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ORIGINAL PAPER

Reflections on a Vision for Integrated Research and Monitoring After 15 Years

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Abstract In May of 1998, Owen Bricker and his co-author Michael Ruggiero introduced a conceptual design for integrating the Nation's environmental research and monitoring programs. The Framework for Integrated Monitoring and Related Research was an organizing strategy for relating data collected by various programs, at multiple spatial and temporal scales, and by multiple science disciplines to solve complex ecological issues that individual research or monitoring programs were not designed to address. The concept nested existing intensive monitoring and research stations within national and regional surveys, remotely sensed data, and inventories to produce a collaborative program for multi-scale, multi-network integrated environmental monitoring and research. Analyses of gaps in data needed for specific issues would drive decisions on network improvements or enhancements. Data contributions to the Framework from existing networks would help indicate critical research and monitoring programs to protect during budget reductions. Significant progress has been made since 1998 on refining the Framework strategy. Methods and models for projecting scientific information across spatial and temporal scales have been improved, and a few regional pilots of multi-scale data-integration concepts have been attempted. The links between science and decision-making are also slowly improving and being incorporated into science practice. Experiments with the Framework strategy since 1998 have revealed the foundational elements essential to its successful implementation, such as defining core measurements, establishing standards of data collection and management, integrating research and long-term monitoring, and describing baseline ecological conditions. They have also shown us the remaining challenges to establishing the Framework concept: protecting and enhancing critical long-term monitoring, filling gaps in measurement methods, improving science for decision support, and integrating the disparate integrated science efforts now underway. In the 15 years since the Bricker and Ruggiero (Ecol Appl 8(2):326–329, 1998) paper challenged us with a new

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paradigm for bringing sound and comprehensive science to environmental decisions, the scientific community can take pride in the progress that has been made, while also taking stock of the challenges ahead for completing the Framework vision.

Keywords Environmental monitoring and research · Dr. Owen P. Bricker · Ecosystem change · Climate change · Adaptive management science · Environmental indicators · Integrated environmental monitoring networks · Interdisciplinary science

1 Introduction

It has been 15 years since Dr. Owen P. Bricker and his co-author Dr. Michael Ruggiero published their seminal paper "Toward A National Program For Monitoring Environmental Resources," which outlined a strategy for integrating the Nation's environmental research and monitoring programs (Bricker and Ruggiero 1998). As other contributions to this tribute compendium of papers illustrate, Owen Bricker's insistence on rigorous geochemical approaches to deciphering the effects of acid rain on soils and streams was the foundation on which many of us built our careers. In the May 1998 paper, Bricker and Ruggiero went beyond geochemistry to recommend a revolutionary shift in the way we organize scientific investigations and long-term data collection in order to identify, understand, and monitor the complex, multi-dimensional changes occurring across broad landscapes and waters. The need for baseline information on the Nation's ecosystems was described as a matter of national security, with an expectation for regular reporting on the state of our environment much as the daily stock market's "index of leading indicators" suggests the state of the national economy. The Bricker and Ruggiero paper summarized the work of a committee convened by the White House National Science and Technology Council (NSTC) to make better, more efficient use of federally-funded environmental science to sustain the Nation's ecosystems, and called for a "fundamental change in our approach to environmental monitoring and research" (NSTC 1997). The other papers in this collection attest to Owen - Bricker's leadership in the development of watershed science and the discipline of biogeochemistry—this contribution explores his leadership in guiding us toward a strategy for using those new science concepts to detect and solve national and global environmental issues, and asks how far we have progressed toward realizing that vision during the last 15 years.

2 The Framework Rationale

The original challenge that prompted the NSTC's Committee on Environmental and Natural Resources (CENR) to design an "Environmental Monitoring and Research Framework" for the Nation was a recommendation from the General Accounting Office (GAO) in 1994 to establish the use of "ecosystem management" practices on Federal lands. The 1994 report called for a new management approach that "recognizes that plant and animal communities are interdependent and interact with their physical environment (soil, water, and air) to form distinct ecological units called ecosystems that span federal and nonfederal lands" (GAO 1994). The GAO pointed out that "understanding the ecology of an ecosystem will require collecting and linking large volumes of scientific data," but

that "available data are often not comparable, and large gaps in information exist." The GAO further stressed a concern over "uncertainty about how ecosystems function-uncertainty that contributes to strong differences in the interpretation of scientific evidence" (GAO 1994).

