ROGER REVELLE COMMEMORATIVE LECTURE - MARCH 2ND, 2010

THE INTERCONNECTED BIOSPHERE

SCIENCE AT THE OCEAN'S TIPPING POINTS

FEATURED SPEAKER - DR. JANE LUBCHENCO
UNDERSECRETARY OF COMMERCE FOR OCEANS AND ATMOSPHERE AND NOAA ADMINSTRATOR

INTRODUCTION BY SENATOR JOHN KERRY

PRESENTED BY THE OCEAN STUDIES BOARD NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

The National Academy of Sciences is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Ralph J. Cicerone is president of the National Academy of Sciences.

The National Academy of Engineering was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. Charles M. Vest is president of the National Academy of Engineering.

The Institute of Medicine was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institute of Medicine.

The National Research Council was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Ralph J. Cicerone and Dr. Charles M. Vest are chair and vice chair, respectively, of the National Research Council.

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DR. JANE LUBCHENCO, a marine ecologist and environmental scientist, is the ninth Administrator of NOAA. Her scientific expertise includes oceans, climate change, and interactions between the environment and human well-being. Raised in Denver, she received a B.A. degree in biology from Colorado College, an M.S. in zoology from the University of Washington, and a Ph.D. in ecology from Harvard University. While teaching at Harvard (1975–1977) and Oregon State University (1977–2009), she was actively engaged in discovery, synthesis, communication, and application of scientific knowledge.

Dr. Lubchenco has studied marine ecosystems around the world and championed the importance of science and its relevance to policy making and human well-being. A former president of the American Association for the Advancement of Science (AAAS), the International Council for Science, and the Ecological Society of America, she served 10 years on the National Science Board (Board of Directors for the National Science Foundation). From 1999–2009, she led the Partnership for Interdisciplinary Studies of Coastal Oceans (PISCO), a large four-university, interdisciplinary team of scientists investigating the large marine ecosystem along the coasts of Washington, Oregon, and California. She has a special interest in Arctic ecosystems, with recent work in Svalbard, Greenland, and the Alaskan Arctic.

Dr. Lubchenco has provided scientific input to multiple U.S. Administrations and Congress on climate, fisheries, marine ecosystems, and biodiversity. Dr. Lubchenco served on the National Academy of Sciences' study on *Policy Implications of Greenhouse Warming: Mitigation, Adaptation, and the Science Base*, providing advice to the George H.W. Bush Administration and Congress. In 1997, she briefed President Clinton, Vice President Gore, and members of Congress on climate change.

Her scientific contributions are widely recognized. Eight of her publications are "Science Citation Classics"; she is one of the most highly cited ecologists in the world. Dr. Lubchenco is an elected member of the National Academy of Sciences, the American Academy of Arts and Sciences, the American Philosophical Society,

and the Royal Society. She has received numerous awards, including a MacArthur ("Genius Award") Fellowship, nine honorary degrees, the 2002 Heinz Award in the Environment, the 2005 AAAS Award for Public Understanding of Science and Technology, and the 2008 Zayed International Prize for the Environment.

Dr. Lubchenco co-founded three organizations that communicate scientific knowledge to the public, policy makers, the media and industry: (1) The Leopold Leadership Program (teaches environmental scientists to be effective communicators); (2) COMPASS (the Communication Partnership for Science and the Sea, communicates marine sciences); and (3) Climate Central (a non-advocacy source of understandable scientific information about climate science and solutions). She co-chaired the Synthesis for Business and Industry of the Millennium Ecosystem Assessment, an international scientific evaluation of the consequences of environmental changes to human well-being. She also served on the Pew Oceans Commission, the Joint Oceans Commission Initiative, and the Aspen Institute Arctic Commission.

JOHN KERRY is the senior United States Senator from the Commonwealth of Massachusetts. Upon graduating from Yale, he served two tours of duty in Vietnam, earning a Silver Star, a Bronze Star with Combat V, and three Purple Hearts. After graduating from Boston College Law School, John Kerry went to work as a top prosecutor in Middlesex County, Massachusetts. He was elected Lieutenant Governor in 1982. Two years later, he was elected to the United States Senate and has won reelection four times since. In 2004, he was the Democratic Party's Nominee for President, and today, he serves as Chairman of the Senate Foreign Relations Committee.

DEAR LECTURE PARTICIPANT: On behalf of the Ocean Studies Board of the National Academies, we would like to welcome you to the Eleventh Annual Roger Revelle Commemorative Lecture. This lecture was created by the Ocean Studies Board in honor of Dr. Roger Revelle to highlight the important links between the ocean sciences and public policy.

ROGER REVELLE

For almost half a century, Roger Revelle was a leader in the field of oceanography. Revelle trained as a geologist at Pomona College and the University of California, Berkeley. In 1936, he received his Ph.D. in oceanography from the Scripps Institution of Oceanography. As a young naval officer, he helped persuade the Navy to create the Office of Naval Research (ONR) to support basic research in oceanography and was the first head of ONR's geophysics branch. Revelle served for 12 years as the Director of Scripps (1950–1961, 1963–1964), where he built up a fleet of research ships and initiated a decade of expeditions to the deep Pacific that challenged existing geological theory.

