A case for applying open science principles to biological assessment

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# Abstract

A critical gap beween the technical advances in the field of bioassessment and the advances needed to link the science with practitioners has impeded forward progress in environmental management. Open science principles that seek to democratize science can effectively bridge the gap between researchers and 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 environmental monitoring programs that establishes a basis of decisions that affect aquatic resources. Decades of research have supported the development of methods that use a variety of 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 significant 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, yet the ability of these tools to reach the management community and to positively affect environmental change is imbalanced relative to the amount of information that is available through research and coordinated monitoring efforts (Kuehne et al. [2017](#ref-Kuehne17)). Morever, existing methods can provide competing benefits due to mismatches between research and management objectives (Stein et al. [2009](#ref-Stein09); Kuehne et al. [2017](#ref-Kuehne17)), may require specialized expertise to implement (Hampton et al. [2017](#ref-Hampton17)), or may not be discoverable beyond specific research applications (Hering et al. [2010](#ref-Hering10); Nichols et al. [2016](#ref-Nichols16)). Practitioners require additional tools that synthesize information and bridge the gap between method and application.

The science of bioassessment has for decades focused on addressing technical challenges for developing indices that accurately describe environmental condition. 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 identifying which biological components respond predictably to environmental change, how these components can be measured with minimum uncertainty relative to natural environmental variation, and what basis of comparison is used to evaluate relative changes between communities. Most bioassessment indices developed at the assemblage-level are characterized as either multimetric, such as the index of biotic integrity, or multivariate where condition is assessed using ratios of observed and expected taxa. The reference-condition approach also 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 developed indices can be broadly categorized within the context of these well-established methods.

Established methods for evaluating and comparing biological communities have generally been accepted by the research community as robust. Kuehne et al. ([2017](#ref-Kuehne17)) documented the prevalence of best practices in bioassessment studies as increasing 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 on bioassessment (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); 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); Kuehne et al. [2017](#ref-Kuehne17)). The process to charactize 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 originally been developed.

What distinguishes bioassessment from others field of ecological study is the link to environmental management. Although bioassessment methods can and have been used to inform basic research, the intended use of these tools, often through legal definitions and requirements, is strictly applied. An argument could be made that an index is only as valuable as its level of integration with management and regulatory communities. Analyses and outputs of bioassessments 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 the power to states, tribes, and territories to develop their own methods, which in turn require 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 (see [here](https://www.epa.gov/wqc/information-bioassessment-and-biocriteria-programs-streams-and-wadeable-rivers) for EPA list). A recent review of assessment methods developed in the United States showed that only 24% were related to any specific freshwater policy (Kuehne et al. [2017](#ref-Kuehne17)). Of those 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 that are routinely used to trigger remediative or restoration actions, or at best serve as early warning indicators (Niemi and McDonald [2004](#ref-Niemi04)). A critical concern is that these tools, although technically sound, are inadvertently 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, could greatly extend the reach of tools that have already been developed.

Bioassessment currently suffers from an excess of information and forward progress will not be made unless this information meets the needs of the management community. 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 even ethical precedents in bioassessment may also necessitate the open sharing of data given that environmental monitoring programs are often publicly funded.

This review will empower the research and management community to embrace open science as 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 a real world scenario of how existing tools can be tailored to address legislative mandates for free and open sharing of data, especially by directly engaging stakeholders. 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 delivering scientific products and more contemporary approaches that align with open science principles share the same goals within the research community. Both approaches are motivated by the same guiding principles of the scientific method that

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

* 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
    - 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

# References

Bain, M. B., A. L. Harig, D. P. Loucks, R. R. Goforth, and K. E. Mills. 2000. “Aquatic Ecosystem Protection and Restoration: Advances in Methods for Assessment and Evaluation.” *Environmental Science and Policy* 3 (1):89–98.

Beck, M. W., and L. K. Hatch. 2009. “A Review of Research on the Development of Lake Indices of Biotic Integrity.” *Environmental Reviews* 17:21–44. <https://doi.org/10.1139/A09-001>.