To adopt "ecosystem" management methods required an understanding of how ecosystems function and change, and highlighted a major scientific limitation: Data on key components of ecosystems were not available to develop and support ecosystem management practices except in a few intensively researched locations. Where data were available, it was rarely collected in a manner that allowed integrated analysis, and the research was often "multi-disciplinary (i.e., multiple discipline-specific research projects done in a similar location) rather than "interdisciplinary" (i.e., research that considers the interactions of water, soil, air, flora, and fauna in a landscape). Important exceptions were research stations that used a "watershed" approach to compute water, energy, and biogeochemical mass-balance budgets for discrete landscape units, many of which Owen Bricker had a leadership role in establishing (Bricker 1986; Glynn et al., 2011). Our monitoring of environmental health to describe the broader landscape was described as "piecemeal, intermittent, and short term," and as a result had "not provided …the information necessary to distinguish natural from human-induced effects" (Bricker and Ruggiero 1998). Resource management requires local information, but measurements cannot be made everywhere in anticipation of where future management decisions will be needed. Ecosystem models were required to expand our understanding beyond individual research sites to other locations or regions of interest, and monitoring data were needed to verify those models and define their uncertainty. The disconnect between existing research, modeling, and monitoring programs in 1998 made it difficult to project research interpretations from the few study locations to the many locations managers needed to manage. Despite 650 million dollars in funding for environmental research and monitoring in 1998, we did not know "the full extent or condition of our natural resources on a national basis, nor how they are changing" (Bricker and Ruggiero 1998).

Recognizing both the pressing need for assessments of ecosystem condition and vulnerability, commonly referred to as "status and trends," and the dearth of interdisciplinary datasets for describing those ecosystems, the CENR established an Environmental Monitoring Team that recommended "a National Framework for integration and coordination of environmental monitoring and related research, through collaboration and building upon existing networks and programs" (referred to hereafter as the "Framework"; NSTC 1997). The proposed Framework was a data collection and analysis structure that nested interdisciplinary research sites (Measurement Tier 1) within spatially representative surveys of a set of core environmental measurements (Measurement Tier 2), which were in turn nested within remotely sensed datasets and/or inventories (Measurement Tier 3) of those same or surrogate measurements (Fig. 1). Models could then be used to map the status and trends of ecosystems across spatial and temporal scales, and the multi-scale datasets could in turn verify those models and define the uncertainty of the model results. The triangular depiction of the Framework in Fig. 1 implies the number of measurement stations at each tier of the observing system design, with few intensive stations measuring multiple parameters at a high frequency at the top and many survey points or remotely sensed pixels measured less frequently and for fewer parameters at the base (Fig. 1). Adjustments in the Framework diagram since 1998 added a tier of data collection between the intensive research sites and surveys, representing networks of ecologically similar sites distributed along a gradient of disturbance (e.g., a range of climate conditions, development pressure,

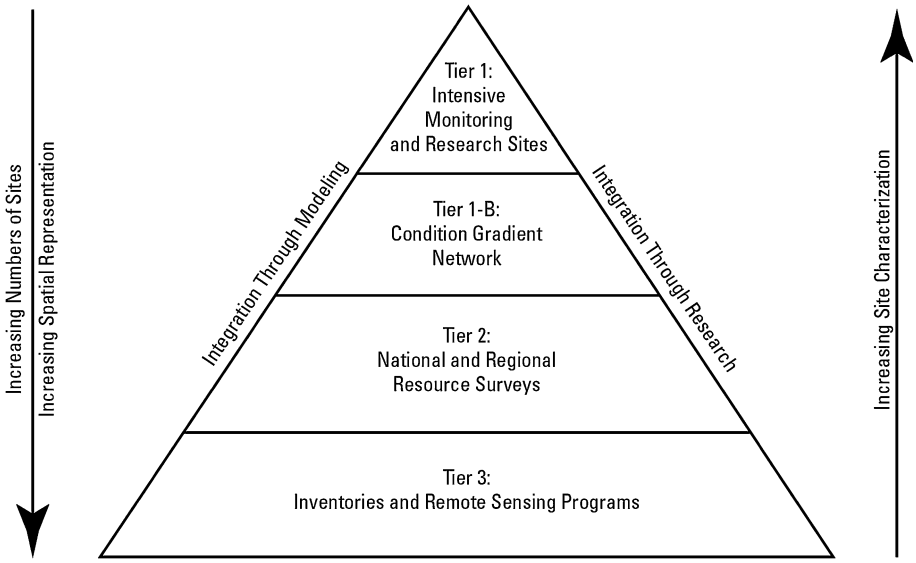

Fig. 1 Conceptual framework for comparing and integrating data from environmental research and monitoring programs (adapted from NSTC 1997)

or acid deposition) (Measurement Tier 1-B; Murdoch et al. 2008). Measurements at these sites were typically for a narrow suite of variables and at a frequency appropriate to a specific environmental issue.

Nesting comparable measurements across temporal and spatial scales in this manner, and making the data collected interoperable among the collaborating networks and programs (i.e., of sufficiently-similar data quality, measurement protocol, and reporting units to allow one dataset to incorporate part or all of another), the CENR Framework allowed datasets for addressing complex ecosystem-scale issues to be assembled. The Framework thus provided for a structured analysis of ecosystem responses to environmental stressors, using data from multiple sources and applied within any integrating landscape unit where comparable data were available, from small watersheds or ecoregions to continental or global scales.

