LETTER

Ecological integrity is both real and valuable

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Abstract
Ecological integrity has been criticized as a “bad fit as a value” for conservation biology and restoration ecology. But work over the past four decades centered on ecological integrity—especially biological integrity—has given rise to effective methods for biological monitoring and assessment to better understand the disintegration of living systems, including under scenarios of rapid climate change. Revealing when and where living systems have been altered by human activity, such methods have been adapted and applied most comprehensively in streams and rivers, but also in other ecosystems, ranging from tropical forests to marine coral reefs and on all continents except Antarctica. Equally important, restoration and maintenance of biological integrity is already a fundamental goal in law and offers an inspiring framework for communication and engagement—among scientists, resource managers, law- and policymakers, and the public. This essay builds the case that ecological integrity has proved both real and valuable as a conservation paradigm.

KEYWORDS
beneficial use, biological integrity, Clean Water Act, ecological integrity, freshwater, index of biological integrity (IBI), multimetric index (MMI), reference condition, river, stream

Rohwer and Marris (2021) (hereafter R&M) have critiqued ecosystem integrity, calling it “a bad fit as a value for conservation biology and restoration ecology.” The authors discuss several definitions of the word integrity, find problems with them, and conclude that the word and concept therefore have no utility for conservation. We are sympathetic to some concerns these authors raise—including challenges in defining ecosystems and the potential for management agencies to misapply concepts in ecosystem integrity—but we completely disagree with their conclusion.

For better and worse, humans have been transforming this planet for tens of thousands of years—from mass mammalian extinctions some 10,000–50,000 years ago; to the advent of agriculture about 10,000 years ago, which shows hints of altering the climate even then; to the dense human civilizations agriculture made possible; to the global transformations of air, land, water, and living systems that we see today (ArchaeoGLOBE Project, 2019; IPCC, 2021; Ruddiman et al., 2015). Now, however, after more than a half century of scientific advances, the concept of biological integrity has given
rise to effective methods for biological monitoring and assessment to deploy against the accelerating disintegration of living systems—multimetric indexes that share familiar properties with measures of economic and human health and, most important, directly measure the status of the biota. In this rejoinder to R&M, we wish to build a case for a counterproposition—that ecological integrity, particularly biological integrity, has proved to be both real and valuable as a conservation paradigm.

The evolution of our ideas was inspired by a convergence between the words of Aldo Leopold and those of the US Clean Water Act (CWA). As Leopold (1949) wrote in one deeply personal and highly philosophical essay (also quoted by R&M), “A thing is right when it tends to preserve the integrity, stability, and beauty of the biotic community. It is wrong when it tends otherwise.” Similarly, the act’s first objective is “to restore and maintain the physical, chemical and biological integrity of the nation’s waters” (Pub. L. No. 92-500, § 2, 86 Stat. 816, codified as amended at 33 U.S.C. §§ 1251–1387 [2013]). Both of these declarations emphasize the centrality of what is alive. It is not about protecting the Earth but about protecting Earth’s living systems. The concept of biological integrity, and the multimetric biological indexes founded on that concept, initially led to many real-world accomplishments in river and water resource protection and later, to assessing and conserving diverse environments (freshwater, marine, wetland, and terrestrial). Starting with fish, indexes of biological integrity (IBI) have incorporated varied biological assemblages as indicators (bacteria, plants, invertebrates, vertebrates, and more; Table 1); such indexes have been demonstrably valuable in conservation biology, restoration ecology, and water resource management.

We disagree with a number of premises in R&M’s article, including their statement that ecosystem integrity and ecological integrity are equivalents and that “the general practice in the field” is to use the ideas interchangeably. In fact, neither the terms nor the concepts are interchangeable. While ecosystems may be difficult to define, ecology—the scientific study of living systems—is not. Ecology, the science, explores biological phenomena across multiple levels of organization: individual health, population demography, community organization, energy flow and nutrient cycling in ecosystems, and the mosaic nature of landscapes. We agree with MacArthur (1972) that “[t]he question is not whether such [levels] exist but whether they exhibit interesting patterns about which we can make generalizations.” A view of biological organization comprising this full spectrum—rather than an ecosystem-by-ecosystem view—is essential to defining biological integrity and to judging when living systems are altered by anthropogenic factors. For example, the effects of toxic pollutants may reveal themselves as observed changes in the health of individual organisms (lesions in fish, extra legs in amphibians). Similarly, altered physical habitat or changes in a river’s flow regime may show up as shifts in trophic organization and in species losses (disappearance of long-lived predators, proliferation of filamentous cyanobacteria).