Revelle's early work on the carbon cycle suggested that the sea could not absorb all the carbon dioxide released from burning fossil fuels. He organized the first continual measurement of atmospheric carbon dioxide, an effort led by Charles Keeling, resulting in a long-term record that has been essential to current research on global climate change. With Hans Suess, he published the seminal paper demonstrating the connection between increasing atmospheric carbon dioxide and burning of fossil fuels. Revelle kept the issue of increasing carbon dioxide levels before the public and spearheaded efforts to investigate the mechanisms and consequences of climate change.

Revelle left Scripps for critical posts as Science Advisor to the Department of the Interior (1961–1963) and as the first Director of the Center for Population Studies at Harvard (1964–1976). Revelle applied his knowledge of geophysics, ocean resources, and population dynamics to the world's most vexing problems: poverty, malnutrition, security, and education.

In 1957, Revelle became a member of the National Academy of Sciences to which he devoted many hours of volunteer service. He served as a member of the Ocean Studies Board, the Board on Atmospheric Sciences and Climate, and many committees. He also chaired a number of influential Academy studies on subjects ranging from the environmental effects of radiation to understanding sea-level change.

SMITHSONIAN'S NATIONAL MUSEUM OF NATURAL HISTORY

The Ocean Studies Board is pleased to have the opportunity to present the Revelle Lecture in cooperation with the Smithsonian National Museum of Natural History through our partnership with the National Science Resources Center. The museum maintains and preserves the world's most extensive collection of natural history specimens and human artifacts and supports scientific research, educational programs, and exhibitions. The museum is part of the Smithsonian Institution, the world's largest museum and research complex. Dr. Christian Samper is the director.

OCEAN SCIENCE INITIATIVE

The National Museum of Natural History is building upon its substantial foundation in marine science to establish a comprehensive Ocean Science Initiative that will:

• Engage, educate, and inspire the public through state-of the-art displays in the Museum's exciting and ambitious Ocean Hall,

• Extend access to the exhibition, collections, and research through the integrated and dynamic Ocean Web Portal, and

• Expand understanding of our oceans through the scholarly, multi-disciplinary Center for Ocean Science.

JANE LUBCHENCO, PH.D.

Dr. Jane Lubchenco, a marine ecologist and environmental scientist, is the ninth Administrator of NOAA. She became a member of the National Academy of Sciences in 1996, and her scientific expertise includes oceans, climate change, and interactions between the environment and human well-being. Throughout her career, she has championed the importance of science and its relevance to policy making and human well-being in concert with her studies of marine ecosystems around the world. Tonight, she will discuss how advances in social and natural sciences provide hope for new approaches to restore the bounty and resilience of the ocean ecosystems that provide life support systems for Earth.

SPONSORSHIP

The Ocean Studies Board thanks the Consortium for Ocean Leadership, the David and Lucile Packard Foundation, Friends of NOAA, the Joint Ocean Commission Initiative, the Lamont-Doherty Earth Observatory, the National Oceanic and Atmospheric Administration, the National Research Council, the National Science Foundation, the National Science Resources Center, the Office of Naval Research, Oregon State University, the Smithsonian Institution, the U.S. Geological Survey, the University of Delaware, and the University of Maryland Center for Environmental Science. This lecture series would not be possible without their generous support.

We hope you enjoy tonight's event.

Donald F. Boesch,
CHAIR, OCEAN STUDIES BOARD

Susan Roberts,
DIRECTOR, OCEAN STUDIES BOARD

THE INTERCONNECTED BIOSPHERE: SCIENCE AT THE OCEAN'S TIPPING POINTS

JANE LUBCHENCO AND LAURA PETES

INTRODUCTION Numerous studies have documented the depletion and disruption of ocean ecosystems at local to global scales; the consequences of these changes to human well-being; and the need for new attitudes, policies, and practices to recover and sustain healthy ocean ecosystems and the variety of human activities that depend upon them (Pew Oceans Commission, 2003; U.S. Commission on Ocean Policy, 2004; Millennium Ecosystem Assessment, 2005; United Nations Environmental Programme, 2006). Depleted fisheries; endangered turtles and marine mammals; dead zones; bleached corals; and outbreaks of jellyfish, harmful algal blooms, and diseases are all symptoms of the population and ecosystem changes occurring. These changes have resulted from a myriad of stressors, including overfishing, chemical and nutrient pollution, destructive fishing gear, climate change, habitat loss, and introduction of invasive species. The threat of additional disruption from climate change and ocean acidification looms large.

Many ocean ecosystems appear to be at a critical juncture. Actions taken now and in the coming decade will likely determine the future health of most, if not all, ocean and coastal ecosystems. In turn, the state of those ecosystems will affect economic and social well-being. Existing scientific knowledge is not being incorporated rapidly enough into public understanding or into management and policy decisions. This essay seeks to focus on some recent advances in social and natural sciences that are relevant to a transition toward more sustainable practices and policies. Some of the advances are beginning to be implemented but need to be scaled up; others have yet to be employed or translated into usable tools. New knowledge in high-priority areas is also needed.

The purpose of this paper is to catalyze interest in using scientific knowledge to maximize the likelihood of achieving healthy, productive, and resilient ecosystems and enabling a vibrant suite of sustainable human uses of oceans and coasts. In the following pages, we (1) highlight new scientific understanding in the broad areas of ecosystem services, coupled natural and social systems, and resilience; (2) focus on a few promising tools and approaches to address the challenges ahead; and (3) describe areas for further work.

