COMMENTARY:

OCEAN ACIDIFICATION AS A PROBLEM IN SYSTEMS THINKING

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The emerging problem of ocean acidification provides a clear signal that we need to think and act differently about our stewardship of the ocean, its resources, and the services it provides to society. No longer can we afford to address environmental problems in the ocean on a reductionist, case-by-case basis, because the number of problems requiring attention has grown so large that the problems now are stacked one on top of another. Moreover, many of these problems are growing rapidly; for example, the contemporary rate of ocean acidification exceeds that at any time in the past 300 million years. Nor are these environmental problems independent of each other: the problems interact via synergies and feedbacks that can amplify or dampen the problems' effects on ocean systems. Uncertainties abound in terms of rates, interactions, and outcomes, and are magnified by the number of variables changing in concert. Clearly, we need to embrace holistic thinking about resource management in the ocean in order to sustain the properties and functions we derive from it.

Systems science offers one means of thinking holistically about ocean systems and its inherent complexity, interconnectedness, and dynamism. Indeed, the existing concept of marine ecosystems is based in systems science, as is the concept of marine social-ecological systems, and systems thinking underlies much of contemporary ocean science. Systems thinking is especially appropriate to the problem of ocean acidification because of its dynamic nature, association

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with other stressors, and cross-scale interactions. Unlike some environmental problems in which the causative drivers are local, ocean acidification is caused by global processes that are expressed regionally and that can be exacerbated at local scales.

Our challenge now is to bring systems-based approaches into the governance of ocean resources, and to do so in ways that do not sharply increase the risk of failure during transition to new management regimes. In other words, we need to turn the ship slowly and carefully, but not so slowly that we cannot avoid obstacles in our path. One way to do this is to begin by using existing management tools in new ways to confront complex environmental problems in the ocean. Such an approach can help us smooth transitions to new management regimes that we will be required to invent and adopt over the longer term.

Here we offer three examples of existing management tools that can be deployed *now* to address ocean acidification as part of a larger dynamic system exposed to rapid environmental change. None is fully sufficient to address the problem, nor will this suite of management responses be sufficient to address long-term change in the ocean. Instead, these three examples illustrate ways of slowly turning the ship towards more holistic, systems-based thinking that can support multiple management objectives despite persistent uncertainties.

1. Fisheries managers are beginning to use ecosystem approaches

In the U.S., fisheries managers are turning towards ecosystem approaches to management as a means of protecting and restoring living marine resources and the ecosystems that support them. For example, the Pacific Fishery Management Council in 2013 adopted the Fishery Ecosystem Plan as a means of moving ecosystem science into planning and policies.[1] The Fisheries Ecosystem Plan exists as an informational framework intended to help address uncertainties that stem from natural and anthropogenic changes in the California Current Large Marine Ecosystem. NOAA's

1. PAC. FISHERY MGMT. COUNCIL, REVIEW OF 2013 OCEAN SALMON FISHERIES: STOCK ASSESSMENT AND FISHERY EVALUATION DOCUMENT FOR THE PACIFIC COAST SALMON FISHERY MANAGEMENT PLAN (2013).

Integrated Ecosystem Assessment contributes to the framework by providing scientific support for ecosystem approaches through the development of tools for assessment.[2] The assessments go beyond natural science to include social and economic attributes. Importantly, the Fishery Ecosystem Plan and the Integrated Ecosystem Assessment both are conceived broadly enough to accommodate and address changes induced by ocean acidification and associated environmental stressors, signaling a fundamental shift towards systems thinking.

2. *The Coastal Zone Management Act can address effects that span terrestrial, nearshore, and estuarine areas*

Coastal management in the U.S. is implemented under the Coastal Zone Management Act to address growth and attendant threats to coastal areas.[3] Shaped by specific needs and opportunities in each state, coastal management offers means of addressing linkages between terrestrial and nearshore areas that can intensify or ameliorate the effects of ocean acidification. For instance, managing local nutrient inputs to the coastal ocean from land-based activities has the potential to reduce eutrophication. Such action has direct benefits on water quality that can indirectly ameliorate local acidification by reducing the amount of carbon dioxide entering the system through respiration.

The Coastal Zone Management Act also established the National Estuarine Research Reserve Program.[4] Estuaries are of growing interest in the context of ocean acidification due to their potential to sequester carbon. Preserving the potential to assimilate carbon via aquatic vegetation, sequester that carbon in sediments, and protect the carbon thus stored is a co-benefit of the establishment of the National Estuarine Research Reserves, as is the opportunity to use these reserves for new research on the management of carbon in the coastal zone.

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2. *See Integrated Ecosystem Management*, NOAA, http://www.noaa.gov/iea/ (last visited May 22, 2016).

3. 16 U.S.C. § 1452 (2012).

4. *Id.* § 1461.

3. Marine reserves offer potential to address direct and indirect effects on marine resources

> Marine protected areas and marine reserves are used as tools to preserve biodiversity and to protect living marine resources. Designed to manage the *direct* effects of human activities [e.g., fishing, seabed disturbance], such approaches could also prove useful in addressing the *indirect* effects of human activities such as those imposed by ocean acidification. Two potential benefits of marine protected areas in this regard are 1) protecting species highly vulnerable to ocean acidification by preserving the embedding ecosystems and associated functions; and 2) protecting species that are tolerant of ocean acidification in order to preserve evolutionary scope for adaptation.

The use of existing marine protected areas and reserves to address ocean acidification reaches well beyond the goals of the establishment of marine protected areas. Consequently, management goals and evaluation metrics for existing reserves may need to be tuned to prioritize the preservation of ecosystem processes and functions over the preservation of species. The establishment of new reserves might prioritize process- and function-based attributes and metrics from the very start. Moreover, marine protected areas and reserves can be used as learning tools for innovation in management as we enter an era of rapid change without analog in human history.

Systems-oriented approaches are information-intensive, requiring information on dynamics, interactions, and feedbacks across nested scales of time and space. Strategic environmental monitoring can provide much of the information required. To be effective, monitoring must be explicitly tied to well-defined information needs and must span the temporal and spatial range of dynamic interactions that are relevant to management.

For example, marine ecosystems, which vary from protected shallow bays to the coastal ocean shelf, are shaped by a wide range of natural and human-influenced dynamics, such as powerful upwelling, warming temperatures, and nutrient runoff, among others. These dynamics in turn influence how the stressors of ocean acidification and hypoxia are manifest across diverse environments. The range and effectiveness of management solutions available to address ocean acidification, hypoxia, and other stressors are proportional to our understanding of changing ocean conditions, ecological vulnerability and resilience to these changes, and the strength and direction of feedbacks. Strategic monitoring that allows for enhanced spatial and temporal coverage, projection of future conditions, and testing of management solutions is essential to acquiring the information needed to guide priorities, innovations, and actions now and in the future.

The West Coast Ocean Acidification and Hypoxia Science Panel outlined four attributes of a monitoring network that can efficiently provide such information[5]. Such a network will support the needs of decision-makers, measure an appropriate suite of physical, chemical and biological variables, build on and enhance existing monitoring efforts, and develop and sustain intellectual capacity.[6] Trans-disciplinary communication and collaboration are vital to the efficacy of such a network, as are sustained support and strategic adaptation.

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5. JAN NEWTON ET AL., OCEAN ACIDIFICATION AND HYPOXIA MONITORING NETWORK: TRACKING THE IMPACTS OF CHANGING OCEAN CHEMISTRY TO INFORM DECISIONS 2 (2016).

6. *Id.*