Envisioning a Marine Biodiversity Observation Network

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Humans depend on diverse ocean ecosystems for food, jobs, and sustained well-being, yet many stressors threaten marine life. Extensive research has demonstrated that maintaining biodiversity promotes ocean health and service provision; therefore, monitoring the status and trends of marine biodiversity is important for effective ecosystem management. However, there is no systematic sustained program for evaluating ocean biodiversity. Coordinating existing monitoring and building a proactive marine biodiversity observation network will support efficient, economical resource management and conservation and should be a high priority. A synthesis of expert opinions suggests that, to be most effective, a marine biodiversity observation network should integrate biological levels, from genes to habitats; link biodiversity observations to abiotic environmental variables; site projects to incorporate environmental forcing and biogeography; and monitor adaptively to address emerging issues. We summarize examples illustrating how to leverage existing data and infrastructure to meet these goals.

Keywords: biodiversity observation network (BON), biosecurity, climate change, ecosystem-based management, ecosystem services

Biological diversity, or *biodiversity*, can be broadly defined as the variety of life, encompassing variation at all levels, from the genes within a species to biologically created habitats within ecosystems (United Nations 1992). Humans depend on biodiversity for food, clothing, medicine, recreation, and biosecurity (MA 2005, Cardinale et al. 2012), but there are also important ethical and cultural justifications for its protection. Although the value and vulnerability of biodiversity have been increasingly recognized since the 1992 United Nations Earth Summit in Rio de Janeiro, that recognition has come more slowly for the ocean, which represents 90% of Earth's habitable volume (Hendriks et al. 2006). Yet, biodiversity is no less important in the sea than on land. The ocean's ecosystems and the associated biogeochemical processes provide humanity with food, oxygen, livelihoods, and a stable climate. These benefits are implicit in the US Interagency Ocean Policy Task Force's final recommendations to the president on 19 July 2010, in which it was declared that "[i]t is the policy of the United States to protect, maintain, and restore the health and biological diversity of ocean, coastal, and Great Lakes ecosystems and resources" (*www.whitehouse.gov/files/documents/OPTF_FinalRecs.pdf*).

A growing body of research demonstrates that maintaining biodiversity is key to the provision of ecosystem services and, more specifically, to sustaining ecosystem health and resilience in the face of growing environmental change (Worm et al. 2006, Stachowicz et al. 2007, Cardinale et al. 2012). In the same way that long-term financial health is stabilized by a diversified portfolio, ecosystem health and resilience are often enhanced by biodiversity (Schindler et al. 2010). These benefits suggest that managing systems to maintain marine biodiversity may provide a way to resolve otherwise conflicting objectives resulting from piecemeal management (Palumbi et al. 2009, Foley et al. 2010). Therefore, in addition to the direct and indirect benefits that it provides, biodiversity can be seen as a master variable for practically evaluating both the health of ecosystems and the success of management efforts. Yet, our knowledge of marine biological diversity remains fragmented, uneven in coverage, and poorly coordinated.

Why a marine biodiversity observation network, and why now?

Developing a marine biodiversity observation network (MBON) to help identify threats and to provide both an early warning and data for forecasting models should be a priority. Marine habitats and organisms are facing an unprecedented worldwide threat from climate change, pollution, overfishing, habitat destruction, and invasive species (Lotze et al. 2006, Doney and Schimel 2007, Halpern et al. 2008). In the last decade, the Pew Ocean Commission, the US Commission on Ocean Policy, and the US National Ocean Policy emphasized the increasing importance of

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addressing such threats to ocean ecosystems. The scarcity of quantitative data on biological baselines in many parts of the ocean—including the current status of organisms and ecosystems and their trends over time—undermines our ability to respond effectively to these threats. Obtaining the essential data to do so would be advanced by establishing a coordinated MBON to allow proactive responses, rather than the current reactive responses, to such threats (Andréfouët et al. 2008a). Knowledge of biodiversity will also facilitate the successful implementation of ecosystem-based management and marine spatial planning and the effective monitoring of biosecurity—that is, guarding against threats posed by the introduction of invasive species and infectious agents. An MBON could provide early warnings of invasions while eradication is still possible. For example, in 2000, divers monitoring eelgrass near San Diego, California, discovered the highly invasive seaweed *Caulerpa taxifolia*, which caused widespread ecological damage in the Mediterranean Sea (Williams and Smith 2007). Because it was detected early, *C. taxifolia* was restricted to a single cove and was successfully eradicated before it could spread. Similar proactive monitoring of plankton communities can facilitate early warning of impending harmful algal blooms (Schnetzer et al. 2007, Campbell et al. 2010). Finally, a systematic approach to monitoring biodiversity and managing information on biological baselines would benefit (and potentially draw support from) public and private sector efforts in environmental assessment by facilitating common standards and by reducing the need for expensive in-house or contracted taxonomic expertise.

