BioScience Advance Access published April 13, 2016

Measuring Ecological Integrity: History, Practical Applications, and Research Opportunities

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The concept of ecological integrity is increasingly being used to guide monitoring efforts across North American public land agencies. We provide a history of this concept and outline its primary components on the basis of the scholarly literature. We then examine established structures and processes that incorporate the best available science, spatial and temporal concerns, and management relevance into frameworks for measuring and reporting on ecological integrity. To understand how this is applied in practice, we provide examples from two land-management agencies in North America that have used ecological integrity as a concept to organize their monitoring programs. Laws, agency guidance, organizational structure, and collaborative processes strongly influence the outcomes of ecological integrity–monitoring programs. Further research in this area would be valuable to better understand how different types of land-management agencies can effectively monitor ecological integrity across various spatial and temporal scales and in the context of climate change.

Keywords: ecological integrity, monitoring, adaptive management, national parks, national forests

Effectively monitoring and reporting on ecological conditions is a crucial component of natural-resource management. Tracking progress toward management goals requires a consistent monitoring program and the development of benchmarks and thresholds for assessing management actions on a continual basis (Harwell et al. 1999, Niemi and McDonald 2004). For instance, scholars have noted that ecosystem restoration, a current management priority in forested ecosystems in the United States and other parts of the world, requires rigorous monitoring of both short-term impacts and long-term effects (Deluca et al. 2010, Hanberry et al. 2015). A well-designed monitoring program can also help to detect trends in resource conditions, threats to resources, and the effectiveness of mitigation or adaptation strategies, both of which are important as resources are affected by climate change (Spellerberg 2005, Larson et al. 2013).

Increasingly, land-management agencies, often in response to new legal requirements, are employing the concept of *ecological integrity* to facilitate and structure their monitoring efforts. Internationally, the concept has been promoted and used as a guiding framework for restoration and monitoring efforts in protected areas (Timko and Innis 2008, Keenleyside et al. 2012). In North America, ecological integrity increasingly is being recognized as an appropriate framework for measuring and communicating progress toward conservation and restoration goals (Barbour 2000, Parrish et al. 2003, Woodley 2010). For instance, the US Forest Service uses ecological integrity as a concept to guide its assessment, land-use planning, and monitoring of forest ecosystems. Ecological integrity also forms a crucial part of its "coarse-filter" (i.e., habitat-based approaches, versus species-specific management and monitoring) biodiversity conservation strategy. Similarly, the US National Park Service (NPS) is incorporating the concept into some of its inventory, monitoring, and assessment programs (Tierney et al. 2009, Mitchell et al. 2014), and the US Fish and Wildlife Service, like the Forest Service, has made ecological integrity a central component within their planning regulations (Forest Service Planning Rule 36 CFR 219 [2012]; Fish and Wildlife Service Manual 602 FW 1 [2000]).

It is important for managers and stakeholders to understand the scientific foundations of ecological integrity and to operationalize it in a way that captures the complexity of the concept and also is measurable, of relevance to managers, and can be understood and supported by stakeholders and the public. Currently, literature on this topic is sparse, and managers are often left to their own devices for how to interpret and apply policies. To support improved practice in light of new policy requirements, we conducted a review of the scientific literature defining ecological integrity and looked at strategies for identifying and prioritizing monitoring

BioScience XX: 1–12.
doi:10.1093/biosci/biw037
Advance Access publication XX XXXX, XXXX

objectives for ecological integrity and communicating outcomes. In particular, we describe the structures and processes that incorporate the best available science, spatial and temporal concerns, and social and managerial priorities into an operational framework for measuring and reporting on ecological integrity. We also look at how the concept has been applied in practice by two land-management agencies in order to highlight the practical applications and tradeoffs that occur when organizations use different strategies for monitoring ecological integrity at multiple scales.

A history and overview of the concept of ecological integrity

The notion of ecological integrity is not new. The most famous early allusion to it can be traced to Leopold (1949), who opined, "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" (p. 224–225). Decades later, the maintenance of biological integrity and ecological integrity were enshrined as legal mandates under the US Clean Water Act of 1972 and the Parks Canada Act of 1988, spurring significant academic debate about the meaning and practical application of the concept (see Woodley et al. 1993, Pimental et al. 2000). Since the late 1990s, practical and measurable approaches to ecological integrity in the context of resource conservation have been grounded in the scientific foundations of conservation biology and community ecology.

Today, ecological integrity is most commonly understood as a holistic concept and framework that focuses on conserving native biodiversity, using the natural or historic range of variation as a reference point, and promoting resilience (i.e., the capacity to "reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks"; Walker et al. 2004, p. 2, see also Woodley 2010, Keenleyside et al. 2012). Ecological integrity emphasizes the importance of ecological processes such as natural disturbance regimes that provide the structures and functions on which the full complement of species in an ecosystem or landscape depend (Angermeier and Karr 1994, Andreasen et al. 2001). Furthermore, ecological systems that retain their native species and natural processes are hypothesized to be more resistant and resilient to natural and anthropogenic stresses over time (Parrish et al. 2003, Woodley 2010). Ecological integrity frameworks also typically emphasize the intrinsic value of native biodiversity, beyond its functional role in supporting the renewal and reorganization of ecosystem function and structure over time (Woodley 2010).

These characteristics of ecological integrity are reflected in a recent and oft-cited definition provided by Parrish and colleagues (2003). They define *ecological integrity* as the following:

> The ability of an ecological system to support and maintain a community of organisms that has species composition, diversity, and functional organization comparable to those of natural habitats within a region. An ecological system has integrity when its dominant ecological characteristics (e.g., elements of composition, structure, function, and ecological processes) occur within their natural ranges of variation and can withstand and recover from most perturbations imposed by natural environmental dynamics or human disruptions. (Parrish et al. 2003, p. 852).