A central goal of the CENR Team was to allow scientists, resource managers, and policy makers "to understand, detect, and predict the status and trends of ecosystems and natural resources… and to distinguish natural from man-induced changes" (NCTC 1997). To increase the use of science in decision-making, the CENR Framework defined research, monitoring, and measurement of management effects as three components of one comprehensive and adaptive strategy. Results from research would inform monitoring strategies, the results of both research and monitoring would inform resource management, and assessments of the utility of recommended management strategies would suggest additional research and monitoring needs. The target scale for interpretation was "where policy and management decisions are most effectively made" (NSTC 1997). As stated by Bricker and Ruggiero (1998), "the Framework is essential if we are to differentiate between actual and perceived environmental issues and address them appropriately, to both avoid unnecessary regulation and serious environmental problems."

2.1 Has the Rationale Changed?

Fifteen years later, the combined stressors of climate change, an ever-increasing list of environmental pollutants, and the rapid expansion of the human footprint across the planet have only heightened the need for ecosystem-level information and a framework for linking existing and new datasets to address complex environmental issues. Several ecosystem models that each require real measurements for verification and to quantify uncertainty are either already in use by decision-makers or rapidly under development (e.g., Thornton et al. 2005, McGuire et al. 2010; Liu et al. 2012; Reilly et al. 2012; McGarigal et al. 2012). Resource management decisions with potential long-term consequences for environmental health are in some cases having to be made without adequate science information to support those decisions, define their uncertainty, or measure their success (Woodbury 2003; Link et al. 2010). For example, managers are reporting that "existing workloads, limited budgets, and lack of targeted climate change science information constrain full integration of climate change scenarios into natural resource management" (Gonzalez 2011). For better science and more scientifically based management, multi-scale interdisciplinary datasets are needed now more than ever.

Shortly after the publication of the Framework paper by Bricker and Ruggiero, the Heinz Center for Science, Economics, and the Environment published a report card on the Nation's ecosystems. A significant conclusion of "The State of the Nation's Ecosystems" report was that "data were adequate in detail and/or spatial extent to report meaningfully on ecosystem condition" for only 58 of the 103 indicator variables assessed (Heinz Center 2002). Of those 58, only 31 indicators had sufficient data to report on trends. A follow-up Heinz report, titled "A Roadmap for the Future", noted that "The current environmental monitoring and reporting programs were developed to meet the many needs of Federal, State, and local governments, as well as those of non-governmental and private groups", but added "A strategic design and sufficient coordination are sorely lacking" (Heinz Center 2008). The authors called for a realignment of National monitoring programs around a suite of environmental indicators, and laid out a structured environmental observing and periodic reporting strategy for the US that roughly paralleled the Framework design of the CENR Team.

In 2007, the Northeastern Ecosystem Research Cooperative assembled a team of internationally known ecologists and National monitoring program coordinators to review the value of environmental monitoring in setting and testing environmental policy (Lovett et al. 2007). They defined environmental monitoring as "a time series of measurements of physical, chemical, and/or biological variables, designed to answer questions about environmental change." While not calling for the integrated, multi-scale strategy of the CENR Framework, they highlighted critical monitoring services, including putting research results into a regional context, verifying models, defining model uncertainty, making data easily used and shareable, and maintaining long-term records for determining trends (Lovett et al. 2007).

Bricker and Ruggiero (1998) did not suggest that the measurements organized under the CENR Framework be obtained through a new large-scale monitoring and research initiative. Rather, they suggested expanding and enhancing measurements and integrating data from existing programs to leverage their length and spatial extent. A primary reason for this approach is that an entirely new network will not be useful to detect change or define trends until a sufficiently long-term record is established. Expanding and enhancing existing measurement networks allowed the entire period of record to be used for trend detection, in some cases extending back more than 100 years. Linking existing

programs is therefore not only the less expensive option for developing the Framework—it is the most effective way to provide science for decision-making in the near term. The need for a coordinated national research, monitoring, and decision-support strategy has therefore remained relatively unchanged since Bricker and Ruggiero (1998) proposed the "National Program For Monitoring Environmental Resources."

3 Progress Since 1998 on the Framework's Foundational Elements

Although attempts have been made since 1998 to pilot or implement prototypes of a framework concept, there is no one collaborative strategy now being used to link the Nation's environmental research stations and observing networks. The most significant progress over the 15 years has been the development of a much clearer picture of the foundational capabilities, partnerships, and leadership required for full implementation of the proposed CENR Framework. Our capacity to manage and share large datasets has improved significantly with advances in technology. New strategies have been tested to compile datasets for specific issues, link datasets across temporal and spatial scales, and improve or develop methods and models to integrate interdisciplinary datasets (e.g., Blodgett et al. 2011; Hallet et al. 2010; LaFontaine et al. 2013). Describing each of the individual improvements in methods for interdisciplinary ecosystem assessment is beyond the scope of this review—those studies have each either provided new capabilities or yielded valuable information on strategies that will not work. These successes and failures over the past decade and a half have shown that there are foundational elements that are essential to establishing a Nationally-integrated science framework. A brief review of progress on each of these elements follows.