The recently completed Census of Marine Life (see table 1 and supplemental table S1, available online at *http://dx.doi.org/10.1525/bio.2013.63.5.8*, for abbreviations of the monitoring efforts and agencies mentioned in the article) was an intensive, decadelong international effort to assess the state of marine biodiversity, which greatly enhanced our knowledge of ocean life and established an unprecedented collaborative network and infrastructure. Large gaps remain, however, in our knowledge of the occurrence and abundance of organisms (Webb et al. 2010). Most regions lack authoritative inventories of their marine organisms, and estimates of the global proportion of undescribed marine species range widely, from as low as 24% (Costello et al. 2012) to as high as 91% (Costello et al. 2010, Mora et al. 2011). Although the Ocean Biogeographic Information System (OBIS) holds more than 33 million records of approximately 120,000 species, about half of the approximately 250,000 known marine species have no records in the database, and two-thirds of those that do are represented by only one or two records each (Appeltans et al. 2012). The scarcity of species-level inventories compiled using standard classifications makes it impossible to reliably estimate even the percentage of species known, the variation among regions, or—perhaps most important—how living marine resources are changing over time. This uncertainty also extends to the microbes that are key players in the ocean's biogeochemical cycles (Amaral-Zettler et al. 2010). Therefore, although sobering estimates of the rate of biodiversity loss in many terrestrial habitats have been produced in recent data syntheses (Butchart et al. 2010, Barnosky et al. 2011), there are few quantitative assessments of how diversity responds to human pressures in the oceans (Hendriks et al. 2006, Sala and Knowlton 2006). Nor is there any standardized, coordinated approach to monitoring marine diversity that could produce a coherent picture of the current status and trends.

We can learn much from experiences with land-based observation networks such as the National Ecological Observatory Network (NEON), but the conceptual and practical design of an MBON involves challenges unique to operating in the sea. These include the misperception that the oceans are so vast that they can absorb all impacts and the technical limitation that remote-sensing satellites penetrate only the top few meters of the ocean. Major logistical challenges also hamper access to marine habitats and organisms. As a consequence, the level of current knowledge about marine biodiversity falls off rapidly with distance from land and from the ocean's surface (figure 1; Webb et al. 2010). Here, we outline a strategy to integrate and leverage existing efforts to scaffold a new MBON. For thematic consistency, we focus on US waters, but we expect that the main principles should translate to other countries and spatial scales.

Building an MBON: Synthesizing expert opinion

To develop a sound basis for informing policy decisions, seven US federal agencies sponsored a 3-day workshop in 2010 involving more than 40 participants. This was followed by active solicitation of commentary from the community, which included a breadth of expertise and experience, with the goal of developing design principles for an MBON (NOPP 2010). The community's input included identifying priorities for taxonomic range and resolution, target habitats, and appropriate methodologies. Below, we present the expert consensus on general features that might constitute an MBON and then suggest implementation opportunities.

There was broad agreement (NOPP 2010) that a coordinated MBON would greatly improve the numerous but scattered existing efforts, would be crucially useful for establishing status and trends in marine biodiversity, would advance both fundamental and applied knowledge for a range of users, and would be less costly than reactive and curative responses to threats to ocean life and ecosystem services. The many ancillary benefits of an MBON include understanding long-term cyclic changes in the environment and in resources to provide a baseline for detecting human impacts, assessing the effects of multiple stressors on ecosystem health, understanding the causes of diversity differences across water masses and regions (for both species and communities), and defining links between biodiversity and ecosystem services at large scales to complement insights from small-scale studies.

Consensus was reached among the workshop participants (NOPP 2010) and the larger marine science

Table 1. Monitoring programs, agencies, and acronyms mentioned in the text.