ECOSYSTEM SERVICES LINK HUMAN AND NATURAL SYSTEMS

Managed and unmanaged ecosystems provide the life-support systems for people and all life on Earth (Daily et al., 2000). Physical, chemical, and biological perturbations of the oceans, land, and atmosphere—especially over the last few decades—have significantly altered the functioning of ecosystems and thus the delivery of their life-supporting services (Vitousek et al., 1997; Lubchenco, 1998; National Research Council, 1999; Millennium Ecosystem Assessment, 2005; United Nations Environmental Programme, 2006). The Millennium Ecosystem Assessment (2005) documents the interdependence of human and natural systems, the global loss of ecosystem services, and the options for reversing the trends. In short, human well-being depends upon services provided by ecosystems, but human activities have so utterly transformed ecosystems and altered their functioning that 60% of ecosystem services are currently at risk (Millennium Ecosystem Assessment, 2005; United Nations Environmental Programme, 2006). However, viable options exist for recovering and sustaining delivery of services.

Ecosystem services are the benefits provided by ecosystems; they result from the interactions among plants, animals, and microbes with one another and with the environment. Services vary according to the type of ecosystem (e.g., coral reef, mangrove, kelp forest, open ocean). Each ecosystem provides multiple types of services: provisioning services (PS), such as seafood; regulating services (RS), such as coastal protection or climate regulation; cultural services (CS), such as recreation; and supporting services (SS), such as nutrient cycling and primary production (Millennium Ecosystem Assessment, 2005; Table 1). For example, a mangrove ecosystem provides wood fiber, fuel, and nursery habitat for numerous species (PS); it detoxifies and sequesters pollutants, stores carbon, traps sediment, and protects shores from tsunamis or storms (RS); it provides beautiful places to fish or snorkel (CS); and it recycles nutrients (SS) (Figure 1). Although people will readily articulate some of the benefits they derive from oceans (Table 2), they often miss the key point that most of those benefits depend on healthy oceans or that those ecosystems are already degraded or threatened.

Ecosystem functioning and the delivery of services are affected by changes in biodiversity, habitat fragmentation and conversion, climate change, and alterations to biogeochemical cycles. When an ecosystem is converted to another use, some services may be lost and others gained. For example, when mangroves are converted to shrimp ponds, agricultural lands, or residential areas, the natural services are lost, but food production or housing services are obtained (Figure 1). Similarly, when river direction and flow are modified to obtain navigation and flood-control services, the replenishment of coastal wetlands and barrier islands is diminished, resulting in loss of habitat and protection from storms. Typically, conversion or other alterations happen without consideration of the trade-offs. In addition, the importance of a service is often not appreciated until it is lost. Post Hurricane Katrina, residents of New Orleans speak openly about the importance of barrier islands and coastal wetlands in acting as "speed bumps" for storms. In the 2004 Indian Ocean tsunami, areas of India with intact mangroves suffered fewer losses of human lives and property than did areas where mangroves had been cleared, demonstrating the importance of the buffering capacity provided by these plants (Kathiresan and Rajendran, 2005). Likewise, the global loss of species from large marine ecosystems has led to a reduction in the ocean's capacity to provide food, improve water quality, and recover from disturbance (Worm et al., 2006).

FIGURE 1. TRADE-OFFS IN ECOSYSTEM SERVICES PROVIDED BY INTACT MANGROVES VERSUS MANGROVES CONVERTED TO OTHER USES (photos used with permission from the National Oceanic and Atmospheric Administration). Ecosystem services provided by intact mangrove forests include nursery and adult habitat, sediment trapping, pollutant detoxification, and coastal protection from erosion and storm surge. If mangroves are converted to shrimp ponds for aquaculture, coastal farms, or land for housing, new services are gained (e.g., food, housing), and the other services are lost.

Clearly, translating general scientific knowledge about the importance of ecosystem services into useful guidance and tools for decision makers is a high-priority challenge. Educating citizens and decision makers about the importance of services is necessary, but it is not sufficient without tools and information to translate that knowledge into practices and policies. Understanding, assessing, and measuring ecosystem services can be difficult (Carpenter and Folke, 2006). Moreover, most of the research conducted on ecosystem services has been in terrestrial systems. In addition, ecosystem services need to be explicitly linked to socioecological scenarios to demonstrate how ecosystems benefit humans (Tallis and Kareiva, 2006).

TABLE 1
ECOSYSTEM SERVICES PROVIDED BY OCEANS

Provisioning	Seafood, habitat, fuel wood, genetic resources
Regulating	Climate regulation, disease and pest regulation, coastal protection, detoxification, sediment trapping
Supporting	Nutrient cycling, primary production
Cultural	Aesthetic, spiritual, educational, recreational

The utility of understanding and communicating trade-offs was demonstrated in the Catskill Mountains, where changes in watershed management to improve water quality for New York City were based on knowledge of the value provided by ecosystem services. In 1996, when drinking water quality fell below Environmental Protection Agency standards due to degradation of the watershed, the City of New York faced the dilemma of whether to invest in Catskill watershed ecosystem restoration ($1–1.5 billion) or a water filtration plant ($6–8 billion; Chichilnisky and Heal, 1998). The decision to invest in "natural capital" (in the form of ecosystem restoration) saved money and restored both the ecosystem services of interest (water purification and filtration) as well as other services, such as carbon storage and opportunities for recreation, none of which would have been obtained through building a new filtration plant (Heal et al., 2001).

