The importance of open science principles for biological assessment

Marcus W. Beck ([marcusb@sccwrp.org](mailto:marcusb@sccwrp.org)), Raphael D. Mazor ([raphaelm@sccwrp.org](mailto:raphaelm@sccwrp.org)), Susanna T. Theroux ([susannat@sccwrp.org](mailto:susannat@sccwrp.org))

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# Abstract

Open science principles that seek to democratize science can effectively bridge the gap between researchers and environmental managers, yet widespread adoption has yet to gain traction for the development and appplication of bioassessment methods. At the core of this philosophy is the concept that research should be reproducible and transparent, in addition to having long-term provenance through effective modes of data preservation and sharing. We discuss core open science concepts that have been advocated more generally in the ecological sciences and will emphasize how adoption can benefit bioassessment for both prescriptive condition assessments and proactive applications that inform planning activities. Examples from the state of California will be used to demonstrate effective adoption of open science principles through data stewardship, reproducible research, and engagement of stakeholders with multimedia applications. Technical, sociocultural, and institutional challenges for adopting open science will also be discussed, including practical approaches for overcoming these hurdles in bioassessment applications.

# Introduction

Bioassessment is an essential element of aquatic monitoring programs that establishes a foundation of decisions for managing the ecological integrity of environmental resources. Decades of research have supported the development of methods that use different assemblages with regional applications in streams, rivers, lakes, and marine environments (Karr et al. [1986](#ref-Karr86); Kerans and Karr [1994](#ref-Kerans94); Fore and Grafe [2002](#ref-Fore02); Beck and Hatch [2009](#ref-Beck09); Borja, Ranasinghe, and Weisberg [2009](#ref-Borja09)). This body of applied tools represents meaningful progress in understanding how biological organisms can be used as accurate and interpretable sentinels of environmental condition. Monitoring programs in the United States and internationally have collected millions of records of biological data spanning decades and hundreds of assessment methods have been developed from these data. Despite these gains, these tools have not been fully integrated into management frameworks relative to the availability of technical information produced through research and coordinated monitoring efforts (Yoder and Barbour [2009](#ref-Yoder09)). Moreover, existing methods may not be discoverable beyond immediate research applications (Hering et al. [2010](#ref-Hering10); Nichols et al. [2016](#ref-Nichols16)) or may be incorrectly applied based on differences between the goals for developing an assessment index and those defined by a management program (Dale and Beyeler [2001](#ref-Dale01); Stein et al. [2009](#ref-Stein09)). Environmental managers require additional tools that synthesize bioassessment information and bridge the gap between method and application.

The development of bioassessment tools has for decades focused on addressing technical challenges (Jackson and Davis [1994](#ref-Jackson94)), rather than implementation challenges of integrating methods with management, conservation, or policy (Dale and Beyeler [2001](#ref-Dale01)). Legal mandates to assess biological condition have set a precedent for developing bioassessment methods in the United States (Clean Water Act), Canada (Canada Waters Act), and Europe (Water Framework Directive). Basic research to address broad legislative objectives has historically focused on predicting biological responses to environmental change, how these responses can be distinguished from natural environmental variation, and determining the impacts of these changes. Many bioassessment indices developed at the assemblage-level are characterized as either multimetric, such as an index of biotic integrity, or multivariate where condition is based on predictive methods that evaluate similarity of taxonomic composition to reference expectations. The reference-condition approach establishes the foundation for many bioassessment methods whereby a set of reference sites are identified and used to evaluate levels of biological deviation to define potential impacts (Reynoldson et al. [1997](#ref-Reynoldson97); Stoddard et al. [2006](#ref-Stoddard06)). Most indices can be broadly categorized in the context of these well-established methods.