3.1 Establishing Core Measurements and Common Data Collection Protocols

The Framework was never meant to orchestrate all measurements of the environment. To establish a workable scope, the Framework focused on a set of core measurements from which indicators of change in ecosystem health or function could be developed. The core measurement list was also meant to be built an issue at a time (e.g., for addressing climate change, invasive species, etc.) with the assumption that as issues were added, the number of additional measurements required would diminish. The CENR Framework report proposed 10 site descriptors and 96 core variables for describing the condition of soil, groundwater, stream, lake, climate, vegetation, animal, landscape, atmosphere, and marine/estuarine ecosystem components (NSTC 1997). These variables would provide the baseline ecosystem information needed to address multiple environmental issues. The report also documented several data collection programs that measured a subset of these variables at a range of spatial and temporal scales in 1998. The CENR list was not comprehensive, and some of these programs have been shut down or reduced in scope since the NSTC report was published, but they represented a potential foundation of existing measurements on which a collaborative data collection framework could be built (NSTC 1997).

Many lists of ecosystem change indicators have been recommended since 1998. Most of the published indicators of ecological change are a combination of measurements, related by a simple equation or a calculated statistic (USEPA 2012; Heinz Center 2002; USGCRP 2013). Recently, the US Environmental Protection Agency (USEPA) and the US Global Change Research Program (USGCRP) National Climate Assessment (NCA) have developed national-scale indicators as tools for detecting the status and trends of ecosystems in

response to climate change (USEPA 2012; USGCRP 2013). Large-scale status and trends assessments such as the NCA remain difficult and time-consuming to produce and update because the required data are not collected or managed in a coordinated manner that facilitates data interoperability or that encourages the maintenance of long-term records. If data collection was cataloged or coordinated through a structure such as the CENR Framework, developing secondary data management systems for specific tasks like the NCA would likely be unnecessary.

There are several examples of how existing programs are or could collaborate to produce consistent data across space (lands and waters) and time (minutes to decades) for narrow subsets of core measurements. Streamflow monitoring is generally approached using protocols and measurements established by the USGS, but data collected by each program are archived separately (Turnipseed and Sauer 2010). The National Atmospheric Deposition Program/National Trends Network (NADP/NTN) is a nationwide monitoring network for precipitation volume and chemistry, and a cooperative effort between Federal, State, Local, and Academic partners (NADP 2012). Strict and consistent protocols are used throughout this network by all participants, a common laboratory analyzes the precipitation samples, and a common database is maintained on the Internet. Collaborations among networks like these can provide the foundation for integrated ecosystem measurements.

The Framework strategy provided an organizational structure within which to compare core measurements among programs and optimize their use. Once a set of core measurements is established, the question of how those data will be combined to address ecosystem-scale problems must be answered. The next challenge is therefore to translate those data into an interoperable form that can be readily assimilated into the assessment process. For that, we need some common practices for data management.

3.2 Data Management

Bricker and Ruggierro (1998) understood that implementing a framework to integrate the Nation's environmental research and monitoring networks is in large part a data management problem. The Framework was "designed to be a collaborative effort building upon existing networks and programs, facilitated by any necessary standardization and data management infrastructure" (NSTC 1997). To implement the CENR Framework with existing monitoring programs, data from those programs must be easily shared to facilitate comparison and analyses.

Advances in information technology (IT) since 1998 have reduced many of the obstacles to integrating data across programs. For example, the development of specialized Web servers such as the Thematic Realtime Environmental Distributed Data Services (THREDDS) Data Servers (TDS) that use an array of data transfer services and standards can now generate virtual databases from multiple sources (UCAR 2013). Other barriers to establishing a distributed, interoperable data management strategy persist to varying degrees, however, including resistance to data sharing (e.g., concern over jurisdiction, publication "scooping," proprietary data, past practices, and unclear benefits), limited funding and staff for upgrades in data management, accessibility, or technical assistance to data providers and users, and a lack of agreement on standards and guidelines for shared data and metadata.

There are three main concepts that would help overcome these barriers and promote data sharing. First, data should be managed at their source unless the data collection program is short term and has no reliable archive (NOAA 2011). This assures that data are collected, quality assured, stored, and delivered by those who are most familiar with the

data, and avoids the cost of duplicate staff and equipment. Second, each data provider must make their shareable data and metadata available according to a set of common standards (NPS 2008; NOAA 2011). Third, shared data must be provided with transparency of how data are collected, quality assured, and stored so users can easily determine quality and compatibility for their analyses (Woodbury, 2003; NOAA 2011). Easily accessible technical assistance greatly improves participation of users and providers. Unless data are well managed, readily accessible, and well documented, they essentially do not exist for collaborative ecosystem assessments.