Name	Acronym	Region	Focus
Australian Institute of Marine Science Long Term Monitoring Program	LTMP	Australia, Great Barrier Reef	Fishes and corals across multiple reefs
Argo Network	—	Global	Temperature and salinity profiling floats, upper 2000 meters
Biodiversity Heritage Library	BHL	Global	Open-access legacy literature of biodiversity
California Cooperative Oceanic Fisheries Investigations	CalCOFI	North America, Pacific Coast	Environment and living resources monitoring
Census of Marine Life	CoML	Global	Cataloging species diversity, distribution, and abundance
Centre de Recherches Insulaires et Observatoire de l'Environnement	CRIOBE	Polynesia	Monitoring of coral reefs and fish populations
Encyclopedia of Life	EOL	Global	Open-access species-level information
Group on Earth Observations Biodiversity Observation Network	GEO BON	Global	Collated terrestrial, freshwater, and marine biodiversity observations
Integrated Ocean Observing System	IOOS	Global	US contribution to global ocean observing system
Intergovernmental Platform on Biodiversity and Ecosystem Services	IPBES	Global	Interface between science community, policymakers
Life in a Changing Ocean	LiCO	Global	Biodiversity knowledge for sustainability
US Long Term Ecological Research Network	LTER Network	North America, primarily the United States	Coordinated interdisciplinary ecosystem research
Martha's Vineyard Coastal Observatory	MVCO	US East Coast	Long-term measurement of meteorological and oceanic processes
Millennium Coral Reef Mapping Project	—	Global	Global coral reef distribution database
Microbial Inventory Research Across Diverse Aquatic Long Term Ecological Research Sites	MIRADA-LTERS	North America, Arctic, Antarctica, Polynesia	Aquatic microbial inventory across US LTER Network sites
Moorea Biocode Project	—	Polynesia	Inventory of nonmicrobial life in a tropical ecosystem
National Ecological Observatory Network	NEON	North America, United States (terrestrial)	Continent-scale ecological observations, synthesis
US National Environmental Satellite, Data, and Information Service Coral Reef Watch	NESDIS	Global	Remote sensing, monitoring, modeling of reefs
National Institute of Water and Atmospheric Research	NIWA	New Zealand	Taxonomic expertise and resources for biodiversity
US National Oceanographic Partnership Program	NOPP	United States	Ocean-related monitoring and programs too large for single US government agencies
New Jersey Shelf Observing System	NJ SOS	New Jersey	Ocean current mapping
New Millennium Observatory	NeMO	Pacific	Undersea volcanic activity
North-East Pacific Time-Series Underwater Networked Experiments	NEPTUNE	Northeast Pacific, North America, Canada	Regional cabled observatory network
The US National Oceanic and Atmospheric Administration's Reef Assessment and Monitoring Program	—	Pacific Ocean islands	Research to support reef ecosystem management
Ocean Biogeographic Information System	OBIS	Global	Alliance to make biogeographic data available on the Web
Ocean Observatories Initiative	OOI	East Pacific, West Atlantic	Sustained ocean measurements
Ocean Research and Conservation Association	ORCA	Global	Observation of water conditions and ecosystem health
Pacific Coast Ocean Observing System	PacOOS	North America, Pacific Coast	California Current Large Marine Ecosystem
Partnership for Interdisciplinary Studies of Coastal Oceans	PISCO	North America, Pacific Coast	Long-term ecosystem research and monitoring program
Smithsonian's Marine Global Earth Observatory	MarineGEO	Global	Expansion of the Smithsonian's biomaterial collections
Smithsonian Oceanographic Sorting Center	SOSC	Global	Processing center for biological and geological specimens
Southern California Association of Marine Invertebrate Taxonomists	SCAMIT	North America, Pacific Coast	Promoting standardized invertebrate taxonomy
Southern California Coastal Water Research Project	SCCWRP	North America, Pacific Coast, Southern California	Collaborative regional monitoring, data analyses
World Registry of Marine Species	WoRMS	Global	Authoritative list of names of marine species