Bioassessment has matured to the point where managers have many options for applying methods in novel contexts. The prevalence of best practices in bioassessment studies has increased over the past few decades, including use of the reference condition approach and methods that separate anthropogenic impacts from natural variability. New assessment tools can also be developed using readily available technical support documents or national protocols that synthesize the body of research and best practices to date (McDonald et al. [2004](#ref-McDonald04); Stoddard et al. [2008](#ref-Stoddard08)). This has in part contributed to the proliferation of hundreds of assessment methods that have been developed for specific regional applcations (Birk et al. [2012](#ref-Birk12)). Although there are logistical and ecological rationale for why location- and taxa-specific methods are needed, concerns about redundancy, comparability, duplicated effort, and lack of coordinated monitoring have recently been discussed within the research community (Cao and Hawkins [2011](#ref-Cao11); Poikane et al. [2014](#ref-Poikane14); Kelly et al. [2016](#ref-Kelly16); Nichols et al. [2016](#ref-Nichols16)). Morever, the abundance of available methods can be a point of frustration for managers given a lack of guidance for choosing an appropriate method among alternatives, particularly as to how a method may relate to specific management, monitoring, or policy objectives (Dale and Beyeler [2001](#ref-Dale01); Stein et al. [2009](#ref-Stein09)). Characterizing how an index could be used in practice to inform decisions and prioritize management actions is often opaque relative to why an index may have been originally developed.

The explicit link to environmental management distinguishes bioassessment from basic ecological research. Although bioassessment can and has been used to inform basic research, the intended use of these tools is to inform management, often through legal mandates and regulatory requirements. Consequently, a bioassessment index is only as valuable as its level of integration with management and regulatory communities. Analyses and outputs of bioassessment products will have limited use if they do not meet the needs of these communities (Bain et al. [2000](#ref-Bain00); Stein et al. [2009](#ref-Stein09); Kuehne et al. [2017](#ref-Kuehne17)). In the United States, the CWA gives power to states, tribes, and territories for method development, which in turn requires federal approval to be implemented into a regulatory framework, e.g., TMDL reporting, permitting, etc. If federal approval is a rough assessment of index efficacy, a tremendous imbalance exists between the methods developed and those that are federally approved for regulatory use. A recent review of assessment methods for ecological integrity in the US showed that few were explicitly connected to freshwater policy (Kuehne et al. [2017](#ref-Kuehne17)). Of those methods that are actively used, a more problematic issue is the manner of application within standard regulatory frameworks. Biological indices are typically used to develop post-hoc diagnoses to trigger remediative or restoration actions, or serve as early warning indicators of environmental change (Niemi and McDonald [2004](#ref-Niemi04)). A critical concern is that these tools, although technically sound, are implicitly being used to document the long-term demise of environmental health. A much broader use for bioassessment to pro-actively guide planning decisions, such as identifying conservation priorities (Linke, Turak, and Nel [2011](#ref-Linke11); Howard et al. [2018](#ref-Howard18)), could greatly extend the reach of tools that have already been developed.

Progress in protecting and restoring ecological integrity requires bioassessment information to be fully integrated with management decisions. A new mode of operation is needed whereby method development is open and transparent and methods are discoverable and reproducible. Most importantly, information transfer to the management community must be intuitive and purposeful. Open science principles that can democratize all aspects of the scientific method can meet these needs, yet bioassessment research and its application to better serve the environment has not fully embraced these principles. Others have advocated more broadly for inclusion of these principles in the ecological sciences (Hampton et al. [2015](#ref-Hampton15), [2016](#ref-Hampton16); Lowndes et al. [2017](#ref-Lowndes17)) and a growing wave of momentum has seen open science permeate how scientists conceptualize research in other disciplines (e.g., archeaology, Marwick et al. ([2016](#ref-Marwick16)); behavioral ecology, Ihle et al. ([2017](#ref-Ihle17)); vegetation sciences, Collins ([2016](#ref-Collins16))). Adopting an open science paradigm in biaossessment is particularly relevant compared to other fields given the explicit need to develop tools that are open and accessible to the management community. Legal and ethical precedents in bioassessment may also necessitate the open sharing of data given that environmental monitoring programs are often publicly funded.

