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PRACTITIONER'S PERSPECTIVE

Practical advice for implementing long-term ecosystem monitoring

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The road to monitoring

Understanding the current status and long-term trends of natural resources is widely recognized as a cornerstone of ecological research and management. As society wrestles with complex environmental issues involving multiple species and dynamic habitat conditions, the call for ecosystem-based management becomes increasingly urgent (Francis *et al.* 2007; Levin *et al.* 2009). However, to effectively implement ecosystem-based management, managers need access to baseline environmental measurements from appropriate temporal and spatial scales that are directly related to programme objectives. Examples of long-term data contributing to policy exist (e.g. UK Environmental Change Network: http://www.ecn.ac.uk/what-we-do/evidence/), but in many places, there remains a lack of credible and commonly shared baseline data that often results in poor decision-making and environmental policy (Yaffee 1997).

Books and articles invoking the value of long-term monitoring have existed for decades (e.g. Holling 1978). The monitoring of carbon dioxide at Mauna Loa and ozone in Antarctica, possibly the two most famous examples demonstrating the importance of long-term studies, alerted scientists to drastic changes in the earth's atmosphere. Recent documentation of natural phenomena such as the Pacific Decadal Oscillation (Mantua & Hare 2002) emphasize the importance of collecting long-term data to detect low-frequency signals with small changes in magnitude that act as drivers of ecosystem patterns (e.g. sea surface temperature).

Despite the acknowledged value of long-term data sets, many basic data gaps remain. For example, recent research examining the effects of climate change on long-term stream temperature trends demonstrated the dearth of seemingly simple-to-collect and essential water quality data (Isaak *et al.* 2011). Without dedicated funding, the detailed planning necessary for long-term collection of basic information is often difficult to incorporate into a resource-limited programme striving to publish results from more fundable short-term projects. Yet, long-term monitoring programmes will continue to gain importance as managers need basic information on the effectiveness of past actions or try to decide whether current natural resource trends call for policy changes. Long-term monitoring bridges theoretical prediction and natural resource management, allowing scientists to determine whether the hypothesized results of management actions come to bear over time.

Within this context, the United States National Park Service (NPS) has made significant strides to institutionalize natural resource monitoring through the Vital Signs Monitoring Program (Fancy & Bennetts 2012). This programme supports the NPS mission to sustain park lands '…unimpaired for the enjoyment of future generations' (NPS 2006). Understanding the meaning of 'unimpaired', or in other words, the essential components and natural dynamics of a resilient ecosystem (Holling & Meffe 1996), requires monitoring at sufficient resolution to detect natural ecosystem variability. The NPS has organized almost 300 parks into 32 ecologically similar networks responsible for long-term monitoring, one of which is the Southeast Alaska Network (SEAN), the authors' organization. Using a small core staff, the SEAN works in three national parks with a total surface area over 1·3 million ha, including a large marine habitat component in Glacier Bay National Park and Preserve. Combined, the three parks hosted over 1·4 million visitors in 2010.

National Park Service defined seven generalized steps for establishing long-term ecosystem monitoring programmes: (i) clearly defining goals and objectives, (ii) compiling and summarizing existing information, (iii) developing conceptual models, (iv) prioritizing and selecting indicators, (v) developing an overall sampling design, (vi) developing monitoring protocols and (vii) establishing data management, analysis and reporting procedures (Fancy, Gross & Carter 2009). While a large body of literature and web-based resources exist to inform monitoring programme development for steps one through five (e.g. Pacific salmon *Oncorhynchus* spp.: Johnson *et al.* 2007; watershed restoration: Roni 2005; National Marine Sanctuaries: http://sanctuaries.noaa.gov/science/monitoring/; Long Term Ecological Research Network:

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http://www.lternet.edu/), we believe applied ecological monitoring literature lacks generalized, practical guidance for the final stages of monitoring programme implementation (steps vi and vii). We promote a carefully balanced programme as the key to long-term sustainability, a monitoring approach that is not too complicated, rigid, or disconnected from programme objectives, or so sparsely measured that the information is not useful. Deciding whether a long-term monitoring programme is appropriate for specific management or research objectives is not trivial (Watson & Novelly 2004; McDonald-Madden *et al.* 2010), but here, we have assumed this decision has been made and the initial scoping process, including the establishment of measurable objectives and priority environmental indicators, has been completed.