Operationalizing ecological integrity: Ecological components and key attributes

Ecological integrity is commonly characterized in terms of the *ecological components* of composition, structure, and function at multiple levels of hierarchical organization, from species to landscapes (Andreasen et al. 2001, Dale and Beyeler 2001). *Composition* may refer to attributes associated with the species within an ecosystem, such as species richness or evenness, and *structure* may refer to physical features, such as canopy openings or patch size. *Function* encompasses dynamic biotic interactions, such as herbivory and predation; biological processes, such as primary productivity; and abiotic processes, including hydrological processes and fire regimes (Dale and Beyeler 2001). Evaluating ecological integrity requires an understanding of the dynamic spatial and temporal relationships, links, and interactions among ecosystem components at multiple levels of the ecological hierarchy.

A rigorous, scientifically based understanding of an ecosystem facilitates the identification of the *key attributes* of composition, structure, and function that are most crucial for biodiversity conservation and ecological resilience. For example, key attributes of composition (or biodiversity) may be species or functional groups of species (e.g., beavers or riparian vegetation) that provide essential structural or functional roles in the ecosystem. Processes such as fire also may be considered key attributes. In addition to composition, structure, and function, it is often also helpful when building a conceptual model of ecological integrity to characterize the ecological drivers, such as climate regimes or geology, that determine or influence the variation in ecological components (Parrish et al. 2003, Tierney et al. 2009). In some applications, dominant disturbance regimes are also characterized as drivers in order to more clearly illustrate the role of critical-ecosystem processes and their effects on other attributes (see Mitchell et al. 2014).

The identification of the key attributes of ecological integrity requires the specification of spatially explicit ecosystems or landscapes for assessment and measurement. The subjective nature of ecological boundaries can make identifying focal ecosystems challenging. Although an ecosystem may be defined on the basis of management goals or compositional elements such as dominant vegetation, it also must take into consideration the spatial and temporal scales of dominant processes and interactions across the wider landscape (Andreassen et al. 2001). A nested, multiple-scale approach for evaluating ecological integrity at both the ecosystem and landscape level may be essential for ecological systems in which cross-scale interactions and processes, such as large-scale disturbances, are particularly relevant for native biodiversity or ecological function.

In order to assess and measure ecological integrity, it is useful to compare the current state and ranges of variation in ecosystem components with desired states and ranges of variation through the use of benchmarks or reference points. This is done to evaluate the influence of anthropogenic or biological stressors on key ecosystem attributes and assess progress toward management goals, such as restoration (Karr and Chu 1998, Parrish et al. 2003). There are different approaches for determining benchmarks and reference points, each with relative strengths and weaknesses. One approach relies on the use of historical ecology to identify the natural or historic range of variation. In North America, the term *historic range of variation* (HRV) is often preferred over *natural range of variation* (NRV) because of the subjectivity and ambiguity of the word "natural"—especially in light of the significant influence indigenous peoples have had on ecological systems (Egan and Howell 2001). Assessing HRV requires reconstructing and interpreting historic conditions and the range of variability in those conditions from limited, often site-specific data sources that may not exist for many ecosystems. Climate change also complicates the use of HRV as a benchmark for ecological integrity, because shifting species distributions and disturbance interactions may produce novel ecosystems without historical analog. Furthermore, HRV may also be inappropriate for irrevocably degraded systems, or systems in which restoration to HRV is not socially acceptable or feasible (Safford et al. 2012). That being said, using HRV as a benchmark for ecological integrity may still be useful for assessing or evaluating restoration actions in modified ecosystems, such as southwestern Ponderosa pine forests, where the restoration of historic disturbance regimes and forest structures is predicted to increase resilience to climate-related stressors, such as drought, insects, and disease outbreaks (Fule 2008). Furthermore, understanding HRV is crucial for providing context about the temporal dynamics and distribution of ecosystems, including the variation and interactions among ecological processes, climatic drivers, stressors, and ecosystem attributes, and offering insight into relevant ecological thresholds that may result in state changes (Safford et al. 2012).

Another approach uses reference conditions in pristine or relatively pristine ecosystems to evaluate and compare ecological attributes in more degraded systems. The ecological attributes of stream systems in undegraded or protected areas have been widely and successfully used to evaluate the effects of human development and use in more managed watersheds or landscapes (Karr and Chu 1998). By using existing reference conditions, the relative ecological integrity of ecosystems may be evaluated over time, allowing inference into the effects of human use or management actions, even when, given the effects of climate change, returning to historic conditions may not be the goal (Hanberry et al. 2015). However, reference conditions must be chosen carefully. For example, in their survey of aquatic and riparian conditions in public lands in the interior Columbia Basin, Kershner and Roper (2010) found that some ecological attributes associated with management objectives were not significantly different between reference and managed sites, potentially a legacy of historic land uses. Where it is impractical to thoroughly evaluate an appropriate HRV or use reference conditions in undegraded systems, benchmarks may still be determined through the use of expert opinion. Whichever of these approaches is used, to inform an ecological integrity framework, practitioners should designate an "acceptable or social range of variation" for key ecosystem attributes, which define the acceptable limits of change and by which progress toward management goals, status, and trends can be effectively measured and evaluated (Parrish et al. 2003, Duncan et al. 2010).