There are several emerging scientific efforts to enhance our understanding of the benefits that humans obtain from ecosystems. The challenge of determining, measuring, and communicating the values of ecosystem services is being addressed by the Natural Capital Project (http://www.naturalcapitalproject.org), a partnership between Stanford University, The Nature Conservancy, and the World Wildlife Fund to develop tools for facilitating incorporation of natural capital (i.e., valuation of ecosystem services) into decision making. Their first tool, InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs), can model and map the delivery, distribution, and economic value of ecosystem services into the future. The tool allows users to visualize the impacts of their potential decisions, which enables identification of trade-offs between environmental, economic, and social benefits. This tool has already been applied successfully using stakeholder-defined scenarios to predict changes in land use and associated trade-offs in the Willamette Valley, Oregon (Nelson et al., 2009). While InVEST was initially focused on terrestrial ecosystems, it is now being applied to coastal and marine ecosystems to provide maps and projections of ecosystem services under different management alternatives for issues, such as trade-offs associated with large-scale implementation of desalination plants in California (Ruckelshaus and Guerry, 2009). This tool offers a promising new approach for incorporating scientific information about ecosystem services into decision making and resource management.

Effective valuation of ecosystem services requires acknowledging that global social change and global environmental change interact with one another (Young et al., 2006). When facing decisions that affect ecosystem services, trade-offs between social values and environmental outcomes can either be win–win, win–lose, or lose–lose, and the challenge is to develop solutions that are "win–win," where both social and environmental goals are achieved (Tallis et al., 2008). Increased emphasis should be placed on incorporation of social data and projections of social distributional effects into ecosystem services valuation in order to determine and maximize "win–win" outcomes (Tallis and Polasky, 2009). One major obstacle to ecosystem services valuation is that detailed information on how people benefit from specific services at scales useful for decision making is currently sparse (Turner and Daily, 2008). In addition, because ecosystem services valuation is a relatively new field of science, there are few examples of "lessons learned" to be able to communicate. Databases are a useful tool for providing centralized, publicly-accessible sources of information. The Natural Capital Database (http://www.naturalcapitalproject.org/database.html), currently under development, will be a compilation of strategies and outcomes from conservation projects that have focused on ecosystem services. This information clearinghouse will allow decision makers and managers to learn lessons from previous efforts that they may be able to apply to their planning processes.

TABLE 2
OCEAN AND COASTAL ECOSYSTEM SERVICES IN LAY LANGUAGE

Healthy seafood
Clean beaches
Abundant wildlife
Clean energy
Good jobs
Stable fisheries
Vibrant coastal communities

UNDERSTANDING COUPLED SOCIAL–NATURAL SYSTEMS AS COMPLEX ADAPTIVE SYSTEMS

Until recently, studies of social systems and of natural systems proceeded independently of one another. Novel interdisciplinary approaches have recently emerged to study coupled human and natural systems (Liu et al., 2007). These efforts seek to understand the interconnectedness of people and ecosystems; the bases of decision making; and perceptions of risk, equity, and scale (Ostrom et al., 1999; Dasgupta et al., 2000; Dietz et al., 2003; Kinzig et al., 2003). Interdisciplinary approaches will enable the changes in practices and policies needed to use ecosystems sustainably and to facilitate human well-being.

Insights from other scientific areas are also informing the understanding of coupled human and natural systems, specifically the study of complex adaptive systems. These systems are defined by the fact that dynamics of interactions at small scales affect macroscopic system dynamics, which then feed back to impact the small scales (Levin, 1998). Across numerous types of complex adaptive systems, the same key features appear necessary for that system to be resilient (i.e., to have the capacity to absorb stresses and continue functioning [Levin and Lubchenco,

2008]). The common elements necessary for resilience include modular structure, redundancy of modules, diversity and heterogeneity of modules, and tight feedback loops (Levin, 1999). Trade-offs exist between elements, and therefore optimum resilience may be obtained at intermediate levels of all of these components (Levin, 1999). Evidence also suggests that ecosystems with higher diversity are more resilient (Millennium Ecosystem Assessment, 2005). This has been documented for areas that are recovering from species loss; as diversity increases, valuable ecosystem services are restored, leading to higher resilience (Worm et al., 2006). The Resilience Alliance (http://www.resalliance.org) is an interdisciplinary research group created to explore the dynamics of socioecological systems to provide a foundation for sustainability. This effort acknowledges that the study of ecosystem resilience is complex, requiring interdisciplinary tools, creative approaches (e.g., network analyses; Janssen et al., 2006), and collaborations (Walker and Salt, 2006; Carpenter et al., 2009).