This review will deonstrate tools and approaches for open science, which will empower the research and management community to embrace a new mode of thinking for bioassessment applications. These approaches are expected to benefit the research community by augmenting existing workflows for developing assessment tools, but more importantly, improve the ability of these methods to address environmental issues by bridging the gap between the scientific, management, and regulatory communities. An overview of the general principles of open science is provided, followed by a discussion of specific benefits and how these principles can be applied to bioassessment. We use examples from the state of California to demonstrate how existing tools can be tailored to address legislative mandates for free and open sharing of data, especially by directly engaging stakeholders that require practical approaches for using bioassessment tools in planning activities. We conclude with a discussion of technical, sociocultural, and instutional hurdles that have, thus far, prevented widespread adoption of open science and provide recommendations for the bioassessment community to address these challenges.

# Principles of open science and what they mean for bioassessment

Conventional modes of creating scientific products and more contemporary approaches that align with open science principles share the same goals. Both approaches are motivated by the same guiding principles of the scientific method that seek to make the process of discovery transparent and repeatable. Where the conventional and open science approaches diverge is the extent to which technological advances in communication are leveraged as instrumental tools that are used during every step of the research process. The distinction in thinking between the two approaches can be conceptualized as the “paper as the only and final product” for the conventional approach, whereas the open science approach is inherently linked to advances in communication that have been facilitated by the Internet and computer science. As a result, the open science approach enhances all aspects the scientific process from idea conception to delivery and longevity of the research result.

The paradigm of the scientific paper as the final research product inhibits forward progress for several reasons, particularly so in the applied sciences. Traditionally, the research paper was viewed as a communication tool to report and share results among peers in the scientific community. Researchers could access periodicals to stay informed of advances in the field and use the information to replicate methods for follow-up analysis. Scientific communities have successfully followed this model for centuries. Although the primary literature continues to provide these fundamental services, this workflow fails to facilitate progress when scientific products are developed to serve interests outside of the research community. The paper as a research endpoint for environmental managers fails to deliver tools that are easily accessible from the practitioners perspective, both in application and interpretation. Inclusion of the applied audience at the terminal end of the research process has routinely been exposed as an ineffective mechanism to engage the managment and policy communities with science. Many scientists and even research institutions that serve the public fail to realize that publishing a paper is rarely sufficient to affect environmental change. Practitioners are more likely to view a research paper as a rubber stamp from within the scientific community that lends credibility to a result. It does not provide a mechanism for engaging those that actively seek to benefit from decisions based on scientific evidence.

The open science approach is best conceptualized by placing the scientist in the role of data steward rather than data owner. This mode of thinking places the scientist in a position where data are treated as a living product rather than proprietary and serving only the needs of an immediate research goal.

Use Bond-Lamberty as example, more than just the paper as final product Fox and Hendler about data viz - similar paradigm where the static plot as not the final product

Ecology and bioassessment by extension have not adopted these tools because modes of communication that are intrinsically linked to subjet matter in other fields, such as computer science, are not common.

* Overview of the open science process – follow Hampton paradigm, distinguish between benefits for the researcher vs research institution vs stakeholder/managers
  + Use the report/manuscript as final product paradigm as old way of thinking
  + Nielsen def of open science cited in hampton
  + A philosophy and set of tools that can democratize scientific analysis by making data and analyses more accessible
  + Emphasis on reproducibility, transparency, communication, and longevity, researchers as data stewards not owners
  + Embraces all aspects of a project from idea conception to delivery of final products, implications for bioassessment
  + Overall, encourages collaboration and access to/sharing of data
* Why is open science particularly relevant for bioassessment?
  + Overall, management of water quality requires science that has been publicly funded and the application of the science is a public service that should be inherently open - but it typically is not.
  + data are publicly funded, typically, so legal/moral mandates necessitate open analysis, see Molloy 2011 for UK example
  + Multiple methods have been developed, an important component of open science is data discovery. Making methods open and transparent can facilitate synthesis and meta-analysis
  + Data used for bioassessment methods are typically not the “long-tail” of the ecological sciences, i.e., the carefully collected observational data meant to address specific research questions. Scientists in the long-tail are potentially more relucant to adopt open-science because of the perception of less benefit to making the data open. This suggests that bioassessment datasets and associated methods are inherently more likely to benefit from openness because more widespread appeal. Conversely, the long-tail datasets individually may not have broad relevance but collectively could serve larger purposes, some countries have abandonated national-scale coordinated monitoring efforts in favor localized sampling (Nichols et al. 2016)
* Aspects of the process that can benefit bioassessment
  + Data provenance and open data
  + Method development – existing software packages to facilitate
  + Method delivery –
    - portable packages and data visualization, emphasis on interactive online tools: Zastrow 2015 describes power of interactive mapping, Kelling et al. 2009 describe data-intensive approaches for biodiveristy to identify patterns born from the data and data viz is one approach, Fox and Hendler 2011 emphasize viz as part of analysis process not as end-product, the case for open computer programs described by Ince et al. 2012 emphasizes the type of problem present in bioassessment - all methods should be complementary with a software packgae as supplement to the primary document
    - Communication within collaborative teadm and management community, Kelling et al. 2009
* Why is open science particularly important for bioassessment? Vs. general ecological research? Vs. other kinds of environmental monitoring? Vs. other publicly funded data collection?

