



California's Big Sur coast, south of Monterey Bay, California. Monterey County is home to renowned marine biodiversity, as well as considerable human impacts to the marine environment, and is the site of eDNA field trials by several of the authors.

ENVIRONMENTAL MONITORING

Harnessing DNA to improve environmental management

Genetic monitoring can help public agencies implement environmental laws

By Ryan P. Kelly,^{1,2*} Jesse A. Port,² Kevan M. Yamahara,² Rebecca G. Martone,² Natalie Lowell,¹ Philip Francis Thomsen,³ Megan E. Mach,² Meredith Bennett,² Erin Prahler,² Margaret R. Caldwell,² Larry B. Crowder²

Responsive environmental policy demands a constant stream of information about the living world, but biological monitoring is difficult and expensive. For many species and ecosystems—especially in aquatic and marine environments—practical monitoring methods are lacking; even where methods do exist, they may be inefficient, highly destructive, or dependent on diminishing taxonomic expertise.

The emerging science of environmental DNA (eDNA) monitoring is one promising path forward, with dozens of publications in the past 2 years defining its contours and with increasingly practical applications in environmental policy (table S1). DNA is ubiquitous in the environment, and eDNA refers to genetic material from whole microbial cells or shed from multicellular organisms via metabolic waste, damaged tissue, or sloughed skin cells. Species' shedding rates and the environmental context likely influ-

ence the spatial scale of detection for eDNA monitoring—flowing rivers might be quite different from soil samples, for example—but species have been detected within meters to kilometers of a monitoring site (1).

Genetic analysis has long been useful to identify source species for whale meat, sturgeon eggs, shark fins, and other high-value (and imperiled) species subject to illegal trade (2). But such applications require invasive or hard-to-obtain tissue samples and focus only on a single species; the potential to distill policy-relevant ecosystem-level information from a glass of seawater is new (3). The aims of this monitoring differ from the large-scale metagenomic sampling prevalent in the past decade (4), which primarily has focused on discovering unknown microbial life. The methods we outline here have the more practical aim of locating and quantifying species already of management concern.

These techniques are broadly applicable—for characterizing soil communities, identifying emerging plant pathogens, or even sensing human pathogens, such as those used in biological warfare (5)—but the first advances in practical monitoring with eDNA have come in large part from aquatic and marine environments (see the

first photo). Because the DNA fragments of interest often degrade beyond detection in days to weeks in contemporary aquatic and marine ecosystems, eDNA provides the here-and-now view of the living world that policy decisions demand (6). Genetic methods are consequently beginning to allow us to collect high-resolution biological information from lakes, rivers, and bays; recent publications have reported surveys of species' distributions, which point the way toward assessing relative abundance or even numbers of key species (7). Takahara and colleagues, for example, used eDNA to estimate the biomass of common carp in freshwater lagoons (8).

eDNA monitoring has two strong advantages over conventional techniques: increased sensitivity and reduced cost. DNA-based detection outperforms other common biological survey techniques in terms of number of species detected (3) and does so with noninvasive sampling. As the costs of sequencing continue to plummet, generating genetic data from environmental samples becomes increasingly affordable. Per-sample costs depend on the depth and coverage of DNA sequencing, but genetic sampling is already less resource-intensive than manual censuses in some cases (9).

Policy-relevant data often derive from management and compliance monitoring required by environmental laws worldwide (table S1). For example, establishing the presence of certain endangered species in a habitat triggers a suite of protections in the United States under the Endangered Species Act, and under equivalent laws in Canada, the European Union (EU), and elsewhere. Where eDNA can help underfunded public agencies perform these kinds of existing duties to implement data-hungry laws

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concerning natural resources, agencies will have powerful incentives to adopt such techniques. New Zealand, for example, has begun developing molecular tools for early detection of harmful algal blooms and invasive species (10), and the U.S. Geological Survey is working along similar lines.