Birk, S., W. Bonne, A. Borja, S. Brucet, A. Courrat, S. Poikane, A. Solimini, W. van de Bund, N. Zampoukas, and D. Hering. 2012. “Three Hundred Ways to Assess Europe’s Surface Waters: An Almost Complete Overview of Biological Methods to Implement the Water Framework Directive.” *Ecological Indicators* 18 (1):31–41. <https://doi.org/10.1016/j.ecolind.2011.10.009>.

Borja, A., A. Ranasinghe, and S. B. Weisberg. 2009. “Assessing Ecological Integrity in Marine Waters, Using Multiple Indices and Ecosystem Components: Challenges for the Future.” *Marine Pollution Bulletin* 59 (1-3):1–4.

Cao, Y., and C. Hawkins. 2011. “The Comparability of Bioassessments: A Review of Conceptual and Methodological Issues.” *Journal of the North American Benthological Society* 30 (3):680–701. <https://doi.org/10.1899/10-067.1>.

Collins, S. L. 2016. “Vegetation Science in the Age of Big Data.” *Journal of Vegetation Science* 27 (5):865–67. <https://doi.org/10.1111/jvs.12459>.

Dale, V. H., and S. C. Beyeler. 2001. “Challenges in the Development and Use of Ecological Indicators.” *Ecological Indicators* 1 (1):3–10. <https://doi.org/10.1016/S1470-160X(01)00003-6>.

Fore, L. S., and C. Grafe. 2002. “Using Diatoms to Assess the Biological Condition of Large Rivers in Idaho (U.S.A.).” *Freshwater Biology* 47 (10):2015–37. <https://doi.org/10.1046/j.1365-2427.2002.00948.x>.

Hampton, S. E., S. S. Anderson, S. C. Bagby, C. Gries, X. Han, E. M. Hart, M. B. Jones, et al. 2015. “The Tao of Open Science for Ecology.” *Ecosphere* 6 (7):1–13. <https://doi.org/10.1890/ES14-00402.1>.

Hampton, S. E., M. B. Jones, L. A. Wasser, M. P. Schildhauer, S. R. Supp, J. Brun, R. R. Hernandez, et al. 2017. “Skills and Knowledge for Data-Intensive Environmental Research.” *Bioscience* 67 (6):546–57. <https://doi.org/10.1093/biosci/bix025>.

Hampton, S. E., C. A. Strasser, J. J. Tewksbury, W. K. Gram, A. E. Budden, A. L. Batcheller, C. S. Duke, and J. H. Porter. 2016. “Big Data and the Future of Ecology.” *Frontiers in Ecology and the Environment* 11 (3):156–62. <https://doi.org/10.1890/120103>.

Hering, D., A. Borja, J. Carstensen, L. Carvalho, M. Elliott, C. K. Field, A. S. Heiskanen, et al. 2010. “The European Water Framework Directive at the Age of 10: A Critical Review of the Achievements with Recommendations for the Future.” *Science of the Total Environment* 408 (19):4007–19. <https://doi.org/10.1016/j.scitotenv.2010.05.031>.

Ihle, M., I. S. Winney, A. Krystalli, and M. Croucher. 2017. “Striving for Transparent and Credible Research: Practical Guidelines for Behavioral Ecologists.” *Behavioral Ecology* 28 (2):348–54. <https://doi.org/10.1093/beheco/arx003>.

Karr, J. R., K. D. Fausch, P. L. Angermeier, P. R. Yant, and I. J. Schlosser. 1986. “Assessing Biological Integrity in Running Waters: A Method and Its Rationale.” Special Publication 5. Champaign, Illinois: Illinois Natural History Survey.