Differences persist in the status of data management among the tiers of the CENR Framework. Most spatially extensive data are stored in well managed, accessible datasets, and some progress on interoperability of spatial datasets is occurring through the National Spatial Data Infrastructure (FGDC 2007). Data collected at intensive monitoring and research sites, represented by the top of the framework triangle (Tier 1 and 1-B; Fig. 1), are more problematic. Most do not reside in large, well-managed databases but rather are stored on the computers of researchers across the Nation. There is a significant risk of losing these data unless they are cataloged and compiled in accessible and secure archives. The goal of making these smaller datasets interoperable may someday be achieved, but the first task is to create places to store the data where they are at least discoverable.

The most commonly used approach for capturing these scattered data is to develop repositories where researchers can upload datasets for archive as discrete files. An example is USGS ScienceBase, which "provides a data cataloging and collaborative data-management platform for USGS scientists and partners" (USGS, 2013). The National Science Foundation (NSF) has also taken the significant step of requiring data management plans for all NSF grant proposals (NSF 2010). The policy states that "Investigators are expected to share…the primary data, samples, physical collections and other supporting materials created or gathered in the course of work under NSF grants." The Data Observation Network for Earth (DataONE), and "EarthCube," a community-guided cyberinfrastructure, are designed to compile vast arrays of multi-disciplinary environmental data and make them easily accessible to researchers (NSF 2013a, b). These repositories ensure data will be archived and discoverable through data catalogs; the interoperability required for automating the compilation and updating of multi-source datasets from these repositories awaits further development.

Some data management systems developed since 1998 have achieved a degree of interoperability among distributed sources for specific science disciplines. The Consortium of Universities for the Advancement of Hydrologic Science, Incorporated (CUAHSI) has aligned over 90 hydrologic datasets to make them interoperable through a Web-based tool for data discovery, access, and analysis (Tarboton et al. 2011). Data are managed at source servers, but shared through an automatically updated catalog of metadata. Users select data from the catalog, which are then gathered from the provider servers into a virtual local database for specific user applications (Ames et al. 2012).

The National Oceanic Atmospheric Administration's (NOAA) US Integrated Oceanic Observing Systems (IOOS) delivers interdisciplinary, interoperable environmental data from a variety of providers and compiles a common database (NOAA 2013). IOOS has been successful because they have implemented a comprehensive, user-designed Data Management and Communication system (DMAC) that address most of the barriers we described above. DMAC requires participants to adhere to a set of common metadata and data standards (NOAA 2011; Mayorga et al. 2010; NOAA 2013). Those standards were developed and agreed upon by the participants. Incorporation of communication strategies and technical services in the data management design has institutionalized those activities.

IOOS used existing practices where possible, and established interagency agreements, dedicated staff, and stable funding to ensure participation (Ball 2003). Programming for models and popular derived products provides a clear return on investment to participants. Products are easily adjustable to meet user needs, and standards allow data and metadata to be easily discoverable, accessible, and integrated for interdisciplinary analysis.

The Framework's core measurements and data management system allowed integration of remotely sensed coverages, spatially extensive surveys, and intensively measured research stations to bring understanding to the "scale where policy and management decisions are made" (NCTC 1997). The next foundation element of the Framework is therefore the functional integration of existing research and monitoring programs.

3.3 Linking Research and Monitoring

A central tenant of the CENR Framework design was an adaptive strategy for science that made research and long-term monitoring components of a common science enterprise. Within such a strategy, research provides methods development and process-level understanding that can be used to continually test and upgrade the observing system, while monitoring can extrapolate research findings across the landscape, reveal new research questions, and verify research-derived models. The combination was seen as the only solution to capture the complexity of ecosystem status and trends in a way that could effectively inform management decisions where and when those decisions needed to be made (NCTC 1997).

Regional-scale pilots of integrating research sites with spatially extensive observation networks have taken place since 1998. A research and monitoring collaboration among the USDA-FS, USGS, and National Park Service (NPS) in the Delaware River Basin included research watersheds that revealed tree stress due to soil calcium (Ca) depletion from acid deposition (Tier 1), and correlated soil Ca depletion with decreases in the acid neutralizing capacity of streams draining the Ca-depleted landscapes (Tier 1-B). Maps of acidic deposition from National Trends Network and Pennsylvania State University precipitation monitoring sites (Tier 1-B), surveys of forest vegetation, soil, and stream conditions (Tier 2), and remote sensing of forest foliar Ca (Tier 3) were then used to correlate acid deposition with soil Ca depletion across the upper Delaware River Basin, and recommend adjustments in forest harvest practices for the Ca-depleted areas (NADP 2012; Boyer et al. 2009; Hallett et al. 2010; Martin et al. 2008; Murdoch et al. 2008). Concurrent measurements of forest growth and soil carbon concentrations also allowed carbon sequestration rates to be determined for acidified forests of the Northeast, illustrating the concept of incrementally adding to the number of core measurements to address multiple issues (Murdoch et al. 2008).