Finally, it is worth noting that there have been significant debates regarding the utility and suitability of ecological integrity as a framework for resource governance and management on the basis of its dependence on scientific—rather than social or cultural—knowledge in setting objectives and defining "naturalness"; its reliance on subjective judgments (e.g., on the relative importance of key attributes); and lack of theoretical rigor (see Goldstein 1999, Manuel-Navarrette et al. 2004). In addition, the reliance on a natural or historic range of variation for evaluating ecological integrity can be problematic in light of climate change, invasive species, and irrevocably altered or degraded systems (Safford et al. 2012). At the same time, ecological integrity is increasingly being recognized as an appropriate framework for measuring and communicating progress toward conservation and restoration goals for both resource managers and the public (Woodley 2010, Keenleyside et al. 2012). By identifying and measuring key attributes of drivers, stressors, composition, structure, function, and disturbance processes, managers may set goals and evaluate trends in ecological integrity over time (see Parrish et al. 2003, Unnasch et al. 2008, and Vickerman and Kagan 2014 for examples of frameworks). Although debates about how to define and operationalize ecological integrity will continue to evolve as managers and stakeholders work to apply the concept, ecological integrity is increasingly being used as a framework for designing and executing monitoring strategies at multiple scales.

Measuring and communicating ecological integrity

Measures of ecological integrity must be based on indicators that are useful for conveying information about the composition, structure, and function of selected ecosystems over time and across spatial scales. Ideally, indicators should provide quantitative measures of the status and trend of key ecosystem drivers and attributes, reflect the influence of natural versus anthropogenic stressors, and serve to identify the causes of environmental change at different hierarchical levels of ecological organization (Andreassen et al. 2001, Dale and Beyeler 2001, Niemi and McDonald 2004). Monitoring indicators will necessarily be a subset of possible measures. This subset must provide enough information to understand the status of ecological integrity, be feasible to measure and cost effective, and provide results with sufficient statistical power for management and decisionmaking (see Noon et al. 2009). Limiting indicators is challenging, but a particularly persistent challenge is selecting indicator species for monitoring ecological integrity, because of the varying responses of species to stressors and their limited ability to represent impacts to associated taxa (Carignan and Villard 2002). Indicators must also be chosen on the basis of whether they assist managers and stakeholders in understanding and communicating ecosystem status. An indicator-selection process must also incorporate social and economic considerations, such as feasibility, relevance, cost, and acceptance (Niemeijer and Degroot 2008, Tulloch et al. 2011). Therefore, developing measures of ecological integrity requires prioritization, often through a deliberative process, of the world of possible measures according to criteria.

Selecting indicators: Incorporating the best available science and social values. One important method for selecting indicators is the use of conceptual ecosystem models that highlight the interactions between key ecological components at different scales and the potential indicators that can be measured to assess them. Conceptual models are necessary for clarifying causal links and feedback loops and for making explicit any assumptions about the influence of drivers and stressors on ecological attributes. They are also an important communication tool, useful for simplifying and conveying the current understanding about ecological systems and the effects of management to stakeholders. Because of the considerable uncertainty within ecological systems, as well as differing views and understandings between experts, the development of conceptual models should be a deliberative and inclusive process (Gentile et al. 2001, Noon 2003, Lindenmayer and Likens 2010). Indicators may also be identified through a *Delphi process*—essentially a set of sequential surveys of experts used to iteratively identify and prioritize potential indicators (see Amici and Battisti 2009)—or collaborative workshops and expert-based panels (Oliver 2002). These processes explicitly incorporate expert opinion and are useful for identifying, out of a long list of potential attributes and indicators, a limited number of indicators of structure, function, and composition.

At the same time, collaboration with managers is essential, because indicators must provide clear and policy-relevant information for decisionmaking. Managers will be able to aid in specifying objectives and identifying indicators that will best measure progress toward desired conditions and are feasible to monitor (Failing and Gregory 2003, Tulloch et al. 2011). The inclusion of stakeholders is also desirable because social legitimacy and support are often paramount for effective and consistent monitoring efforts (Moir and Block 2001, Biber 2011). A deliberative process involving the use of criteria to filter monitoring indicators can be designed to address these many issues (Niemeijer and Degroot 2008).

Communicating ecological integrity. In order to provide useful guidance for policy and management, measures of ecological integrity must be articulated in a format that is accessible and can effectively communicate status and trends to both managers and the public. One option is to develop a composite index derived from aggregated measures of different indicators that can be compared with baseline measures from high-integrity systems or historical reconstructions. The most well-known example is the Index of Biological Integrity developed by Karr and Dudley (1981) for use in water-quality assessment, which has been used to demonstrate the influence of different stressors and provide quantitative measures of integrity in US and Canadian waterways (Karr and Chu 1998). Developing composite indices for terrestrial systems is possible but has proven more difficult because of the complexity of terrestrial systems and the value judgments needed to determine the respective weights of different indicators (e.g., endangered species versus other general indicators of ecological function; Andreasen et al. 2001).

Conditions and trends are often communicated through the use of scorecards, which sometimes are required by law and have been used in various ecosystem-management and –ecosystem-restoration contexts, including the implementation of the Northwest Forest Plan, the Upper Great Lakes regional initiative, and wetland restoration in South Florida (Harwell et al. 1999). Scorecards often use a "stoplight" symbology to denote the status of select ecosystem characteristics in reference to a desired endpoint or reference condition (see Harwell et al. 1999, Parrish et al. 2003, Unnasch et al. 2008). This format provides "assessment points" that may guide management actions or help to identify knowledge gaps that may be resolved through additional monitoring or adaptive management (Bennetts et al. 2007). Regardless of whether ecological thresholds are known, assessment points can be based on HRV or baseline conditions to track trends and changes, can provide a signal to managers and stakeholders that further evaluation is warranted, and can represent agreed-on points at which management actions must be reevaluated or changed (Groffman et al. 2006, Mitchell et al. 2014).

Practical applications of measuring and reporting ecological integrity

In this section, we examine efforts to measure and report levels of ecological integrity with two land-management examples: the US National Park Service (NPS) and Parks Canada, both established examples of agencies that have implemented and reported on ecological integrity–monitoring programs (see Tierney et al. 2009, Woodley 2010). We base all information herein on public documents describing the content of these monitoring programs, including reports and any available information on processes that the two agencies used in their development, implementation, and interpretation of monitoring requirements and programs. We also supplemented this with several informal and confidential interviews for clarification purposes. To understand these multilevel monitoring programs, we focused on national program design and regional monitoring from the NPS's North East Temperate Network and Parks Canada's Rocky Mountain Bioregion. Both of these regionally integrated monitoring programs are well known for their development of ecological-integrity monitoring for upland terrestrial systems (Tierney et al. 2009, Woodley 2010, Mitchell et al. 2014). These examples provide insight into how the concepts above have been implemented in practice, with a focus on the specific structures and processes used to integrate credible science and social and managerial concerns.