Kelly, M. G., S. Birk, N. J. Willby, L. Denys, S.Drakare, M. Kahlert, S. M. Karjalainen, et al. 2016. “Redundancy in the Ecological Assessment of Lakes: Are Phytoplankton, Macrophytes and Phytobenthos All Necessary?” *Science of the Total Environment* 15 (568):594–602. <https://doi.org/10.1016/j.scitotenv.2016.02.024>.

Kerans, B. L., and J. R. Karr. 1994. “A Benthic Index of Biotic Integrity (B-IBI) for Rivers of the Tennessee Valley.” *Ecological Applications* 4 (4):768–85. <https://doi.org/10.2307/1942007>.

Kuehne, L. M., J. D. Olden, A. L. Strecker, J. J. Lawler, and D. M. Theobald. 2017. “Past, Present, and Future of Ecological Integrity Assessment for Fresh Waters.” *Frontiers in Ecology and the Environment* 15 (4):197–205. <https://doi.org/10.1002/fee.1483>.

Lowndes, J. S. S., B. D. Best, C. Scarborough, J. C. Afflerbach, M. R. Frazier, C. C. O’Hara, N. Jiang, and B. S. Halpern. 2017. “Our Path to Better Science in Less Time Using Open Data Science Tools.” *Nature Ecology & Evolution* 1 (0160):1–7. <https://doi.org/10.1038/s41559-017-0160>.

Marwick, Ben, Jade d’Alpoim Guedes, C. Michael Barton, Lynsey A. Bates, Michael Baxter, Andrew Bevan, Elizabeth A. Bollwerk, et al. 2016. “Open Science in Archaeology.” *SAA Archaeological Record* 17 (4):8–14. <https://doi.org/10.17605/OSF.IO/3D6XX>.

McDonald, M., R. L. Blair, D. Bolgrien, B. S. Brown, J. J. Dlugosz, S. S. Hale, S. F. Hedtke, et al. 2004. “The US Environmental Protection Agency’s Environmental Monitoring and Assessment Program.” In *Environmental Monitoring*, edited by G. B. Wiersma, 649–68. Boca Raton, Florida, USA: CRC Press.

Nichols, S. J., L. A. Barmuta, B. C. Chessman, P. E. Davies, F. J. Dyer, E. T. Harrison, C. P. Hawkins, et al. 2016. “The Imperative Need for Nationally Coordinated Bioassessment of Rivers and Streams.” *Marine and Freshwater Research* 68 (4):599–613. <https://doi.org/10.1071/MF15329>.

Niemi, G. J., and M. E. McDonald. 2004. “Application of Ecological Indicators.” *Annual Review of Ecology, Evolution, and Systematics* 35:89–111.

Reynoldson, T. B., R. H. Norris, V. H. Resh, K. E. Day, and D. M. Rosenberg. 1997. “The Reference Condition: A Comparison of Multimetric and Multivariate Approaches to Assess Water-Quality Impairment Using Benthic Macroinvertebrates.” *Journal of the North American Benthological Society* 16 (4):833–52. <https://doi.org/10.2307/1468175>.

Stein, E. D., M. Brinson, M. C. Rains, W. Kleindl, and F. R. Hauer. 2009. “Wetland Assessment Alphabet Soup: How to Choose (or Not Choose) the Right Assessment Method.” *Society of Wetland Scientists Bulletin* 26:20–24.

Stoddard, J. L., A. T. Herlihy, D. V. Peck, R. M. Hughes, T. R. Whittier, and E. Tarquinio. 2008. “A Process for Creating Multimetric Indices for Large-Scale Aquatic Surveys.” *Journal of the North American Benthological Society* 27 (4):878–91. <https://doi.org/10.1899/08-053.1>.

Stoddard, J. L., D. P. Larsen, C. P. Hawkins, R. K. Johnson, and R. H. Norris. 2006. “Setting Expectations for the Ecological Condition of Streams: The Concept of Reference Condition.” *Ecological Applications* 16 (4):1267–76. <https://doi.org/10.1890/1051-0761(2006)016[1267:SEFTEC]2.0.CO;2>.