Incorporating social sciences into decision making and adaptive management is an arena where significant new advances have begun. The 2009 Nobel Prize in Economics to Elinor Ostrom explicitly recognizes the importance of interdisciplinary approaches, the key role that institutions play, and the multiple scales of decision making relevant to managing common-pool resources. Organization of human institutions can have a large impact on ecosystem resilience; therefore, participatory processes that facilitate experimentation, learning, and change will benefit planning efforts (Dietz et al., 2003). Because changes in environmental and social conditions are occurring, institutions must also be prepared to change, a core tenet of adaptive management (Dietz et al., 2003). This raises the need to design strategies and institutions for integrating incomplete knowledge with experimental action into programs of adaptive management and social learning (National Research Council, 1999). In addition, it is important to understand what scientific information best meets the needs of decision makers and managers attempting to prepare for and respond to environmental change. Information users must be able to articulate their needs to the scientific community, who can in turn provide them with information that fits the scales and topics necessary for decision making. These interactions will require the creation of new relationships, institutions, and channels of communication, which social science research can help to inform. Studies on strategies for successful communication of complex scientific issues and uncertainty will also benefit these ongoing dialogues. A better understanding of social, cultural, and economic barriers to adaptive action and management are needed. Identifying barriers and designing strategies to eliminate them when possible will allow for action at all scales of governance.

TABLE 3
A SHIFT IN APPROACHES TO MANAGEMENT IS UNDERWAY FOR COASTAL AND MARINE ECOSYSTEMS

HISTORICAL APPROACH

Short-term perspective
Single-sector focus
Natural science approach
Single-species management
Management focused on commodities
Greater use of fines
Regulation of fishing effort
Command and control, centralized, top-down regulation
Focus on delivery of products

NEW APPROACH

Long-term and evolutionary perspectives
Multi-sector focus
Coupled natural and social science approach
Ecosystem-based management
Management focused on ecosystem functioning and ecosystem services
Greater use of incentives
Regulation of outcome
Top-down plus bottom-up decision making; more local control.
Focus on resilience of system

EMERGING APPROACHES AND TOOLS TO ENHANCE ECOSYSTEM RECOVERY AND RESILIENCE

As emphasized by the Pew Oceans Commission (2003), the current problems in oceans are both a failure of understanding and a failure of governance. Most people are unaware of the current state of oceans or that the benefits they seek from oceans are at risk unless changes are made. The mindset that oceans are so vast and bountiful that they are infinitely resilient persists. Likewise, few are aware of how their individual choices affect oceans or other people. Providing credible information from trusted sources will be critical for raising awareness about the need to improve practices and policies. In other words, the scientific advances described above need to be incorporated into public understanding.

This knowledge must also be translated into new tools, guidelines, and approaches for communities, interest groups, decision makers, and resource managers. A significant shift is underway in approaches to ocean management (Table 3), creating more demand for practical guidance and tools. Some of the new tools and approaches have already been mentioned, such as the Natural Capital Project's InVEST tool and coupled social–natural approaches to decision making. Others include integrated ecosystem assessments, ecosystem-based management, marine spatial planning, catch shares, nutrient-trading schemes, biodiversity banks, marine protected areas and marine reserves, and decision-support and visualization tools. Three of these tools are described below.

MARINE SPATIAL PLANNING

Marine spatial planning (MSP) is an ecosystem-based management tool for minimizing user conflicts and impacts on ecosystem functioning. Increasing demands on ocean space for diverse uses, including tourism, recreation, fishing, shipping, national security, oil and gas exploration, and wave and wind energy, have led to more and more conflicts among users, as well as additional impacts on already stressed ocean ecosystems (Douvere, 2008). MSP is a process that enables integrated, forward-looking decision making through an ecosystem-based, spatially explicit approach (Ehler and Douvere, 2007). Spatial planning has been practiced on land for centuries, as humans have determined how to allocate specific areas for multiple uses, including forestry, conservation, development, and agriculture.

The concept of zoning in the oceans is a relatively new idea. The first comprehensive MSP was developed in the 1980s

FIGURE 2. MARINE SPATIAL PLANNING IN ACTION THROUGH THE MASSACHUSETTS OCEAN MANAGEMENT PLAN.
A. Governor Deval Patrick announces the Oceans Act of 2008 (photo used with permission from the Massachusetts Governor's Office). B., C., D. Development of the Plan involved extensive participation of stakeholders, decision makers, and managers through workshops and other forms of communication (photos used with permission from the Massachusetts Ocean Partnership).

for the Great Barrier Reef Marine Park in Australia. Specific areas are zoned for different uses, including fishing and tourism, and other areas are designated as fully protected, helping to minimize user conflicts and ecosystem impacts (Douvere, 2008). Because of the interdependency between human and natural systems, the MSP process is most successful when it involves broad participation by stakeholder groups, scientists, and managers (Pomeroy and Douvere, 2008). In addition to consideration of human uses, it is important for planners to understand the biological communities and key processes that maintain them in order to create plans that maximize ecosystem resilience (Crowder and Norse, 2008).

Efforts are currently underway to develop marine spatial plans for the United States. On December 14, 2009, President Obama's Interagency Ocean Policy Task Force released an interim framework for effective coastal and marine spatial planning. Two weeks later, the Commonwealth of Massachusetts became the first U.S. state to release a comprehensive ocean management plan for its 1,500-mile coastline (Figure 2). Other states and nations are pursuing use of this tool as a vehicle for more holistic management of ocean resources and ecosystems.

MARINE PROTECTED AREAS

Marine protected areas (MPAs) provide a complementary tool for protecting habitat, biodiversity, and ecosystem functioning. MPAs are areas of the ocean that are managed for a conservation benefit. This tool provides an ecosystem- and place-based approach to management, as opposed to a species-based approach. MPAs may be used alone or as part of an MSP framework.