When fully implemented, the combination of remote sensing and research plots planned for the National Science Foundation's National Ecological Observatory Network (NEON) will yield a significant increase in the potential for integrating research sites with spatially extensive observations (NEON, 2013; Kao et al. 2012), particularly if the NEON observations are linked to ground-based environmental surveys such as the USDA-FS Forest Inventory and Analysis (FIA; Smith 2002) and the EPA National Aquatic Resource Surveys (NARS; Paulsen et al. 2008).

With core measurements established and data interoperability among research and monitoring programs attained, the next steps are to apply that combined dataset to determine the status and trends of ecosystem health, and to develop best management practices where ecosystem health is compromised. Those steps require a scientific capacity

to define and detect ecosystem change, which is the next foundational element of the Framework strategy.

3.4 Discerning Natural from Human-Induced Changes

To detect ecosystem change and to differentiate natural from man-made change, we first need a clear picture of baseline or reference conditions from which the change can be detected (Stoddard et al. 2006). Reference conditions are not well defined for many indicators that have been used to track ecosystem health and vulnerability (Heinz Center 2002). In this time of global pollutants and climate change, no landscape or water body is pristine, but change can be measured through time by monitoring reference, or least-disturbed, condition.

Examples of "sentinel" monitoring stations (Tier 1) were established in watersheds in southern Chile in the early 1990s, to define pristine conditions for global ecosystems (Perakis and Hedin 2002). These watersheds are some of the least impacted by direct human disturbance or air pollution in the world. However, even remote ecosystems are affected by some global pollutants and climate change, and require study over time to define reference conditions before the pollution began. A further challenge is to make the data produced at intensively measured reference stations interoperable with regional surveys and remotely sensed coverages for comparative analysis across spatial scales. For example, Hill et al. (2013) used a combination of temporally-intensive measurements and modeling to extrapolate water temperature in reference streams to a regional scale.

Forested watersheds established for acid deposition research provide some of our best historical records for least-disturbed ecosystems in the United States. The Hydrologic Benchmark Network, and Water, Energy and Biogeochemical Budgets (WEBB) watersheds of the USGS, Organization of Biological Field Stations and Long-term Ecosystem Research (LTER) watersheds of the NSF, agriculture and range watersheds of the Agricultural Research Service, and Experimental Forests of the USDA-FS are perhaps the most persistent, but certainly not the only examples of field laboratories where reference conditions can be assessed (Murdoch et al. 2005; Baedecker and Friedman 2000; NEON 2013; Knapp et al. 2012; Locke 2004; USDA-FS 2008; OBFS 2013). These research sites (Tier 1), coupled with the USEPA stream and lake surveys conducted under the National Aquatic Resource Surveys (Tier 2; NARS; Paulsen et al. 2008; USEPA 2013) and improved methods for remote sensing of ecosystem condition (Tier 3; Wylie et al. 2008; Rigge et al. 2013), could provide a significant base of information for discerning natural from human-induced change.

4 Challenges that Remain

The challenges for establishing the foundational elements that would sustain a national Framework of environmental monitoring and research remain significant. Available funds for environmental research and monitoring are limited. Models without data for verification yield uncertain information for making decisions, yet modeling is often seen as a less expensive option to actual measurements. Research, monitoring, and modeling are all necessary to make sound resource management decisions. Skepticism of environmental science as a critical and reliable component of decision making continues to disrupt meaningful discussion of societal issues from local to national scales, and both time and financial constraints have tested the collaborative will and mechanisms for supporting a

Framework strategy among the scientific community. A few challenges of particular significance to the Framework are also worth mentioning in the context of this review.

4.1 Protecting Existing Long-term Monitoring Stations

When the CENR Team was convened in 1997, environmental monitoring programs were being cut back or eliminated, and there was no frame of reference available for assessing whether the data being collected were important to issues outside of a program's original mission. An expected early product of the Framework strategy was an assessment of the value of existing monitoring capabilities, a conceptual network of networks that linked those monitoring capabilities, and a resulting defense of monitoring networks deemed critical to the Framework in the coming years. The challenge then was "to build upon and enhance existing keystone networks and programs" before those programs were cut back or terminated (Bricker and Ruggiero 1998).

Monitoring and research programs are still commonly managed as independent budget items, and both Federal and State funding for monitoring may continue to decrease in the coming years (Witze 2013; ENS 2013). The importance of maintaining or enhancing existing networks, however, cannot be overstated. Continued indications of global change since the mid-1900s underscores the importance of extant monitoring programs, such as SNOTEL (NWS 2013), FIA (USDA-FS 2013), USGS hydrologic gaging stations (Turnipseed and Sauer 2010), the National Atmospheric Deposition Program (NADP 2012), and biological monitoring such as the Breeding Bird Survey (USGS 2001). These and many other programs have provided data critical to documenting environmental change, and in some cases enabling scientifically grounded legislation. New networks such as NEON will add significantly to the national capacity for observing and understanding global change, but no new network will replace the role of existing data collection stations with historical records. Without the overarching justification for observing systems that a Framework strategy offered, the value of individual research and monitoring programs can be easily overlooked in the pursuit of budget reductions.