We further disagree with R&M’s contention that the concept of ecological integrity cannot explain losses of conservation value as ecosystems change. They note that ecosystems are always changing, that not all changes are bad, that ecosystems cannot therefore possess integrity, and that “ecosystem integrity” cannot be valuable.” The implication is that any notion of ecological integrity inherently lacks value and can therefore not be used to explain any loss in value. Yet surely we can agree that value is lost if a stream community harboring multiple species of mayflies, stoneflies, and caddisflies is replaced—for example, downstream of a waste treatment plant—by a community dominated by sewage sludge worms. Or when a river is dammed, replacing miles of free-flowing water with a slow-moving reservoir, wiping out an entire spawning population of 100-pound chinook salmon and thereby removing the marine-derived nutrients the fish had brought to the watershed every year for millennia.

It is a pioneering accomplishment of ecological assessments based on the concept of ecological integrity, which incorporate direct measures of biological condition, that such assessments are able to document and quantify losses in value, particularly, losses due to human impact. Grantham et al. (2020), for example, have developed a globally consistent, continuous index of forest condition in relation to degree of human modification—the forest landscape integrity index, or FLII—which has shown that only 40.5% of global forest has “high landscape-level integrity,” clearly a loss in conservation values. Indeed, many changes in ecosystems represent a severe loss of the supporting, provisioning, regulating, and cultural services critical to (and therefore valuable for) human survival (Millennium Ecosystem Assessment, 2005).

R&M further assert that “integrity has a hard time explaining common judgments about loss of ecological value” and that “other such goals, such as biodiversity and complexity, seem to do a better job of accounting for common judgments about the loss of value.” Again, we disagree. R&M never define “common judgments.” If common judgment sees timber production as the highest and best use of forests on Washington State’s Olympic Peninsula, should that judgment dictate conservation practices there? If common judgment says, in contrast, that only old-growth forests have value, should logging never be permitted? Well before a recent boom in functional trait–based ecology
Multimetric measurement of biological condition after passage of the CWA continues as an active area of research and application. A Google Scholar keyword search (February 28, 2017) on IBI and biological integrity produced 12,200 hits, which had increased to 18,300 hits 4 years later (November 11, 2021). The breadth of habitats (e.g., rivers, lakes, reservoirs, wetlands, coral reefs, estuaries, forest, shrubland, grassland, caves); taxonomic groups (e.g., fish, macroinvertebrates, vascular plants, algae, diatoms, birds, amphibians, microbes, nematodes); and geographical areas span the world (at least 100 countries on all continents but Antarctica). Selected examples appear here.

| Reference               | Taxa, location, habitat                                      | Results and applicability                                                                 |
|-------------------------|--------------------------------------------------------------|------------------------------------------------------------------------------------------|
| Ruaro et al. (2020)     | Reviews past work across taxa and habitats globally          | Recommendations for best practices and standardization in developing and using multimetric indexes (MMI); context for successful programs and cautions about pitfalls and unresolved issues |
| Feio et al. (2021)      | Global-scale review of river assessment, study design, sampling methods, taxa, etc. | Comprehensive exploration of the reasons for biological assessment and the need to apply such assessments to improve restoration; identifies major gaps and describes characteristics of successful programs; calls for coordination for global river conservation and restoration |
| Hilderbrand et al. (2020) | Microbes in Maryland, USA, headwater streams                  | Stream microbe samples used to document relationships between microbial biotic index, environmental attributes, and invertebrate and fish IBIs; creates new microbial biotic index to apply to river restoration |
| França et al. (2019)    | Macroinvertebrates in Brazilian urban streams                 | Urban water body assessments revealing degradation of physical habitat, water quality, or biology in 91% of sampled urban stream sites; local example of participatory scientific monitoring, education, and community science |
| Liu et al. (2020)       | Algae in US lakes                                           | Addition of blue-green algal metric in diatom multimetric index improves detection of anthropogenic disturbances to lakes, especially in medium- and highly disturbed lakes |
| Schrandt et al. (2021)  | Nekton index for urbanized Tampa Bay estuary, Florida, USA    | Development of nekton biological index (macroinvertebrate and fish) for estuary monitoring; index sensitive to prolonged red tides |
| Hallett et al. (2019)   | Fish community in urbanized southwestern Australia estuary    | Fish community index: success from collaborative partnership, index testing and validation, robust monitoring regime, sustained resources from managers; platform for assessing and reporting bioregional estuarine condition |
| Carter et al. (2019)    | Shrublands of Nevada, USA                                    | Tracks plant community metrics to assess shrubland communities influenced by and in relation to diverse human uses; quantifies natural reference and socially desirable conditions |
| Spyreas (2019)          | Wetland plants in Illinois, USA                              | Floristic quality assessments to evaluate habitat conservation value, ecological integrity, and naturalness, including systematic discussion of successes and failures |
| Wang et al. (2021)      | Fish in global freshwater and marine environments            | Molecular surveillance approaches like eDNA; promising new opportunities to guide conservation actions |
| Birk et al. (2013)      | Europe’s aquatic ecosystems: rivers, lakes, coastal waters   | Success in protecting aquatic ecosystems across state boundaries and administrative barriers |
| USEPA (2016)            | Many taxa across US freshwater habitats                      | Development and application of a biological condition gradient to measure biological integrity across freshwater habitats |
| Evans et al. (2020)     | Global links between ecological integrity and human health   | Links ecological degradation, infectious disease, and other aspects of human health |