Fully protected (also called "no-take") marine reserves are a type of MPA that are completely protected from all extractive and destructive activities (Lubchenco et al., 2003). Benefits of marine reserves include habitat protection; biodiversity conservation; enhancement of ecosystem services; recovery of overexploited stocks; export of individuals outside the reserve; insurance against environmental uncertainty; and sites for scientific research, education, and recreation (Allison et al., 1998). Scientific analyses of the hundreds of no-take marine reserves around the world provide compelling evidence that they do indeed protect biodiversity and habitats. Density, diversity, biomass, and size of organisms are higher inside reserves as opposed to outside (Halpern, 2003; Partnership for Interdisciplinary Studies of Coastal Oceans, 2007; Hamilton et al., in press; Figure 3). On average, these benefits are rapid (often occurring within 1–3 years) and long lasting (Halpern and Warner, 2002). However, not all species respond rapidly, and the rates at which populations change depend on life histories and the availability of colonists.

Marine reserves provide a unique mechanism for protecting large-bodied individuals of fish and invertebrates. Large females (otherwise known as big, old, fecund females [BOFFs]) have much greater reproductive potential than smaller females (Figure 4) and are understood to be especially important for sustaining populations. Protection of BOFFs may also help counter the negative evolutionary impacts of fishing that result in reproduction at smaller sizes (Baskett et al., 2005), and in some cases, the distortion of size structure and social structure for fish that are sequential hermaphrodites.

Productivity within marine reserves also leads to "spillover," the migration of animals from inside the reserve to the outside, potentially enhancing commercial and recreational fisheries surrounding the protected area or contributing to recovery of depleted fisheries (Roberts et al., 2001; Partnership for Interdisciplinary Studies of Coastal Oceans, 2007). For example, coastal areas surrounding the Merritt Island, Florida reserve exhibited a rapid increase in the number of world record-sized black drum, red drum, and spotted sea trout once the fully protected area was established (Roberts et al., 2001).

Reproduction within reserves produces young that may be transported by ocean currents outside the reserve. This "export" of larvae is more difficult to quantify than "spillover" of juveniles or adults, but both processes transport benefits from inside a reserve to the surrounding areas. A network of marine reserves, which is a set of reserves separated by non-reserve waters but connected by the movement of young, juveniles, or adults, can be designed to maximize transport of benefits to the outside. Because of spillover, export, and other benefits provided by reserves, optimal fisheries harvest occurs when some areas of a region are temporarily or permanently closed (Costello and Polasky, 2008). Planning and implementation of marine reserve networks are facilitated by access to biological and socioeconomic information. The availability of high-quality spatial information on the location of fish populations allows for spatial optimization in the implementation of marine reserve networks that lead to increased profit margins for surrounding fisheries (Costello et al., in press). For all of these reasons, no-take marine reserves and MPAs are increasingly seen as useful tools in a larger strategy to protect and restore coastal and ocean ecosystems.

CATCH SHARES

Catch shares provide an alternative to traditional fishery management by incorporating new understanding from social and economic sciences. Instead of individual commercial fishermen being incentivized by the "race to fish" to outcompete others, rights-based fisheries' reforms offer an alternative solution (Hilborn et al., 2005). In lieu of industry-wide quotas, fishermen are allocated individual quotas, referred to as "catch shares" of the total allowable catch, and the goal is to provide fishermen and communities with a secure asset in order to create stewardship incentives (Costello et al., 2008). Catch shares thus align economic and conservation incentives. They also hold fishermen accountable for adhering to the rules.

The concept of catch shares, pioneered in Australia, New Zealand, and Iceland, has now been implemented for hundreds of fisheries throughout the world. Effectiveness of catch shares

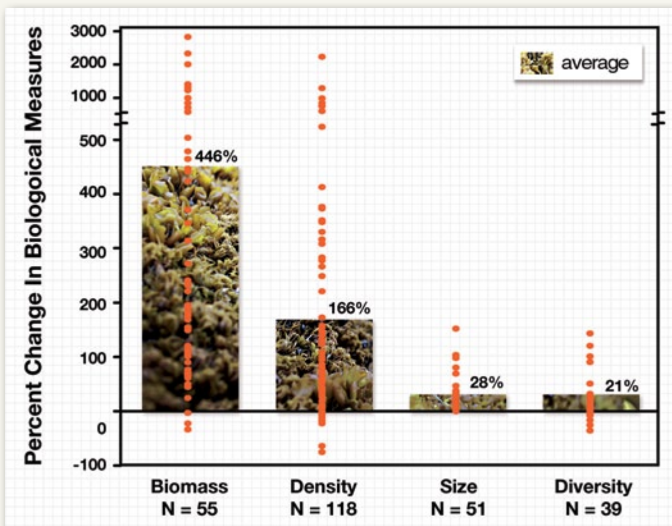

FIGURE 3. IMPACT OF NO-TAKE MARINE RESERVES ON BIOMASS, DENSITY, SIZE, AND DIVERSITY OF SPECIES INSIDE OF A RESERVE

(used with permission from the Partnership for Interdisciplinary Studies of Coastal Oceans; data from Lester et al., 2009).