We consolidated SEAN experiences into practical monitoring advice (Table 1) supported by examples from recently developed oceanographic and seabird monitoring programmes. We expect this perspective will be of interest to government agencies, not-for-profit organizations, individual researchers maintaining long-term programmes and academic institutions with scientific mandates funded for extended periods. Our guidance may also be relevant to existing monitoring efforts not functioning as planned or unsustainable owing to limited resources or overly broad scope. This advice evolved through observing the approaches of other NPS monitoring networks and working as a small core staff managing monitoring projects in over 1·3 million ha of Alaska parks. Because of our small size, the network's success continues to depend on working closely with park staff and other partners to design collaborative data collection and reporting approaches. This advice can be characterized as 'formal but flexible', advocating that programmes are developed with some rigidity, but retain mechanisms for implementing future changes. We hope to accelerate the development of effective long-term ecosystem monitoring programmes by offering practical planning and operational guidance applicable across a range of ecological contexts.

Table 1. Guiding principles and practical approaches towards achieving the final two steps of the National Park Service seven-step process for establishing long-term ecosystem monitoring programmes: (vi) developing monitoring protocols and (vii) establishing data management, analysis and reporting procedures

Guiding principle	Practical approach
Rigorous data, sustainably collected	Connect data collection to programme objectives
	Leverage existing efforts, when appropriate
	Report regularly
	Designate specific roles and responsibilities
	Allow for a pilot season
Data for the masses	Use a customer-centric approach for defining data and reporting products
	Create data resilience
	Provide long-term data publicly over the internet
	Establish a single authoritative source

Rigorous data, sustainably collected

Successful monitoring programmes rely on the commitment of many individuals and the establishment of an independent institutional memory that does not hinge on the continued participation of current stakeholders. Engaging multiple stakeholders ensures that a programme is well designed and relevant, but broad and diverging viewpoints can pose obstacles to the development of clear, concise monitoring objectives. This makes our first lesson, ***connect data collection to programme objectives***, potentially the most difficult to apply. To successfully collect consistent data over long time periods, it is important to reach consensus and develop monitoring protocols focused on achieving measurable objectives guided by the larger scientific or management priorities of the organization(s) conducting the work (Nichols & Williams 2006). We recommend separately managing short-term research projects unless they are part of a planned adaptive management component of the monitoring effort (e.g. testing a new sampling design). For small work groups, especially, it is helpful to streamline data processing by dedicating data management duties to one person. *Ad hoc* short-term projects can take as much or more time to manage than long-term monitoring programmes and should be integrated into the data manager's workload cautiously. Foregoing opportunistic data gathering in favour of targeted data collection can be difficult, but adhering to rigorous collection of core data will help to ensure success and long-term programme sustainability.

We still advocate for flexible monitoring programmes that prioritize the continuity of a core data set but can adapt to emerging technological trends, unforeseen management needs or promising collaborative opportunities. NPS has established mechanisms for updating long-term monitoring efforts. Three years after the start of a Vital Signs programme, external programme reviews are conducted to assess and critique the progress of individual monitoring networks, and if necessary, adjust programme direction. For each SEAN Vital Sign, standard operating procedures (SOPs) describe the process for updating monitoring protocols with both minor (e.g. analytical software version upgrade) and major (e.g. addition of new sampling design) changes. If protocol revision is necessary, meetings with stakeholders such as park natural resource staff, park superintendents and external agency staff are convened to develop changes. Depending on the magnitude of changes, protocol revisions are either internally vetted or thoroughly peer-reviewed. Each revised protocol document is given a unique version identifier, and data subsequently collected under each version are tagged with that identifier.

Oceanographic monitoring in Glacier Bay, which measures a standard set of parameters such as salinity and turbidity, was the first long-term monitoring programme for which SEAN took responsibility and has undergone several recent adjustments. For example, based on protocol peer-review comments, a new site outside the mouth of Glacier Bay was added to the core sites within the bay in 2010 to

improve spatial resolution and broaden the geographic context for trend interpretation. Because of the large amount of data collected, work flow modifications were implemented by adding a Data Steward, a role responsible for assisting the Project Leader in developing time-consuming components of deliverables such as figures and tables for annual reports (*roles and responsibilities* are discussed further down). Most recently, a 3-year ocean acidification study was added to the core monitoring programme to address an emerging important question in Alaskan waters and provide additional support to programme objectives.

As an organization works toward paring down a long-term monitoring programme to its essential components and finalizing an approach, it may become apparent that an existing sampling design is appropriate and should be integrated. Our second lesson, ***leverage existing efforts, when appropriate***, asks that developing programmes carefully consider partnering with or adopting existing efforts. This approach can be extremely efficient and lead to interorganizational collaboration, but before committing to an existing protocol, it should be considered whether the approach is consistent with long-term programme objectives. Consider what the best decision would be 20, 50, 100 years from now, not the one that is most convenient today. Does the existing protocol have enough power to detect trends within the desired time frame? If starting a new protocol makes the most sense, retain the logical justification for doing so within the programme narrative.