There are two major challenges to maintaining research and monitoring networks: the potential for entire networks to lose support or the potential for individual sites within networks to be decommissioned. The first challenge can be addressed by clearly linking networks to issues beyond those for which the network was established. The Framework provides those links. The latter possibility, like species extinction for ecosystems, weakens the entire network in a manner similar to removing rivets one by one from an airplane (Ehrlich and Ehrlich 1981); the uncertainty of environmental assessments could increase with the loss of each monitoring site. Determining which research or monitoring programs and stations are critical versus which are expendable requires an issue-by-issue assessment of research and monitoring needs. Such an assessment requires a conceptual framework within which the programs and stations can be compared.

The USGS stream-gaging program is an example of a network experiencing annual challenges to maintain monitoring stations (Tier 1-B). Many stream gages (approximately 70 %) are funded through collaborative agreements between the USGS and State or municipal governments. Since 2003, the USGS National Stream Information Program (NSIP) has been absorbing the cost of selected stream gages of national significance, but that program is not designed to replace funding for each gage that loses a cooperator (Norris 2009). Likewise, the replacement of aging satellites (Tier 3) that provide data used to monitor weather, natural disasters, and climate change has in some cases been uncertain or delayed, creating a potential for up to a 75 % reduction in satellite-based observing

capacity by 2020 (National Research Council 2012; Newer 2012). A research and monitoring framework within which the value of each of these types of monitoring could be assessed could help identify priority stream gages and satellite sensors for protection.

4.2 Methods Development

One of the challenges in establishing the proposed CENR Framework since 1998 was to fill several gaps in measurement and analysis methods that limited our capability to describe background conditions, detect trends, and project understanding across temporal and spatial scales. In many locations, before the exact measurements to be taken could be selected or data from multiple networks combined, conceptual models and cost-effective methods for describing resources and detecting change needed to be established.

An example is the problem of estimating permafrost thickness and extent in vast roadless areas of the Arctic where sufficient well drilling to map permafrost would be prohibitively expensive. The permafrost in central Alaska is thawing rapidly, yet no baseline of permafrost extent or carbon release from thawing soils had been established because of the difficulty of drilling in remote areas (Wylie et al. 2008). USGS applications of airborne electromagnetic imagery tested in the Yukon Flats of central Alaska in 2010, coupled with ground-based measurements in research plots and distributed survey points of ice thickness or late-summer depth to frozen ground, allowed development of a 3-dimensional picture of permafrost structure across a portion of the Yukon River valley and surrounding hillslopes (Minsley et al. 2012). Research plots nested within regional surveys of soil chemistry, forest condition, and carbon flux provided the multi-scale, interdisciplinary datasets to test and verify new hydrologic, fire recovery, and ecosystem models for central Alaska (Wylie et al. 2008; Walvrood et al. 2012). Scientists are now applying the methods developed in the Yukon Flats to other parts of central Alaska and the lower 48 states (Wylie et al. 2008; Rigge et al. 2013). This example and many others represent important progress in the methods of assessing ecosystem condition across space and time, methods that will require much more development and application in the coming years for a Framework strategy to be successful.

4.3 Establishing an Observing System for Decision Support

With the need for climate adaptation now generally accepted by the resource management community, demand for environmental science investigations focused on decision support has rapidly increased. A key element of the Framework as described by Bricker and Ruggiero (1998) was to "measure the effectiveness of environmental policies."

A recent commentary in *Nature* has called for the nation to forge "network connections among rapidly changing communities of decision-makers and researchers….to foster effective adaptation to climate risks" (Bidwell et al. 2013). Their recommended goal was to establish "adaptive risk management" (ARM), by tracking and communicating the activities of multiple "bridger" organizations that are linking scientists and decision-makers through already established working relationships—the decision-support equivalent of the Framework's existing monitoring programs.

The success of such an integration of existing decision-support relationships is dependent on the scientific assessment of both background ecological conditions and the environmental response to a given management action. Adaptive management without clear information on local ecological conditions before the adaptation takes place, or that lacks research and monitoring for tracking of the complex ecosystem responses following a

management change, will be difficult to meaningfully critique or improve. Ecosystem models may be too general to address specific management issues without local verification data. Those data are often either non-existent or too fragmented to provide sufficient certainty for resource managers. Simplified decision-support models may eventually be possible for resource managers to use directly, but only if the complexities behind our simplifications are fully understood, and those models are periodically updated as changes in those complexities occur. Uncertainty in regional ecosystem models can increase substantially at small spatial scales when focused on a few pixels of landscape being managed (Woodbury 2003).