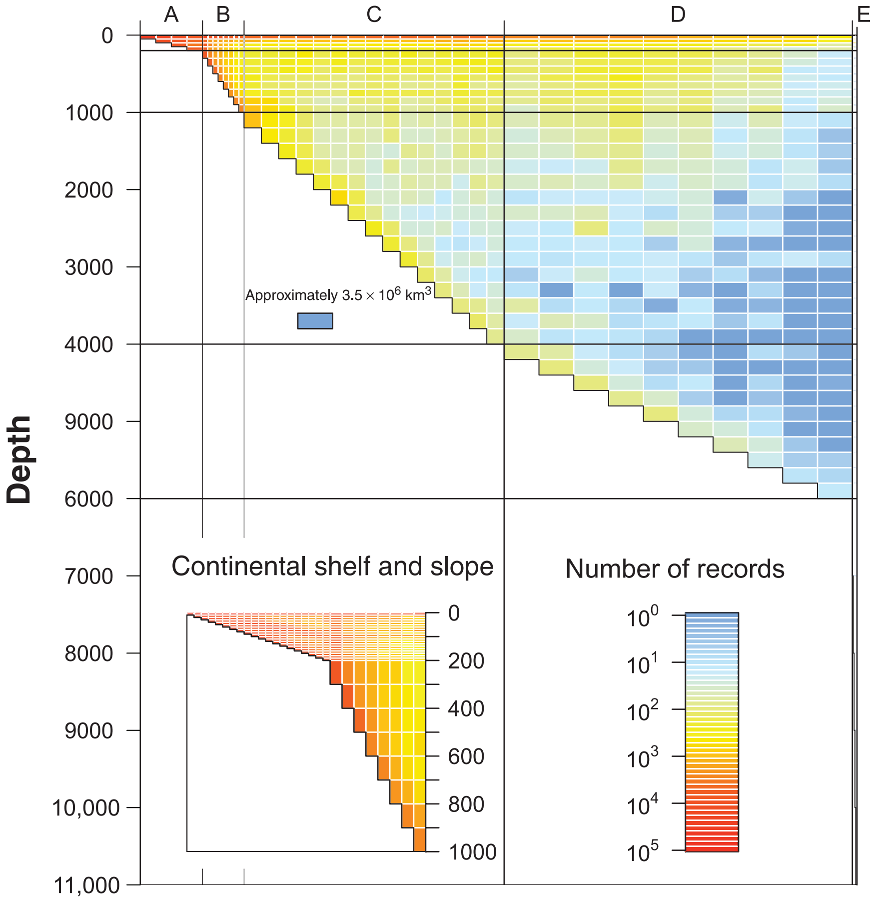

Figure 1. The number of observations of biodiversity with depth (in meters) for pelagic organisms. Abbreviations: A, continental shelf; B, continental slope or mesopelagic; C, continental slope or bathypelagic; D, abyssal plain; E, hadal zone; km³, cubic kilometers. Source: Adapted with permission from Webb and colleagues (2010).

community queried thereafter that implementing an MBON is not limited by ideas or by technology. Both expertise and well-developed techniques already exist for assessing and quantifying marine diversity at all levels. Instead, the most significant barriers are inadequate coordination and personnel. Many methods are currently available to capture diversity at multiple levels across taxonomic and spatiotemporal scales and habitats (figure 2), although improvements are possible in most approaches, and new ones will certainly be developed (table 2). For example, many methods developed for shallow water can be adapted to deep habitats, and similar sampling approaches can capture pelagic diversity across a taxonomic range, from microbes to phytoplankton and metazoan zooplankton. A recurring theme was the need to link sampling approaches across scales and environmental conditions by coordinating existing methods (table 2).

How to build an MBON: Integrate and leverage

The common overarching themes that emerged from the synthesis of expert opinion (NOPP 2010) were that considerable efforts are already being expended on monitoring related to biodiversity and resource management, but these are not integrated; therefore, an MBON could make progress rapidly by building on existing facilities and programs, integrating with new approaches at all levels. An MBON should build on, coordinate with, and learn from the foundation of networks, infrastructure, and experience established by prior global efforts such as the Census of Marine Life, as well as the multitude of regional and large-scale environmental research and observation efforts. Larger-scale regional to global efforts include the Group on Earth Observations (GEO) BON, NEON, the Ocean Observatories Initiative, the Integrated Ocean Observing System, Life in a Changing Ocean, the Smithsonian's Marine Global Earth Observatory, and the recently established Intergovernmental Platform on Biodiversity and Ecosystem Services (tables 1 and S1). Regional BONs that include a marine component appear to be gaining traction outside the United States and include the European BON, the Japanese-led Asia-Pacific BON and the Canadian-led Arctic BON. A successful model seems to be one that is funded through local government support and that can interact with the rest of the world through collaborative engagement with other regional BONs. The GEO BON can therefore serve as a coordinating entity to synergize and leverage regional BON activities.