Note: A search on related keywords (November 11, 2021) showed the breadth and depth of scholarly work on relevant topics: ecological integrity of streams (202,000 hits), ecological integrity and human health (427,000 hits), ecosystem integrity (864,000 hits).
Abbreviations: CWA, Clean Water Act; eDNA, environmental DNA; IBI, index of biological integrity; MMI, multimetric index.
(Malaterre et al., 2019; McGill et al., 2006), ecological integrity was specifically conceptualized to incorporate a wider set of metrics (Angermeier & Karr, 1994)—metrics including, but not limited to, biodiversity and not dependent on ill-defined “common judgment.” As widely practiced today, indexes founded on ecological integrity improve our understanding of when and where living systems have been altered by human activity. This understanding in turn provides a foundation for societal decisions and policymaking about whether ecosystem services—and therefore ecological values—have been gained or lost.

The objectives of the CWA enjoin compliance and enforcement activities that protect the quality of water resources and the health of ecosystems, as well as that of human communities dependent on those resources (Hitt & Hendryx, 2010). The concept of biological integrity is particularly useful in this regard. After multimetric measures of biological integrity were first implemented in the 1980s, they became widespread over the next 40 years, informing restoration, conservation, and regulation under the act (Kuehne et al., 2017). Previously, nearly a century of enforcement under the Water Pollution Control Act had relied on water quality criteria centered on chemical pollutants and toxicology. Two exceptions—studies of diatoms (Patrick, 1949) and of benthic macroinvertebrates (Hilsenhoff, 1977)—used a single biological metric to indicate organic enrichment in streams. Then, Karr et al. (Fausch et al., 1984; Karr, 1981; Karr, 2006; Karr et al., 1986) proposed the first multimetric biological index, the IBI, and operational criteria for biological integrity that could be applied under the CWA.

IBI speaks directly to the act’s broadly conceived “beneficial use” mandate; it has long documented and emphasized that impairment cannot be reversed solely by curbing point-source chemical pollutants (Karr & Dudley, 1981). Metrics incorporated into the first IBI included several measures of taxonomic diversity (akin to R&M’s preferred biodiversity criterion), in combination with relative abundances of fish species that were tolerant or intolerant of pollutants or sediment, relative abundance of species at different trophic levels, and others. Under the umbrella of conserving or restoring beneficial uses to humans, the CWA called for the explicitly biological conditions of “fishable and swimmable” waters. For people, landscapes that lack safe drinking water (Westling et al., 2020), places to swim (Fesenmyer et al., 2021), or fish to eat (Gibson-Reinemer et al., 2021) are less valuable than landscapes supplying these benefits. What more logical way to measure and restore very real biological benefits than by applying biological standards?