The US National Park Service's Northeast Temperate Network. In the 1990, the NPS came under fire for fostering an organizational culture that was sometimes indifferent to scientific research and its relevance for effective park management (Parsons 2004). A 1992 report by the National Research Council helped to underscore the problem by identifying weaknesses and possible solutions, including a recommendation for budgetary and organizational autonomy for a NPS science program. Congress responded with the 1998 National Parks Omnibus Management Act, which called on the NPS to "undertake a program of inventory and monitoring…to establish baseline information and to provide information on the long-term trends in the condition of National Park System resources." As a result of the congressional mandate and subsequent funding for the Park Service's Natural Resource Challenge initiative, the NPS developed the Inventory and Monitoring Program to track trends and conditions and provide information to support management objectives. To create efficiencies, the 270 individual units within the National Parks System are organized into 32 regional inventory and monitoring networks. Each network shares funding and staff, with five to seven full-time, professional specialists devoted to the development and implementation of the program (Fancy et al. 2009).

Monitoring in each inventory and monitoring network is organized under the concept of *vital signs*. Vital signs "track a subset of physical, chemical, and biological elements and processes of park ecosystems that are selected to represent the overall health or condition of park resources, known or hypothesized effects of stressors, or elements that have important human values" (Fancy et al. 2009, p. 161). The concept of vital signs shares many characteristics with criteria for indicators of ecological integrity, a fact noted by observers who have advocated for the use of an ecological-integrity framework in the selection of vital signs monitoring measures (Unnasch et al. 2008). As a result, many inventory and monitoring programs have developed monitoring protocols on the basis of the ecological-integrity paradigm, often working in close collaboration with the conservation nonprofit Natureserve (see Tierney et al. 2009).

We examined the development of a forest ecosystem–monitoring program by one of these networks, the Northeast Temperate Network (NETN). A vital-signs inventory and monitoring program was based on the three-phase framework developed by the NPS. Within the NETN, ecological integrity was used explicitly as a framework for identifying key attributes and monitoring indicators of forest health (Tierney et al. 2009). Phase one centered on defining goals and objectives, synthesizing the best available science, and articulating key ecological components and processes through the development of conceptual models; phase two involved prioritizing and selecting vital signs (i.e., attributes); and phase three entailed specifying indicators, sampling protocols, and designing and implementing data-management and reporting strategies (figure 1; Mitchell et al. 2006).

In phase one, the NETN formed a *core science team*, or a network-wide committee, composed of NPS and third-party ecological experts from academic institutions and Natureserve. This group conducted an extensive literature review and then developed conceptual models for terrestrial, aquatic, riparian, and intertidal resources in scoping meetings with staff at each park in the network. In meetings, they identified key elements of ecological integrity and focal resources of local social or managerial relevance. In phase two, the core science team identified over 100 potential attributes and indicators. These were then prioritized, using criteria for relevance, management significance, response variability, and feasibility (table 1), in collaboration with over 40 park staff, managers, and scientists from across the network in a three-day workshop to identify network-wide indicators. The resulting short list was then sent to the technical steering committee (composed of NPS inventory and monitoring staff, academics, and other government representatives) and a board of directors (composed of park superintendents) for final approval. These committees helped to ensure the feasibility of a monitoring program and placed fiscal sideboards for implementation. Respondents indicated that these oversight groups were also useful for promoting manager buy-in, ensuring legitimacy and credibility for the process, and providing cover for difficult decisions, such as what to prioritize when budgets are cut. Finally, a revised list of monitoring indicators for the NETN was sent to the national inventory and monitoring oversight committee for approval (Mitchell et al. 2006). In phase 3, measurement protocols for the approved list of indicators were also developed in close collaboration with external, issue-specific experts and organizations. In order to ensure credibility, transparency, and continuing quality, all monitoring protocols are also peer-reviewed and published on the NPS inventory and monitoring website (Tierney et al. 2013).

In order to effectively communicate trends and conditions of ecological integrity, researchers with the NETN adopted a