# California examples

* Example approach
  + What is the legal/policy framework for supporting/impeding open science in CA? Are we living up to our aspirations?
    - On July 10, 2018 the The State Water Resources Control Board “adopted a resolution on open data principles committing it and the Regional Water Boards to providing broader access to the data used to make local, regional and statewide water management and regulatory decisions in California.” [press release](https://www.waterboards.ca.gov/press_room/press_releases/2018/pr_water_data_071018.pdf), [resolution](https://www.waterboards.ca.gov/board_info/agendas/2018/jul/071018_5_drft_reso.pdf)
  + AB 1755, Dodd. The Open and Transparent Water Data Act. Passed in 2016, requires state water quality institutions to “create, operate, and maintain a statewide integrated water data platform that, among other things, would integrate existing water and ecological data information from multiple databases and provide data on completed water transfers and exchanges” and “develop protocols for data sharing, documentation, quality control, public access, and promotion of open-source platforms and decision support tools related to water data”
  + The California vision – describe legal/policy demands for bioassessment, current methods developed, developing tools to link technical products with management
  + Existing applications – assessment methods packaged as standalone applications complete with documentation, vignettes, versioning
  + Bioassessment as proactive vs reactive – SCAPE for regulatory applications, SCAPE for conservation, other examples

# Challenges and recommendations for bioassessment

* Challenges for application
  + Technical hurdles – technical and constantly expanding skillset is required, immediate returns difficult to see (e.g., for data sharing Hampton et al. 2015, need to find citation for learnign tech skills)
  + Sociocultural hurdles – unwillingness to share hard-earned data (less so for bioassesssment than traditional ecology, but could be an issue), vulnerability to criticism (Lewandowsky and Bishop 2016 describe concerns of transparency leading to damage of scientific integrity)
  + Institutional barriers – entrenched modes of operation can discourage novelty and exploration, no incentive for adoption
* The way forward
  + The holy grail is widespread adoption of open science in bioassessment, but this will never be completely integrated, see challenges above
  + Teaching as an approach – let the trainee become the trainer, Hampton et al. 2017 describes training initiatives to close the skill-transfer gap, Touchon and McCoy 2016 describe mismatch between grad programs and tech skills used in contemporary ecological analysis
  + Who is likely to adopt? Cultivate adopters (researcher benefits, institution benefits, stakeholder benefits), work with non-adopters (institution benefits, stakeholder benefits)
  + Roles for adopters, roles for non-adopters
  + Development as an approach – roles for adopters, develop specialized software packages (require vetting, Borregard et al. 2016, could link in to new but existing pathways for review such as ROpenSci or peer review journals like the R Journal), Touchon and McCoy 2016 advocate for a role of adopters as specialists to facilitate collaboration with “less quantitatively trained or interested students” rather than the latter analysizing their data in potentially suboptimal ways.
* Call to implement now - field is transitioning to molecular approaches where information acquisition will be orders of magnitude greater than traditional taxonomic-based approaches. Data acquisition and management will require systematic methods for documenting, cataloging, and sharing information - start now. Use of online eDNA archives have been established. Baird and Hajibabaei 2012 describe the bioassessment paradigm with molecular approaches

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