Whether eDNA alone—in the absence of traditional data—will drive environmental policy decisions remains to be seen (see the second photo). One hurdle to the regulatory use of eDNA is unknown false-positive or false-negative detection rates: for example, whether multiple vectors of invasive species' DNA may be conflated and how eDNA error rates compare with those of traditional monitoring (11). Recent work to assess eDNA error rates due to primer bias and variable eDNA concentrations in the field—key to making more sensitive techniques into more useful ones—has begun to establish the parameters of practical eDNA use (12), but acceptable error rates will differ across applications. In the interim, one value of eDNA is in supplementing existing monitoring for invasive species or public health threats. Two-tiered monitoring—genetic screening of environmental samples to guide subsequent conventional monitoring—can make use of eDNA even when error rates are unknown but where false-negative rates are likely to be lower than traditional monitoring techniques. The U.S. Fish and Wildlife Service has used two-tiered surveillance for invasive Asian carp in the Great Lakes basin, and California has similarly developed tiered monitoring at the intersection of environmental and public health by developing genetic detection methods for human pathogens along the state's beaches (13). Such monitoring is likely to reduce overall sampling time and cost, even as agencies work to validate molecular techniques for routine use.

Policy applications demand varying levels of quantitative information. Detecting an invasion front, for example, merely requires presence and/or absence data that eDNA studies already provide. Other applications require counts—for example, stock assessments under the Magnuson-Stevens and the Marine Mammal Protection Acts (U.S. Public Laws 94-265 and 92-522, respectively, with amendments). Although eDNA concentration is positively correlated with biomass or population density, estimates of absolute abundance remain elusive. If eDNA is to become a viable approach



Sampling water for eDNA analysis. Natalie Lowell samples water for eDNA analysis in the Lake Washington Ship Canal in Seattle, an area heavily affected by human uses.

for stock assessments or other quantitative applications, multiple new molecular markers and further microcosm and mesocosm studies involving communities of known composition will be necessary to link recovered eDNA reads to some measure of organismal abundance. The use of multiple markers simultaneously allows researchers to correct for amplification bias, while replication and internal controls further improve reliability; these safeguards are increasingly common in eDNA studies (14). In the future, these methods could obviate the use of the polymerase chain reaction (with its attendant bias).

Finally, the dynamism of environmental settings (rivers and oceans, for example) makes it challenging to determine where recovered DNA has been generated and how stable its measurement is over time. Incorporating models of environmental dynamics and eDNA degradation into genetic surveys will be a further critical step toward independent validation of the emerging monitoring methods.

By using genetic information to link biological processes to existing physical and chemical data, we can better leverage existing investments in environmental observing systems and begin to disentangle the mechanisms that drive ecosystem dynamics. As

genetic monitoring techniques become more quantitative, by addressing the challenges described above, it should become possible to simultaneously track many species in different trophic levels—measuring environmental change, comparing ecosystem-level shifts over time relative to natural or human-induced stressors, and determining whether the magnitude of change exceeds permissible limits. Quantifying the baselines of ecosystem structure and departures from those baselines are core questions underlying, for example, any environmental impact assessment required by the U.S. National Environmental Policy Act (Public Law 91-190).

In sum, eDNA is beginning to influence management and policy decisions, although current applications by management agencies remain relatively experimental. To animate regulations and accordingly influence human behavior, data must be reliable enough to satisfy legal standards and to justify public confidence. Working toward these goals will require careful and integrated effort by researchers in collaboration with local, state, and

federal agencies but are more probably years (rather than decades) away because of growing interest worldwide. ■

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SUPPLEMENTARY MATERIALS

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¹School of Marine and Environmental Affairs, University of Washington, Seattle, WA 98103, USA. ²Center for Ocean Solutions, Stanford University, Stanford, CA 94305, USA.

³Centre for GeoGenetics, Natural History Museum of Denmark, University of Copenhagen, Copenhagen, Denmark
*Corresponding author. rpkelly@uw.edu.