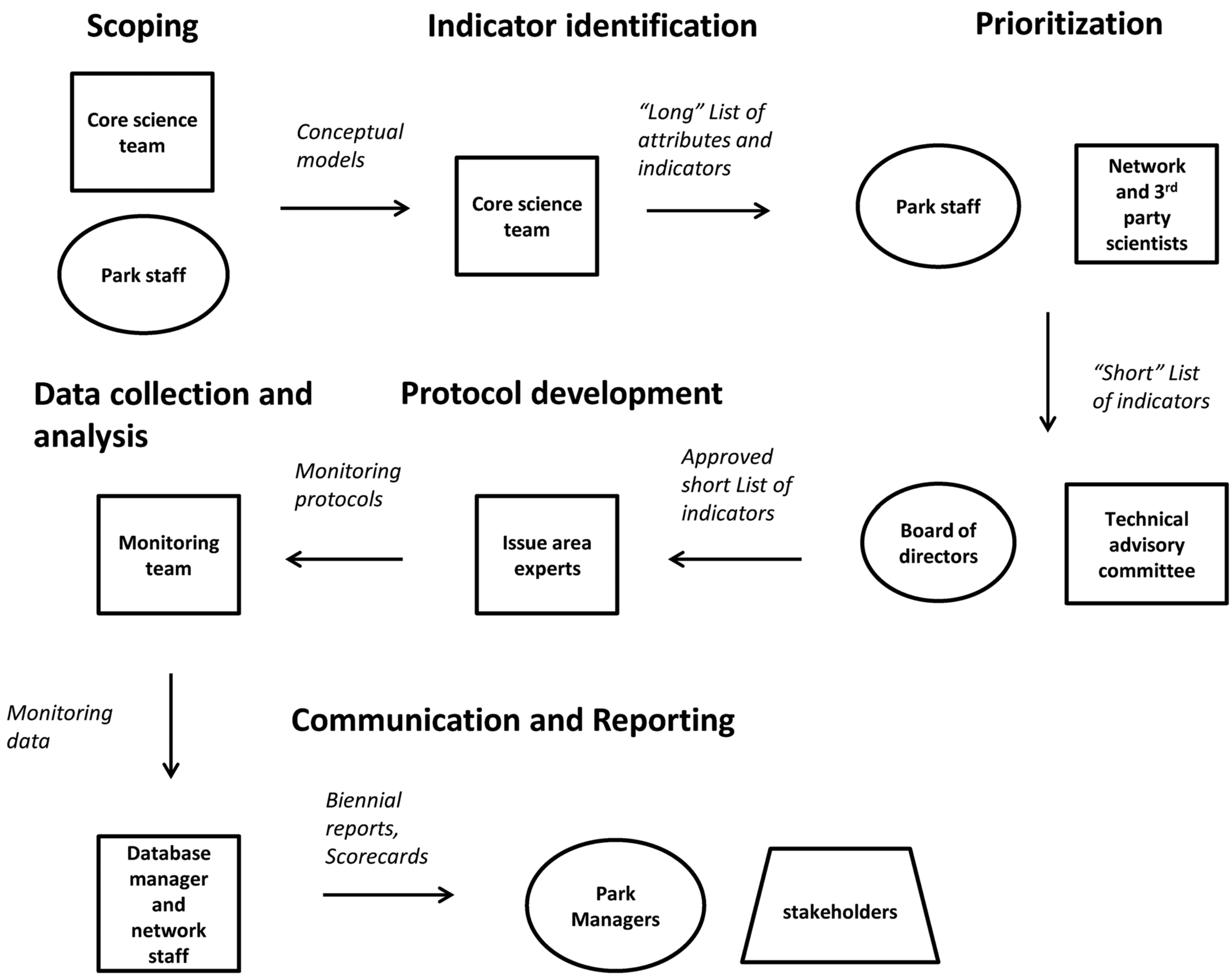

Figure 1. Ecological integrity measurement and communication process in the Northeast Temperate Network: Squares represent network staff and external scientists, circles represent park staff and managers, and the trapezoid represents external stakeholders and members of the public.

"stoplight" symbology to create scorecards with thresholds or assessment points to differentiate between *good*, *caution*, or *significant concern* regarding specific indicators. Assessment points were often informed by known thresholds for ecological functions or the natural range of variation or derived from peer-reviewed studies of historic conditions. For example, landscape-level thresholds for forest structural classes were based on peer-reviewed reconstructions of historic forest size classes, composition, and density (Tierney et al. 2013). Each indicator for structure, composition, and function was given its own value and reported in a scorecard (figure 2). Network-wide monitoring results were, and continue to be, reported in annual monitoring reports, and park-specific results are reported in two-page resource briefs for local managers and stakeholders. These reporting efforts are facilitated by full-time database-management and science-communication positions (Dieffenbach 2006). However, although there are effective strategies for reporting and communication, there are few mechanisms for ensuring that monitoring information is incorporated into park-management plans or management decisionmaking processes.

Parks Canada's Rocky Mountain bioregion. Perhaps more than any other natural-resource management agency in the world, Parks Canada has the most experience managing and monitoring for ecological integrity. In 1988, an amendment to the National Parks Act in 1985 established the maintenance of ecological integrity as the first priority in national-park zoning and visitor-use management (Woodley et al. 1993). By 1997, the agency was using a basic framework for assessing ecological integrity to evaluate the relative ecological integrity of the various parks. In 2001, in response to a government report highlighting significant threats to ecological integrity, a stronger legal mandate (i.e., one that ensured that ecological integrity was the overriding goal) was issued; it defined ecological integrity by law

Table 1. Northeast Temperate Network monitoring indicator criteria.

Rating category	Rating criteria
Management significance and utility	Relevant to assessment questions Relevant to determining quantitative thresholds Sensitive to or indicative of stress Not redundant unless improves performance Linked to management actions Widely applicable (e.g., useful for multiple purposes)
Ecological Relevance	Clear links to ecological function, integrity, or specific resource Anticipatory Indicative of the status of other resources
Feasibility of implementation	Availability of standard, well-documented methods Lack of sampling impacts on indicator Rapid, cost efficient, and can be bundled with other indicators for measurement Easily measured with little equipment of specialized knowledge and large sampling window Baseline data available Long-term data management feasibility
Response variability	Low or controllable measurement error, high repeatability of measurement Temporal variability predictable or described Spatial variability understood or controllable Sufficient discriminatory ability

Source: Mitchell et al. 2006

Park	Structural stage distribution	CWD ratio	Snag abundance	Invasive exotic plants	Tree condition/ Forest pests	Tree regeneration	Tree growth and mortality	Soil Ca:Al	Soil C:N
Acadia national park	Caution	Caution	Caution	Good		Good / Caution	Good	Caution	Good
Marsh-billings rockefeller NHP	Caution	Caution	Sign. Conc.	Caution			Caution	Good	Sign. Conc.
Minute man NHP	Good	Sign. Conc.	Caution	Sign. Conc.			Good	Caution	Sign. Conc.
Morristown NHP	Good	Caution	Sign. Conc.	Sign. Conc.			Caution	Good	Sign. Conc.
Roosevelt-vanderbilt NHP	Good	Good	Caution	Sign. Conc.			Caution	Good	Sign. Conc.
Saint-gaudens NHP	Caution	Caution	Caution	Caution			Caution	Sign. Conc.	Sign. Conc.
Saratoga NHP	Caution	Caution	Caution	Caution			Caution	Good	Sign. Conc.
Weir farm NHP	Good	Caution	Caution	Sign. Conc.			Caution	Caution	Sign. Conc.