In the United States, numerous marine monitoring efforts, spanning a range of scales, are carried out by municipalities, state and local agencies, the US Environmental Protection Agency, and the private sector, with some efforts tracking thousands of species at hundreds of sites. For example, the Southern California Coastal Water Research Project helps coordinate collaborative regional programs that monitor water quality and marine habitats, combining the efforts of a large number of separate programs in those regions (Ranasinghe et al. 2010, Pondella et al. 2012). Coordinating more broadly among such programs could add value to all parties by linking data, experimenting with and diffusing best practices, standardizing protocols, and sharing infrastructure and personnel through economies of scale. One possible goal is a network with a node for each of the nation's (or the world's) large marine ecosystems, each coordinated by a consortium of academic institutions within the region.

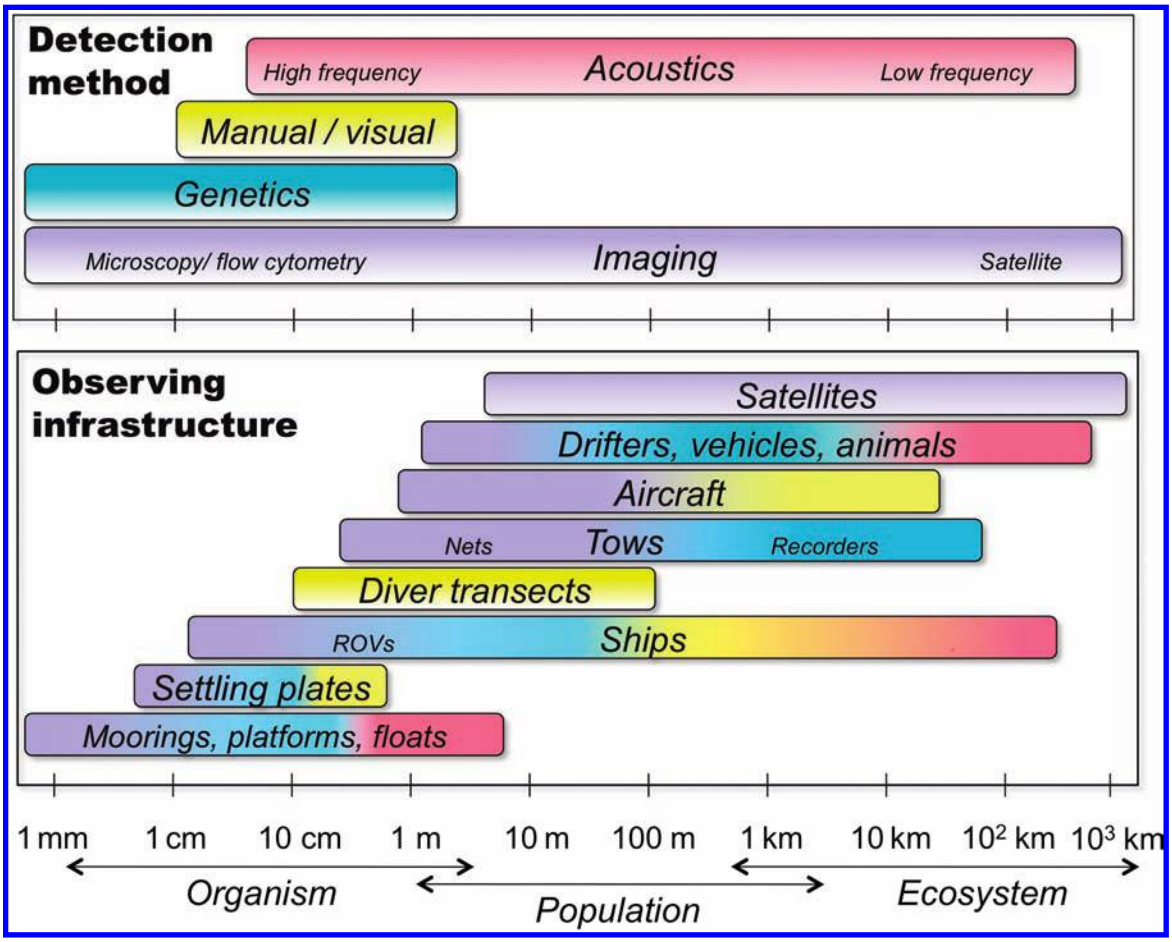

Figure 2. Aquatic biodiversity can be assessed over spatial scales from millimeters (mm; cm, centimeters; m, meters) to thousands of kilometers (km) using a combination of detection methods (top panel) and observing infrastructures (bottom panel). Some observing infrastructures can accommodate multiple detection methods, indicated here by different colors: For example, ships can accommodate all four detection methods, whereas satellites use only imaging methods. The relevant spatial scales refer to the range of a single unit and single sortie for each instrument type. Abbreviation: ROV, remotely operated vehicle.

To achieve the desired integration, a comprehensive MBON program must explicitly include incentives and resources for coordinating and standardizing. In addition, legacy data should be assembled and synthesized to extend and identify trends and gaps in taxonomic, spatial, and temporal coverage. It is important to link biodiversity surveys that capture data at all scales—from microbes to whales, instants to centuries, and Niskin bottles to entire ecosystems—as well as to determine the appropriate scales at which to address particular questions. Initially, sampling will have to be frequent and intensive; as knowledge of an area grows, sampling can be focused on particular places, taxa, or times of year.

Comprehensive understanding will require the use of both conventional and new technologies. Extending existing operational systems is a practical way to capitalize on existing logistics. Well-tested methodologies can be adapted to study taxa, regions, or processes beyond those for which they were designed. For example, routine automation of new acoustic and imaging technologies could expand their ranges and resolution.

Toward an operational MBON: Recommendations