The SEAN monitors spatial distribution and annual abundance of the rare seabird, Kittlitz's murrelet *Brachyramphus brevirostris* (Vigors) in Glacier Bay. This species is difficult to enumerate owing to its small size, cryptic colouration and co-occurrence with the marbled murrelet *Brachyramphus marmoratus* (Gmelin), a more abundant species of similar appearance. Five separate sampling efforts over nearly 20 years resulted in several population estimates that were not directly comparable and, therefore, unable to detect long-term abundance trends. After fully considering previous sampling approaches and accounting for the costs and benefits of different designs, we determined that a new approach was needed to assess long-term abundance trends with the desired power (Hoekman *et al.* 2011). This decision represented a multiyear design and field-testing commitment, but ultimately resulted in an efficient, spatially balanced design with considerable reductions in field effort and increases in abundance estimate precision relative to some past surveys. For other Vital Signs such as nearshore marine contaminants, freshwater quality and streamflow, we found it advantageous to adopt existing protocols and data management systems by partnering with other agencies and programmes.

Once a long-term monitoring protocol is finalized and implementation begins, programme objectives and data collection remain relevant by committing to ***report regularly***. We suggest using both simple summary reports prepared in concert with the data collection schedule (e.g. annually) and in-depth periodic reports that synthesize long-term trends from larger data ranges. During protocol development, all report products should be well defined and related directly to programme objectives. Opportunistic or *ad hoc* analyses not prescribed by the SOP for the annual report should be appended to, but not included in, the main body. The main product should have standard formatting, be realistic to produce in a short time frame (e.g. <3 months after annual data collection ends) and develop year-to-year expectations for report customers. Annual reports should also include an abstract or executive summary that presents findings in easily accessible language.

National Park Service Vital Signs monitoring protocols include SOPs for composing annual and periodic (often 5-year) synthesis reports. These documents contain instructions for report formatting as well as specific tables and figures to be presented each reporting year. The goal is not to limit analyses, but to ensure that quality information is consistently reported by the monitoring programme regardless of author. Periodic synthesis reports present more in-depth analyses and provide an opportunity to review programme objectives and decide whether they require discussion or potential modification. Analyses and data are always available for additional exploratory investigations.

To ensure that data collection, handling and reporting are completed each year, long-term monitoring protocols must ***designate specific roles and responsibilities***. Unassigned duties are likely to slip by undone. The SEAN has adopted a Park Lead/Project Lead/Data Manager/Project Manager model for completing monitoring activities. Park Leads are mainly responsible for conducting field work, maintaining sampling equipment during the field season and delivering data to the Project Lead. The Project Lead is responsible for coordinating and overseeing monitoring activities, training park staff and reporting. The Project Lead should also be qualified to assist or lead field efforts when Park Leads cannot. The Data Manager defines dataflows, leads data quality control and assurance procedures, develops databases, works with the Project Lead to properly archive and grade the quality of each data set and disseminates information products on the web. The Program Manager is a technical expert that oversees programme direction, ensures the availability of necessary resources to conduct monitoring and leads administrative duties such as budgeting and employee supervision. Because of the small staff size of the SEAN, this model depends on good communication between park and network staff and has worked well for completing a large annual scope of work efficiently.

Despite the years of hard work that go into creating rigorous long-term monitoring efforts, it is inevitable that best laid plans go awry. Once all the elements of a protocol are complete, ***allow for a pilot season*** to fully test all dataflow and reporting processes before finalizing the document. Real-world constraints will not be apparent until SOPs are scrutinized under actual field conditions. Our experience has shown that during the pilot phase, the intricate details of successfully managing data become apparent and lead to minor but essential modifications for finalizing data management routines.

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Data for the masses

> Documents prepared without carefully considering how people access or read information inevitably end up as digital landfill: either inaccessible or, if inadequately networked, forgotten. (Martin & Coleman 2002)

The importance of data management is explicitly recognized in the NPS natural resource monitoring strategy, which states that each monitoring network is expected to commit at least one-third of resources to data management, analysis and reporting (Fancy, Gross & Carter 2009). Of course, every organization cannot commit the same magnitude of resources, but following some practical advice ensures that collected data remain relevant and accessible to future customers.

Data management is connected to each aspect of a monitoring programme, so data management functions must be structured to support monitoring objectives. While a monitoring programme naturally operates from the collection of field data to data processing to analysis to reporting, a data management system must be built in the opposite direction using the desired end information products. In this way, the monitoring programme and data management system design the information and report endpoints, then the distribution mechanisms and repositories that service them, then the validation processes that ensure the quality of the underlying data, and, finally, the collection of field data.