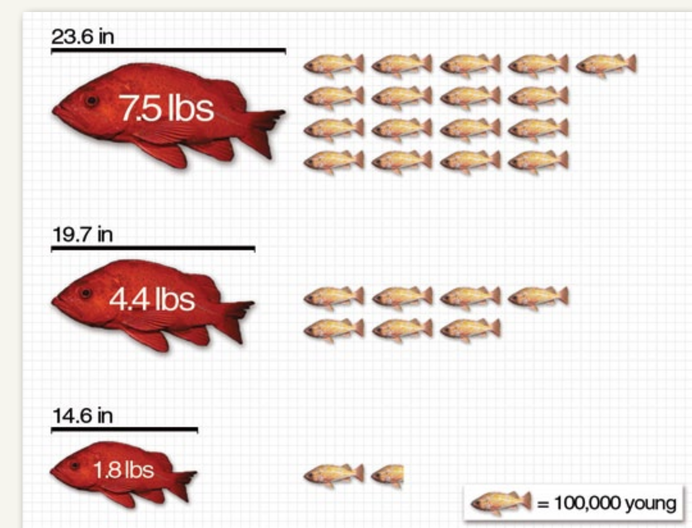

FIGURE 4. RELATIONSHIP OF NUMBER OF YOUNG PRODUCED TO BODY SIZE OF FISH FOR VERMILLION ROCKFISH.

A 23-inch vermillion rockfish produces 17 times more young than when it was 14 inches long (used with permission from the Partnership for Interdisciplinary Studies of Coastal Oceans; data from Love et al., 1990).

was documented in a global analysis of over 11,000 fisheries. Results indicated that implementation of catch shares can halt, and even reverse, trends toward widespread fishery collapse (Costello et al., 2008; Heal and Schlenker, 2008). This evidence suggests that catch shares offer a promising tool for sustainable fisheries management.

To date, 12 fisheries in the United States have adopted this management approach. The results have been impressive: sustainable fisheries, improved economic performance of the fishery, decreased environmental impact, and increased safety at sea. For example, in Alaska's halibut and sablefish fisheries, the length of the fishing season was extended from less than a week to eight months per year, bycatch dropped 80%, and safety improved sharply. In the Gulf of Mexico's red snapper fishery, commercial overfishing ended for the first time in decades, fishermen are receiving higher dockside prices for their catch and reducing costs as they are able to plan their trips better, and discards have decreased 70%. Catch shares are not necessarily suitable for every fishery, but they appear to hold promise for many.

Another tool that seems ripe for development (but which does not yet exist) is a nutrient-trading scheme to decrease the flow of excess nutrients from agricultural and livestock areas to coastal waters. Dead zones (areas of low oxygen) in coastal oceans have spread exponentially since the 1960s as a result of nutrient runoff due to changes in agricultural and land-use practices; dead zones now occur over a total area of 245,000 km^2 (Diaz and Rosenberg, 2008). Fertilizer use in the Mississippi River watershed, draining 41% of the continental United States, now leads to a severe, seasonal dead zone in the Gulf of Mexico that extends across 20,000 km^2 (Rabalais et al., 2002). One proposed approach for combating excess nitrogen input might be the establishment of cap-and-trade policy for nitrogen, where a limit would be set on nitrogen input for each region (Socolow, 1999), with regions able to trade quotas. A similar approach was used successfully by the Environmental Protection Agency under the Acid Rain Program to cap emissions of sulfur dioxide and reduce the occurrence of acid rain. The program was so effective that sulfur dioxide reductions were achieved at significantly lower costs and at much faster rates than originally estimated.

None of these tools is a panacea, but each provides useful approaches that build on existing understanding from both natural and social sciences. Maintaining the suite of ecosystem services requires protecting the functioning of ecosystems. Integrated ecosystem assessments that elucidate how the different social and natural components interact are important to provide a decision-making framework. Place-based, ecosystem-based, and adaptive management approaches are essential. New tools to facilitate understanding of and decisions about trade-offs will be key. In short, effective management of coastal and marine ecosystems will require forward-thinking, holistic, and ecosystem-based approaches that involve users, as well as managers.

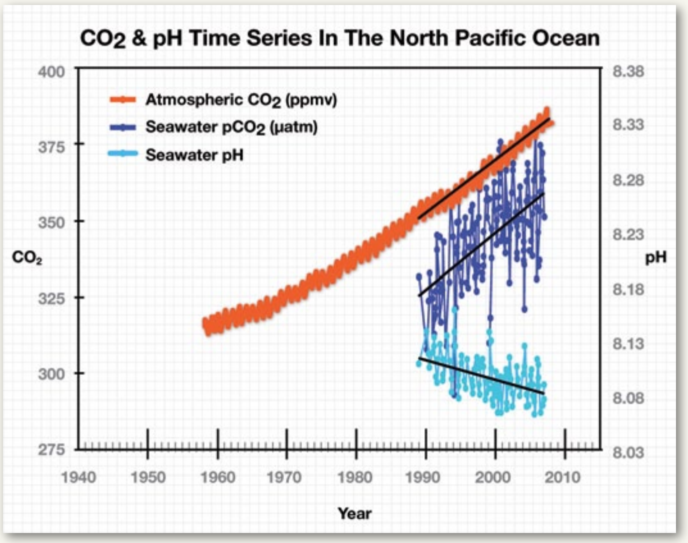

FIGURE 5. UPTAKE OF CARBON DIOXIDE BY THE OCEAN
in the North Pacific (dark blue line) tracks changes in atmospheric concentration of CO_2 (red line) and results in lower seawater pH (light blue line) (modified from Levinson and Lawrimore, 2008; data from Feely et al., 2008).