The multimetric framework of IBI has equally real analogs in other complex systems and shares core conceptual components with those analogs—specifically, a framework to diagnose ecological (specifically biological) condition, validated metrics used for diagnosis, and reference benchmarks. Familiar multimetric indexes include the consumer price index or Dow Jones Industrial Average and the Appgar test for assessing a newborn’s condition right after birth. Indicators like these for economic and human health are assessed against normative reference conditions defined by, for example, body temperature, urine chemistry, or cholesterol levels prevailing in healthy individuals. Applying lessons learned from public health and medicine, measures of biological condition are first calibrated against a gradient of human influence, then chosen and validated as metrics that indicate changes in key biological attributes, the way a fever indicates illness in people. Validated metrics are then assessed against regional reference benchmarks (see Karr & Rossano, 2001 and Elosegi et al., 2017 for more discussion of medical and public health templates). The idealized reference condition—ecological integrity—is defined as an ecological system able to support and maintain an adaptive biological system comprising the full range of parts and processes expected for that region, a system whose evolutionary legacy remains intact (Karr, 2009; Karr & Chu, 1999).

In reality, however, as R&M note, we cannot know or measure such an idealized condition anywhere: historical data are absent, and humans have already changed living systems globally (ArchaeoGLOBE Project, 2019; Ruddiman et al., 2015). R&M contend that conservationists have regarded pre-European reference conditions in North America as essential to ecological integrity. Not so; bioassessment, particularly of rivers and streams, has long used benchmarks independent of historical baselines. Moreover, as IBI-like tools were implemented worldwide over the past half century, practical and effective definitions of reference condition have been established in diverse ways according to available data, including in areas experiencing thousands of years of intensive human use (e.g., Fausch et al., 1984 and Stoddard et al., 2006 for North America; Pont et al., 2006 and Poikane et al., 2017 for Europe; and Liu et al., 2017 for China).

Unlike R&M’s complicated discussion of the meaning of integrity, we define biological integrity as one endpoint on a gradient of biological conditions, ranging from relatively free of human disturbance to nothing left alive. In practice, however, defining biological reference conditions does not mean that all places can, or even should, be managed with a goal of achieving biological integrity. For example, it might be reasonable to set a conservation goal for a stream in Mount Rainier National Park at or near biological integrity, but such a goal would be unreasonable for a stream...
running through Seattle. For lands under intensive human use—farms, cities, or timberlands—a more reasonable goal would be ecological health. Maintaining ecological health on such lands means managing them to prevent degradation of the land for future use, as well as to prevent degradation of areas beyond the site (Karr, 1996). Soils, for example, should not be eroded or depleted to preclude future productivity, and atmospheric contamination from a factory should not poison downwind regions. No land uses that have such deleterious effects are sustainable.

Key to the utility of bioassessment tools founded on integrity, such as IBI, is the ability to assess biological condition; to diagnose human and nonhuman causes of ecological degradation; and, on the basis of these results, to prevent more degradation or propose remedies. In water bodies, such as Jordan Creek in Illinois, for example (Figure 1), human transformations go far beyond adding pollutants. They can and have altered water quality, habitat structure, flow regime, energy sources, and biotic interactions, with cascading consequences for river life (Karr, 1991; Karr et al., 1986). Both the index and component metrics can be examined to identify human actions likely to be responsible for declining biological condition in rivers, leading to numerous real-world successes. To date, multimetric biological assessments have been completed in the United States for over a million stream and river miles nationwide (United States Environmental Protection Agency [USEPA], 2020). A special reservoir fish assessment index has even been developed to track the biological condition of fish communities living in entirely artificial environments, such as reservoirs managed by the Tennessee Valley Authority (Jennings et al., 1995). Such assessments have transformed water resource management on a global scale (Ruaro et al., 2020, Feio et al., 2021; see the selected examples in Table 1).

Consider the progress in Ohio’s rivers, for example, thanks to 40 years of leadership by Ohio EPA. Multimetric biological indexes helped the state’s water resource managers bring the biological condition of the Scioto River into compliance with biological criteria newly established under CWA water quality standards and, in so doing, enhance fishing, hunting, canoeing, and other outdoor recreation (Karr et al., 2020; see Figure 2). With similar work in the Auglaize River watershed, the percentage of cultivated acres under soil-conserving tillage practices rose from less than 5% to more than 90%. Soil erosion and nonpoint pollution from sediment- and nutrient-containing runoff decreased, in turn reducing stream sedimentation and blooms of organic matter; less soil erosion will also sustain the watershed’s long-term agricultural productivity. And the Auglaize’s fish community, assessed using Ohio’s fish IBI, came into compliance with the state’s biological criteria for warm-water and excellent warm-water habitat.