Figure 2. Northeast Temperate Network ecological integrity scorecard: "Good" indicates that the condition of the ecological attribute is within the historic or acceptable range of variation, "Caution" indicates that problems may exist, and "Significant Concern" indicates undesired conditions that may warrant management action. Pie charts reflect the proportion of plots in each park that are within each condition category. Source: Miller et al. 2013. Abbreviations: NHP, National Historical Park; Sign. Conc., Significant Concern; CWD, Coarse Woody Material.

as "a condition that is determined to be characteristic of its natural region and likely to persist, including abiotic components and the composition and abundance of native species and biological communities, rates of change and supporting processes" (Fluker 2010, Canada National Parks Act S.C. 2000 c.32, s. 2(1) [2001]). The agency received additional funding for monitoring and restoration in 2003 but recently has been hit with significant budgetary cuts, resulting in challenges for meeting statutory requirements (OAG 2013).

The Parks Canada system is informally organized into different bioregions on the basis of ecological similarities among different parks. However, each individual park's superintendent is ultimately responsible for allocating funding for all monitoring efforts and reporting trends and changes to ecological integrity in individual parks (Parks Canada 2011). In order to promote consistency in measuring and reporting ecological integrity within this structure, Parks Canada has issued detailed national guidelines for developing indicators and implementing monitoring. To limit the scope of possible efforts, the guidance specifies a limited number of 12 nationwide ecosystem types for which to assess ecological integrity and five indicators for each general ecosystem (i.e., forests, wetlands, and grasslands). It also provides a means of aggregating measurements for indicators across multiple parks to report general trends in ecosystems over time. Measures used to assess ecological integrity in each ecosystem fall into the categories of biodiversity, ecosystem function, and stressors (Parks Canada 2011).

In addition to shared measures across ecosystem types, individual parks also maintain or develop their own park-specific monitoring and indicators. The Rocky Mountain region of Parks Canada, in particular, has a long history of robust "in-house" monitoring within its individual parks. In 2005, in response to the updated legal definition of ecological integrity from 2001, parks in the Rocky Mountain Bioregion collaborated with the Alberta Biodiversity Monitoring Institute, a nongovernmental organization, to identify an initial list of potential monitoring items for ecological integrity. Resource-conservation staff from across the bioregion subsequently came together in collaborative workshops to discuss and prioritize potential shared bioregional indicators and protocols. Regional workshops also allowed park staff in the bioregion to share their experiences with different monitoring measures, helping to identify measures or sampling protocols that were effective and meaningful. Staff used decision frameworks that defined criteria, such as relative statistical power, feasibility, and relevance, to evaluate and to filter existing and new monitoring indicators across the bioregion. Newly identified, shared indicators were piloted in individual parks before being adopted by other parks in order to ensure reliability and feasibility. Collaboration with managers, third-party participants, and public stakeholders also occurred at the individual park level but more often through informal mechanisms. Additional workshops at the park level were often used to assess priorities and assure feasibility and relevance. Communication between managers and monitoring personnel regarding the feasibility and potential to meet management goals occurred iteratively throughout the process and continues today. As a result of collaboration across the bioregion and at the park level, parks in the Rocky Mountain region today have measures that are both unique and locally important, in addition to measures for bioregional indicators that are shared by at least one other park—and often several other parks.

Each park is required to report on the status of ecological integrity in State of the Parks Reports, which are required before initiating a new park-management plan, provide a measure of accountability, and help to ensure that monitoring is linked to planning and management. Condition and trend are conveyed using arrows and stoplight symbology. Thresholds are based on a target or desired state determined from baselines acquired from previous long-term monitoring or expert opinion. Scores for individual measures are aggregated into indices for broader categories or ecosystems (Parks Canada 2011). Although many monitoring indicators are scaled up across the region, there are not, as of yet, regional reports for shared indicators. Additional annual or biennial reports on monitoring also vary from park to park, but they are targeted toward the general public primarily and, on the basis of public interest, centered largely on wildlife. These reports are typically brief and do not use the stoplight symbology.

Discussion

These monitoring programs offer several key lessons for agencies developing ecological integrity–monitoring programs. Because these efforts are relatively new and we did not conduct comprehensive or comparative case studies, we include below an exploration of potential research questions that might be addressed as such monitoring programs are developed and implemented.

Tradeoffs in the design of an ecological integrity–monitoring program. The literature and our interviews suggest that legislative mandates have been central to the success of both the NPS and Parks Canada monitoring programs. Both agencies were criticized heavily in the 1990s for failing to address ecological declines because of lack of monitoring and research capacity; in response, lawmakers issued mandates for monitoring the status and trends of park resources and allocated funding to develop and implement them (Parsons 2004, OAG 2005). Within the NPS, ongoing congressional allocation of funding has been supported by annual accomplishment reporting, favorable reviews from the National Academy of Public Administration, and support from Park-level managers (Fancy and Bennetts 2012). For Parks Canada, significant budget cuts for the agency have hit monitoring programs particularly hard, resulting in inconsistent implementation of agency guidelines for scientifically credible monitoring across different Parks (OAG 2013). Interviewees from Parks Canada noted that there was significant opposition from within the agency for building administrative structures at the bioregional level—a pertinent consideration in light of scarce resources. This reveals a potentially important tension, which is that centralized monitoring programs may have advantages in effectively communicating the value of monitoring to national political institutions and local managers, and providing consistency, accountability, and scientific credibility for monitoring programs across multiple units. These attributes are essential for ensuring political and institutional commitment but may require substantial funding from the outset (Fancy and Bennetts 2012).