CHALLENGES AHEAD

Continuing to educate citizens and to implement and develop new tools and approaches based on the more holistic understanding described above will undoubtedly bring significant benefits. For those approaches to be maximally effective, additional information about ecosystem and human patterns and processes is needed, such as data about basic patterns of biodiversity, understanding the scales over which key ecosystem processes operate, and socioeconomic information at relevant scales. This will also require significant advances in ecosystem-based science, ecosystem services, and resilience from a coupled human–natural system perspective.

In addition, information is not always available at the relevant spatial scale for management. For example, the majority of climate change scenarios have been developed for the global scale, but most of the impacts will be felt at the local to regional scale. This mismatch of scales makes it difficult for managers to incorporate climate information into their planning processes. Similarly, effective, sustainable management of large-scale resources (e.g., large marine ecosystems) requires collaboration among national, regional, state, and local levels, which can create tension (Ostrom et al., 1999). The need to address problems at the local to regional scale associated with shared global resources is increasing. Globalization is occurring throughout many of our coupled human–natural systems, leading to increased connectedness, with both positive and negative results (Young et al., 2006). A diversity of scales is necessary for effective, resilient management; by building on local and regional institutions to focus on global problems, the likelihood of success can be increased (Ostrom et al., 1999). The focus on understanding impacts of climate change at the regional scale (United States Global Change Research Program, 2009) is leading to increased attention towards the ability of climate models to resolve regional scales.

Both climate change and ocean acidification (Figure 5) are likely to transform coastal and ocean species, ecosystems, and ecosystem services. Priority should be given to understanding the likely impacts of climate change and ocean acidification, as well as ways to ameliorate those impacts. Given the rapid pace at which ecosystems are changing, "learning by doing" becomes more difficult because past lessons no longer accurately predict the future (Ostrom et al., 1999).

Even though today's challenges are already substantial, climate change and ocean acidification will interact with and exacerbate the other drivers of change. Hence, to be relevant and useful, management and policy must focus on tomorrow's coupled human–natural systems, not today's or yesterday's. Doing so is not easy but not impossible. Likely keys to success include the following approaches:

• Avoiding irreversible changes (such as extinctions)

• Managing for resilience

• Managing with the expectation of surprises

• Preserving as much biodiversity (genetic, species, and habitat) as possible

• Developing rules of thumb for managers in lieu of precise targets

• Minimizing impacts from stressors over which there is more immediate control

• Sharing information and lessons via learning networks

Incorporating climate and ocean acidification adaptation strategies into management and policy approaches provides a useful focus to integrate a number of the above-mentioned strategies.

CONCLUDING REMARKS

Our future depends upon maintaining healthy ocean and coastal ecosystems and healthy human communities. Both are in flux. Each is coupled to the other. Ecosystem services link ecosystems to human well-being and provide a focus for understanding, policy, and management. Awareness that natural systems can undergo rapid change once a tipping point is reached lends urgency to the need for embracing novel tools and approaches, scaling up their use and creating new knowledge, information, and tools.

Global threats to our coastal and marine ecosystems are rapidly increasing. We are currently operating in a "no analogue" state, in which human activities have driven global environmental change to a point that has never before been observed (Steffen et al., 2004). Biodiversity is declining, our natural resources are being depleted, and habitats are being destroyed. Along with these changes come the losses of valuable ecosystem services on which humans depend.

In addition to rapid shifts in ecosystems, social systems can also undergo rapid change once a tipping point is reached. Knowledge that rapid societal shifts occur can provide hope that successes in some places can be quickly adopted and implemented. The plethora of new advances and effective tools; successes at many local levels; and engagement of citizens, businesses, and scientists around the world provides impetus for further engagement and hope that these efforts will succeed in transitioning to more sustainable practices and policies.

Priority actions include educating citizens and policy makers about the benefits of new approaches, strengthening interdisciplinary approaches to problem solving, reducing the stressors over which we have direct control (e.g., fisheries management, pollution, invasive species), reducing emission of greenhouse gases to slow down the rates of change in the climate and ocean acidification, protecting as much biodiversity as possible, and managing for ecosystem resilience. Holistic strategies for engaging stakeholders and for preserving or restoring ecosystem functioning and resilience are critical to success. Momentum is building, informed by scientific advances and public involvement. It's time to "seas the day."

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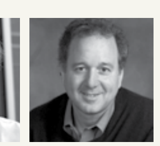
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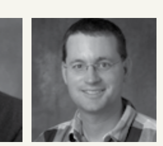
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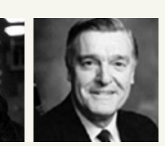
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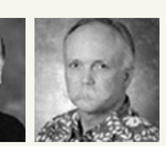
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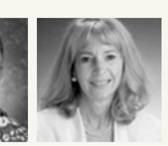
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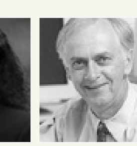
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