Once data management protocols are established for a specific programme, they are typically difficult to modify in major ways. Therefore, in addition to clearly linking monitoring products to stated objectives, it is essential to ***use a customer-centric approach for defining data and reporting products*** before data collection begins. Data customers are both the reporters and readers of monitoring data. Modifications in data collection procedures are not only difficult to implement in an established programme, they also introduce opportunities for errors in future data interpretation and compromise overall data set quality. Before dedicating field time, clearly articulate the content and look of desired end products that, once produced, will assure the programme meets its stated objectives and remains meaningful to data users. Consider who the data users will be, their desired formatting for tables and figures, and the content of specific data products.

By clearly articulating end products, a monitoring programme will not rely on the institutional memory of individuals. Protocols written to outlive one person's tenure ultimately ***create data resilience***. Each future product should be well defined, the process leading to the creation of a step-by-step product development description (SOP) that allows a new employee with the proper background knowledge and training to quickly begin their responsibilities.

The level of detail prescribed by this essay takes time to develop. And once this development nears completion, it is both to the programme's advantage and the programme's responsibility to ***provide long-term data publicly over the internet***. Publicly available data reduce data-sharing obstacles across national and organizational boundaries and ensures that the value of the collected data is maximized by allowing as many interested parties as possible to use the information.

Publicly available information introduces the possibility of data being redistributed with form and content diverging from the original. Thus, programmes must ***establish a single authoritative source.*** This is not to say that data cannot be housed in places beyond the original source. Indeed, the NPS has implemented protocols that send data to national and global repositories frequented by the research community. But, in all cases, when data sources are questioned, an authoritative data source should be explicitly identified and made available to maintain data integrity and assure data are the best quality and certified to conform to protocol specifications. In the SEAN, our commitment to this fundamental belief is demonstrated by acting as our own customers. All SEAN Park and Project Leads use only authoritative certified data products for the production of annual reports and other analyses; they do not rely on local copies of files assumed to be accurate. The SEAN explicitly defines data deliverables on a public website. Links are directly related to data products defined in each monitoring protocol. For example, within the oceanography monitoring web page, all protocol-specified data deliverables (e.g. the protocol document, raw and validated data files, reports, etc.) are mapped directly to the project's home page. Using these practices, internal and external audiences and collaborators can be assured of data integrity, from data discovery to analysis and reporting.

We hope that long-term monitoring practitioners find our advice useful and continue a dialogue that provides further monitoring programme lessons. Each of the practical lessons presented in this essay could benefit from being honed with detailed case studies. It would be especially informative to describe the principles of long-term programme management across multiple objectives and collaborators or illustrate the application of long-term monitoring data to adaptive decision-making processes such as regularly updating Bayesian belief networks to assess potential outcomes of various management options (McCann, Marcot & Ellis 2006).

Parting thoughts

> Who reports the works and ways of the clouds, those wondrous creations coming into being every day like freshly upheaved mountains? And what record is kept of Nature's colors – the clothes she wears – of her birds, her beasts – her livestock? – John Muir, 1875

John Muir was not thinking about long-term ecosystem monitoring when he wrote those words over 100 years ago, but they suggest that nature's patterns are not easily revealed. Muir would probably have agreed that, to unravel earth's mysteries and be good stewards, it is society's obligation to actively pursue and preserve environmental knowledge. Today, the rapid advance of technology and information sharing are providing the tools necessary for preserving this knowledge. Our evolving vision for preserving natural resource information for Southeast Alaska national parks, including finalized and developing

monitoring protocols, searchable databases, reports and links to other NPS monitoring networks, can be found at the SEAN website: http://science.nature.nps.gov/im/units/sean/.

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Biosketch

The SEAN conducts monitoring in three United States national parks: Glacier Bay National Park and Preserve, Klondike Gold Rush National Historical Park and Sitka National Historical Park. Chris Sergeant is the ecologist for the SEAN. He received a B.S. and M.S. in Aquatic and Fishery Sciences from the University of Washington. His research background includes freshwater ecology with an emphasis on salmonids and food web dynamics. Brendan Moynahan is Program Manager and senior ecologist for the SEAN. He received his Ph.D. in Wildlife Biology and M.S. in Restoration Ecology from the University of Montana, and his B.A. in Political Science from Bates College. He enjoys working at the interface of science and natural resource management. Bill Johnson is Data Manager for the SEAN. He received his B.S. in Economics from the State University of New York at Albany. His background includes developing production data management systems in the resource management, computer engineering, investment and finance fields.

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