We also suggest there is likely a tension between management relevance and centralization of monitoring programs. Within Parks Canada's system, responsibility for funding and reporting monitoring efforts ultimately lies with the individual park superintendent. Interviewees indicated that because funding for monitoring is just one of many administrative costs for park superintendents, individual monitoring indicators may be subject to elimination if management feels they are not worth the cost. Consequently, they said, monitoring efforts are more strongly targeted toward issues of short-term management relevance. By contrast, the Northeast Temperate Network represents a more centralized administrative structure, designed with the expressed intent of facilitating scientifically rigorous long-term monitoring (Fancy and Bennetts 2012). With funding and responsibilities for implementation separated from individual park management, it is less likely that long-term monitoring indicators will be cut. A centralized structure also ensures coordination and standardization for regional indicators and reporting strategies. However, this design may constrain the ability of the network to monitor the effectiveness of management actions or pursue adaptive management at the park level. Many parks across the NPS system still have their own local monitoring, but funding for local effectiveness monitoring has not been forthcoming as originally expected (Fancy and Bennetts 2012). Regionally coordinated monitoring programs also may suffer from less buy-in from those in management positions within the agency.

Reporting strategies are dependent on effective data management and information technology, and further research is needed to examine how different organizational strategies may influence to the development of information management systems to facilitate analysis and reporting of ecological integrity across scales. Within the National Park Service, effective data management has been a primary goal of the Inventory and Monitoring Program, with each network allocating approximately 30% of its budget to information management. In the Northeast Temperate Network, interviewees indicated that effective database management and reporting have been facilitated by a full-time database manager and a science communicator at the network level, and this has a played a pivotal role in ensuring timely analysis, reporting, and effective communication to managers. By contrast, staff with Parks Canada said their database management system is cumbersome and difficult to use, which may be because responsibility for the management of the database is centered at the national level. There are also information gaps in the national database, complicating the creation of national assessments—an issue the agency is currently struggling with (OAG 2013). Because of the importance of effective database management for both analysis and reporting, future research should investigate the trade-offs inherent in the different types of database-management strategies associated with ecological monitoring across multiple units or scales.

There are also trade-offs in terms of the efficacy and utility of different reporting strategies for ecological integrity. Aggregated single measure indices, such as those used in Parks Canada, are more accessible for the general public and national-level decisionmakers. However, in simplifying complex ecological conditions to a single measure, they provide little actionable guidance for management and planning. Indeed, ecosystem scorecards are disliked by many scientists and resource managers for this very reason. In the Northeast Temperate Network, the primary audience for monitoring reports is the park managers themselves. In this context, individual rather than "rolled-up" indicators may be a more effective and useful communication strategy, because they provide information on the status and trends of specific attributes of forest integrity, such as downed woody material, that can provide actionable targets for management actions. Future research should explore to what extent different communication formats, such as ecological-integrity scorecards and rolled up versus site-specific indicators for different resources, are useful for public communication and decisionmaking at different levels of organization.

Another pressing area of future research is how to address the challenges and trade-offs inherent in measuring ecological integrity at different scales. Measures of ecological integrity in both of our examples are largely limited to ecosystem or community-level indicators, rather than landscape-level metrics derived from remote-sensing applications (i.e., coarse-filter metrics that look across larger geographical areas encompassing multiple ecosystems and jurisdictions; e.g., see Theobald 2013). For instance, although the NETN monitors patch size within parks, it has yet to implement protocols designed to evaluate trends in land-cover change and land use outside of park boundaries that can be linked to changes in site-specific indicators for forest integrity (although this protocol and strategy is currently in development). This is a significant challenge for future research and application; land-use change outside of park boundaries is arguably one of the greatest threats to ecological integrity within parks (Defries et al. 2007, Hansen et al. 2012). However, evaluating the interactions between different ecosystems and the effect of landscape patterns on the ecological integrity of specific parks is challenging, because of the complexity of analysis and the unique threats that each park faces (Piekielek and Hansen 2012). Evaluating and measuring trends in key landscape-level metrics and prioritizing and implementing the management actions that are essential for ecological integrity at the landscape scale may require collaboration between agencies and researchers, the use of modeling to identify and prioritize areas that facilitate connectivity, and monitoring efforts to validate the uncertainties present in model assumptions and predictions (see Rudnick et al. 2012).

Addressing ecological integrity at the landscape level also requires attention to political and administrative issues both within and between agencies. For instance, ecological data collected by the US Forest Service (located within the US Department of Agriculture) is not always easily accessed by staff in the National Park Service (an agency within the Department of the Interior), even when the land they manage is spatially contiguous. Data integration is also often confounded by the use of different measurement and data management protocols.

Expanding ecological-integrity monitoring to other agencies and into the future. Operationalizing ecological integrity may be particularly challenging within the regulatory and administrative bounds of a "multiple-use" land-management agency, as opposed to national park agencies, for which preservation is a clearer priority. Multiple-use agencies must contend with the practical and political challenge of promoting and measuring ecological integrity while also providing opportunities for commodity production and development. For instance, the US Forest Service's legal mandate to manage for multiple uses—including commodity extraction, recreation, biodiversity protection, etc.—has resulted in challenges for balancing resource use with effective ecosystem management (Biber 2009). However, ecological integrity is still a relevant guide for these agencies and is particularly useful for prioritizing and identifying management and monitoring associated with restoration goals (Keenleyside et al. 2012)—a current priority within many land-management agencies, including the Forest Service (see 36 CFR 219 [2012]). In setting restoration goals, the concept of ecological integrity may be useful for identifying key ecological functions and processes that will maintain structure and key aspects of biodiversity (Higgs and Hobbs 2010, Hanberry et al. 2015). Identifying key attributes of ecological integrity may also help managers design specific management strategies for resource uses, such as timber production, that conserve key compositional and structural attributes of ecological integrity, or mimic natural disturbance processes (Fischer and Lindemayer 2006).

