species under surveillance; a procedure for chain of custody in case of legal challenges; and a suite of management actions to be undertaken when warranted. (B) Decision tree that provides step-by-step guidance for managers when eDNA sampling commences. Specifying detailed directives upfront will minimize uncertainty in how to interpret eDNA results. The photo on the top left: Collecting an eDNA river sample from the Yellowstone River (Montana). Photo courtesy of A. Sepulveda, USGS.

to tolerate minimal loss) might mean a manager's intent to move more quickly with implementing a response because of an agricultural water supply or endangered species. Characterizing risk tolerance will help clarify what is at stake if eDNA detections are heralds of a new invasion.

Roots of the decision-support tree are based on best practices from fields like DNA forensics, including implementation of validated methods and protocols in qualified laboratories, an operations and communications plan that is signed by pertinent managers and researchers (see Supplemental information online for an example) and includes jointly defined definitions of

terms including what constitutes a positive eDNA result, characterization of waterbody risk tolerance, and stakeholder outreach pertaining to the Operation and Communications plan (Figure 1A). Comparable steps and rationale are discussed in [38]. These steps must be taken before eDNA sampling begins so that there is stakeholder confidence in the methods and all decisions are transparent.

Branches of the decision tree integrate information about the trend in eDNA positives over time relative to waterbody risk tolerance and direct managers when to make decisions using eDNA results (Figure 1B). Each successive decision-tree branch helps managers gage the uncertainty of eDNA results, with the initial branches that rely on a single eDNA positive having much higher uncertainty (e.g., potential for false or misleading positive) than the later branches that rely on multiple eDNA positives over time. Arguably, decision-support trees such as ours or [54] are broadly applicable to many natural resource issues challenged with uncertainty.

Concluding Remarks

We use the overwhelming evidence for meeting the Daubert standard to conclude that eDNA as a method is not the problem or the concern when validated protocols are used. Rather, the lack of interface between eDNA results and management action needs attention. In its current use, most eDNA applications lack decision-support frameworks for integrating the uncertainty of eDNA detections into natural resource management. For solutions, managers and researchers should jointly develop a decision-support tree that outlines eDNA surveillance, guides management actions, considers risk tolerance for acting versus not acting, and simply and clearly communicates results to decision makers and the public lacking molecular backgrounds. This tree should be developed prior to when eDNA sampling commences, be based on validated eDNA methods performed by qualified laboratories, and include communication and education strategies for stakeholders and the public. We conclude that if most or all of the above solutions are in place, eDNA results should be considered in policy actions and eDNA should be another tool for early detection, monitoring, and managing the growing number of problematic and threatened species (see Outstanding Questions).

Outstanding Questions

What are appropriate standards (i.e., scientific and manager vetting process) for validating molecular tools prior to implementation?

How can we better characterize the uncertainty of eDNA positive detections?

Can the trend (space or time) of eDNA positive detections objectively and simply discriminate between the likelihood of species presence versus absence?

What other ecological or social science models (e.g., triage and treat in human health care) exist for guiding decision making when information is incomplete or uncertain?

How can eDNA researchers and invasive species managers better integrate social science into decision-support tools?

How can waterbody risk tolerance be characterized across multiple axes (e.g., ecological, economic, social, political, and cultural)?

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Supplemental Information

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