The goal of the Framework concept was to bring science to the scale "at which management and policy decisions are made," so regional and even local attempts to develop interdisciplinary, multi-scale datasets for ecosystem assessments would be used as building blocks for a strategy that can eventually expand nationally (NCTC 1997). Examples are numerous, but one is the creation of a regional air pollution policy that was based on long-term coordinated research and monitoring at a Tier 1 station in the Loch Vale watershed in Rocky Mountain National Park. Here, integrated interdisciplinary research provided the scientific foundation to set limits on pollution from nitrogen deposition along the Colorado Front Range, a highly urbanized and agricultural region east of Loch Vale (State of Colorado 2013). The resource management goals identified in the Nitrogen Deposition Reduction Plan are based on research of ecological responses to nitrogen deposition at Loch Vale over many years. The Loch Vale station integrated 25 years of watershed research with long-term wet deposition data from the NADP/NTN (NADP 2012; Tier 1). Combined ecological, hydrologic, and biogeochemical datasets from Loch Vale were also compared with datasets from other research watersheds (Tier 1-B; University of Colorado 2013; USGS 2010), wet deposition from other NADP/NTN sites (Tier 1-B), the USEPA Western Lake Survey (Tier 2; Eilers et al. 1987), remotely sensed data on regional physiography and ecology (Tier 3; Baron et al. 2011), and ecosystem models (Baron et al. 1998). This integration of data across all tiers of the Framework provided policy makers the information needed to justify changes in regional nitrogen emissions regulations.

4.4 Integrating the Integration Efforts

As discussed, there have been several examples of important experiments in integrated observing since the CENR Framework was proposed. Multiple data management, data collection, and decision-support systems are developing through short-term projects or regional network clusters. National repositories for data are beginning to be used by researchers to consolidate disparate datasets. These efforts are important first steps in developing interdisciplinary, multi-scale datasets for tracking ecosystem health. Challenges remain to bring these smaller scale integration efforts together into the type of broader framework Bricker and Ruggiero described in 1998. The risk of replacing the discipline- or program-specific "stovepipes" of data from the past with multiple stovepipes of interdisciplinary data clusters representing a few programs or scientific disciplines is a new challenge for the scientific community to address. Coalescing environmental data collection around broad science issues that require data from multiple sources, and institutionalizing the capacity to easily share data on core measurements across those sources through a structured approach like the Framework, would be valuable next steps.

In 2008, the Department of the Interior initiated an example of institutionalizing a department-wide integrated strategy for delivering science-based decision-making on Federal lands (Salazar 2009). The design consisted of 8 regional Climate Science Centers

(CSCs) for research, 22 Landscape Conservation Cooperatives (LCCs) for delivering that science in a form useable by resource managers, and an enterprise data management and integrated observation network for making the environmental science datasets and monitoring capabilities of the DOI Bureaus interoperable and accessible to scientists and resource managers (DOI 2013; USFWS 2013). The first 2 components of this design (the CSCs and the LCCs) have been initiated and have enhanced both effort and interest in building science-based decision-support tools among Federal, State, Tribal, NGO, and local partners for coping with climate change effects on wildlife and their habitats. Shared data management systems are also being tested by the DOI Bureaus. Strategies for establishing interoperability of DOI observing networks and databases are still under development, but the overall design is one of the more conceptually complete attempts at integrated research, monitoring, and decision support within a Federal Department to date.

5 A Vision in Progress

Owen Bricker was not able to observe a national implementation of the vision he and Michael Ruggiero described in their 1998 paper. Big visions take time, and often fail without the kind of leadership they provided during the ambitious days of the Framework's inception. The need for an integrating framework as a strategy to address the complex environmental issues faced by our next generation remains clear. The trial and error (and successes) of the various attempts at developing integrated science since 1998 have highlighted the importance of foundational elements that are required for its success—core measurements, data interoperability, linked research and monitoring, and discerning natural from human-caused changes. The pilot exercises of the past 15 years have not rendered the original vision outdated, but rather allowed the vision to evolve toward a practical strategy.

A common science framework that enables collaboration among research and monitoring programs, and across scientific disciplines, may seem out of reach at this time. However, in periods of declining science budgets, a common strategy for integrating the multiple research and monitoring programs could also provide the best argument for why resources devoted to specific environmental research or monitoring programs are being wisely spent and should continue. Our scattered, competitive system of science support can be a blessing in the way it locates and accelerates cutting-edge discoveries, but it can also be a curse when it discourages data sharing and long-term commitments to data collection. Those long-term records, if effectively integrated across space, time, and ecosystem components, and linked to research and decision support as 3 pieces of one common enterprise, are the foundation for future understanding of environmental change, and in combination are critical tools for the detection of undesired changes early enough to allow successful adaptive management.

Fifteen years after the Bricker and Ruggiero (1998) paper challenged us with a new paradigm for bringing sound science to environmental management decisions, the scientific community can take pride in the progress that has been made while also taking stock of the challenges ahead for completing the Framework vision. Our ability to solve the Nation's toughest environmental issues is now dependent on integrated, multi-scale, interdisciplinary science translated into new resource management practices and science-based policy. Meeting that challenge may take a renewed commitment to the vision that Owen Bricker and Michael Ruggiero described in their 1998 paper, and an expanded level of collaboration among our research, monitoring, and resource management institutions.

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