At the landscape level, ecological integrity frameworks may be especially relevant for land-management planning in multiple-use agencies. For instance, Dellasalla and colleagues (2013) noted that in the Sierra Nevada region of California "complex early successional forests" are important components of ecological integrity. In order to ensure an appropriate spatial and temporal distribution of these ecological conditions, forest plans should specify standards and guidelines that minimize impacts from salvage logging or grazing in recently burned areas and designate zones where mixed-severity fires will not be suppressed. Because the US Forest Service recently included ecological integrity as a guiding concept in its new regulations guiding forest planning under the National Forest Management Act (Forest Service Planning Rule 36 CFR 219 [2012]), there is a unique and valuable research opportunity to track how the agency operationalizes this new concept in their planning and monitoring activities.

Because of the political and administrative context associated with multiple-use agencies, particular care will need to be taken in designing and implementing ecological integrity–monitoring programs. Legal mandates and political pressure for commodity production, along with the costs and incentives associated with active management in multiple-use agencies, complicate the development and implementation of effective ecological monitoring programs at every step, from indicator selection to communication and reporting. Because of the subjectivity of the indicator-selection process, for instance, there is the danger that multiple-use agencies will select indicators that are politically salient rather than scientifically credible. Political pressures and budget constraints may also threaten the ongoing implementation of monitoring programs over time, especially if the results threaten or constrain resource use by private actors, such as timber or grazing interests. In addition, even if monitoring data are collected, there may be barriers to communicating or reporting information to stakeholders and higher-level decisionmakers, particularly within the litigious context of multiple-use resource management. Managers may not want to acknowledge the failures of management actions or provide evidence of detrimental impacts to public constituencies. The specification of thresholds or assessment points may also be highly contentious, especially if they are designed to trigger changes in management associated with extractive use (Biber 2011).

In light of these challenges, multiple-use agencies should promote transparency and stakeholder participation in the design and implementation of ecological integrity–monitoring programs. The development and public documentation of *detailed* monitoring plans that specify monitoring protocols, funding strategies, and responsibility for implementation and reporting is an important mechanism for ensuring the transparency and accountability that are often neglected within the context of many multiple-use agencies. In this regard, the NPS Inventory and Monitoring program is an excellent model for multiple-use agencies. Stakeholder engagement and participation may also improve the indicator-selection process, support implementation through citizen science and multiparty monitoring, improve strategies for communication and reporting, and provide accountability for monitoring implementation over time. However, additional agency capacity and governance structures, such as advisory boards, may be needed to facilitate and coordinate productive engagement and collaboration. Monitoring programs associated with the Forest Service's Collaborative Forest Landscape restoration programs are one example of how these goals may be accomplished in practice (see Larson et al. 2013, Schultz et al. 2014).

Multiple-use agencies will also need to consider how and whether regulatory monitoring requirements may be integrated into an ecological integrity framework. Some regulatory requirements—such as water quality monitoring—may be easily integrated into a holistic measure of ecological integrity. However, particular care will need to be taken with regard to fulfilling regulatory monitoring requirements for threatened and endangered species or other *species of conservation concern* (see the Forest Service's regulations at 36 CFR §219.9 [2012] and Schultz et al. 2013). For at-risk species that are not measured as part of an ecological integrity approach, separate conceptual models and processes for monitoring may be needed. This reality is reflected in the NETN, in which vital signs associated with, for example, forest ecological integrity are separate from those for amphibian and breeding birds (NETN). Although they are complementary, effective scale-specific strategies for monitoring ecological integrity that balance ecosystem-resilience monitoring (which has a primary emphasis on structural and functional elements) and biodiversity monitoring (which emphasizes knowledge of specific species' life histories) need to be carefully investigated and considered.

Finally, further research will be needed to evaluate how to define and operationalize ecological integrity in an era of climate change. To be sure, many indicators of ecological integrity, such as invasive species or vegetative growth, will reflect the effects of a changing climate, but it will be crucial to link them to direct measures of climate (Joyce et al. 2009). Incorporating climate-change scenarios into conceptual models of ecological integrity may help managers identify and evaluate specific ecosystems or ecosystem attributes that are vulnerable or resilient to climate change (see Cross et al. 2012). In the long run, because of species individualistic responses to climate change (Parmesan 2006) and the potential for novel ecosystems and no-analog communities (Williams and Jackson 2007, Hobbs and Higgs 2009), ecological integrity may not be appropriate, or it may need to be redefined in such cases so that it is not explicitly linked to the natural or historic range of variation. Within Parks Canada, for instance, legal guidelines for the maintenance of ecological integrity recognize that systems with integrity may exist in several states but that changes to ecosystems must occur "within acceptable limits." However, there is considerable uncertainty as to how this will be interpreted by park managers (Lemeiux et al. 2011). In some cases, it may be more appropriate over longer timeframes to manage primarily for resilience, emphasizing the structural and functional attributes of ecological integrity rather than ensuring the persistence of specific species (Hobbs et al. 2010). In other words, while retaining actual ecological integrity may be difficult in some situations, the concept is nonetheless useful as a framework for facilitating collaboration and communication among scientists, managers, and stakeholders, helping to ensure that targets for management and monitoring are both scientifically credible as well as socially relevant. It also provides a format for facilitating constructive debate about strategies for both biodiversity conservation and resilience in an era of climate change.

Acknowledgments

This work was supported by the US Forest Service Rocky Mountain Region and Grand Mesa, Uncompahgre, and Gunnison National Forests through agreement no. 12-CS-11020400-049 and the Rocky Mountain Research Station through agreement no. 13-JV-11221611-171.

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