This systematic work had five lessons to teach: (1) standardized monitoring enables connecting the dots
among stressors, exposures, and responses; (2) biological data represent the gold standard for monitoring any living system, even in artificial environments, powerfully complementing physical and chemical data; (3) biological benefits from improved agricultural practices are fast and easy to see; (4) more biological data mean less need for chemical data to show progress toward attaining designated uses under the CWA; and, arguably most important, (5) better land management leads to dramatic improvements in the biological condition of rivers (Karr & Yoder, 2004). All this and more illustrate precisely the clear, specific values and reasons motivating protections and interventions that R&M say are desirable.

Multimetric biological assessment has demonstrated its effectiveness in diagnosing and understanding human and natural causes of ecological changes across time and space for nearly half a century, and it can and will continue to do so. Biological responses to human-fueled global change are well studied in birds and plants, and global change researchers are starting to pay attention to these bioindicator patterns (Menzel, 2002). In the Northern Hemisphere, some bird species, for example, migrate earlier in spring or shift their breeding areas farther north; some species whose phenology does not shift have suffered population declines (Moller et al., 2008). Advances or delays in plant and insect phenology and in species' distributions have produced mismatches between birds and insect food sources and between plants and pollinators (Hughes, 2000). Such complex coevolutionary mutualisms—relationships R&M dismiss as too fleeting or otherwise out of step with integrity—are critical for maintaining global ecosystem services. The full gamut of these bioindicators will be important for understanding climate change and making societal decisions in the future.

Even so, because species and ecosystems have adapted to natural and human-catalyzed climate change throughout geological time, R&M conclude that ecological integrity has no utility with regard to conservation under the accelerating and ever more obvious consequences of human-induced climate change. Quite the contrary: the biological signals that multimetric biological assessments are designed to track are precisely what conservationists need to know as this latest massive human transformation of our own habitat unfolds. The ability of assessments founded on ecological integrity to measure rapid changes on land and in water can tell us which restoration or adaptation actions are working in response to climate change and which are not. Such assessments can and will help us understand which of multiple human causes of degradation most acutely alter living systems in particular places as the climate changes. Beavers moving north and climate refugees from rapidly altering habitats (both invoked by
Such deep looks at the whole biology of places can tell us whether or not a given watershed is recovering following beaver reintroductions (Dittbrenner et al., 2018) can tell us whether or not a given watershed is recovering. Such deep looks at the whole biology of places—not only at one species or another—are the most valuable means to understand what we are doing to, and what we can do to protect, the places we live.

In sum, nearly everyone can agree that healthy living systems are central to the future of human society. Our direct experience and the evidence proffered in this essay have shown that the concept of ecological integrity—particularly, biological integrity—can be and has been translated into measurable, practicable criteria for protecting living ecosystems and the services they provide. Multimetric indexes based on these principles have proved effective for assessing the health of living systems, from water resources to tropical bird communities and on all continents but Antarctica (Ruaro et al., 2020). Multiple metrics, each calibrated along a gradient of human influence, do a better job than unidimensional benchmarks, including biodiversity, of gauging success toward meeting specific biological criteria and of capturing overall ecological health. As R&M note, biodiversity as a sole benchmark leads to the “bizarre” logic that diverse tropical ecosystems are inherently more valuable than less-diverse boreal or high-latitude ecosystems.

In contrast, multidimensional assessments founded on integrity and calibrated for unique living systems show great past and future promise. Moreover, the words integrity and health evoke important human values, thereby opening the door to wide-ranging societal conversations and collaborations among scientists, resource managers, law- and policymakers, and especially the general public (Karr 1993). They offer an inviting framework for constructive debate about conservation strategies, especially in this era of rapid climate change (Wurtzebach & Schultz, 2016). To integrate ethics, science, and law, Bridgewater et al. (2015) propose a “scientific and legal construct for ecological integrity” that would become part of the rule of law—“a global environmental constitutional norm,” no less, for “maintaining the integrity of Earth’s ecological systems.” We need every strategy we can muster to realize the vision articulated by Leopold and the CWA: to restore and maintain the integrity of the living world.

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CONFLICT OF INTEREST
The authors declare no potential conflict of interest.

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