In the expert synthesis process (NOPP 2010), we identified several cross-cutting themes and potentially transformative approaches to developing an MBON (box 1). Most fundamentally, biodiversity observations must be systematically linked to and must interact with observations of appropriate abiotic environmental variables—for example, those flowing from the developing network of ocean observing systems (see also Carr et al. 2011). Efforts must also be coordinated across scales, from local to international networks (see also Costello et al. 2010). These themes are reflected in the following recommendations, which include actions judged to be implementable now or in the near future with existing technology and infrastructure (see the subsequent sections for details), as well as longer-term actions that will require substantial investment or development.

Table 2. Overview of approaches and methods potentially useful in monitoring marine biodiversity over a range of spatial and taxonomic scales and on the basis of currently available technologies.

Method category	Example approaches and programs	Target taxa	Environment
Colonization-trap methods	Autonomous reef monitoring structures, sediment trays, granite blocks, disc racks, settlement plates	Macroinvertebrates	Benthic substrata, shallow to deep sea
Field survey methods	Photoquadrats, Multi-Agency Rocky Intertidal Network, coastal biodiversity surveys, the Australian Institute of Marine Science's Long Term Monitoring Program, SeagrassNet	Macroinvertebrates, algae, fish	Benthic substrata, reefs
Sample-based methods	The Continuous Plankton Recorder survey, plankton nets, a pelagic and benthic monitoring program, trawl surveys, high-performance liquid chromatography pigment analysis, gene microarrays, DNA and RNA sequencing, nucleic acid sequence-based amplification, environmental sample processor, the All Taxon Biodiversity Inventory	Plankton, fish, benthos	Pelagic and benthic
Mixed sample, video, and acoustic methods	Remotely operated vehicle surveys, the Bio-Optical Multi-frequency and Environmental Recorder	Plankton, fish, macroinvertebrates	Pelagic, benthic, shallow, midwater, deep sea
Acoustic methods	Autonomous acoustic habitat monitoring, multifrequency echosounding, passive acoustic monitoring (towed, cabled, moored or glider based)	Sound-producing animals, fish, micronekton, zooplankton	Pelagic and benthic
In situ optical methods	*In situ* zooplankton imaging systems, holographic imaging systems, flow cytometry, absorption spectrometry, fluorescence spectrometry, Bathysnap camera system	Plankton, macroinvertebrates	Pelagic, benthic substrata
Remote sensing (optical or spectral methods)	The Airborne Visible Infrared Imaging Spectrometer, imaging spectroradiometers, ocean color radiometry satellites	Phytoplankton, habitat-forming macroinvertebrates and algae	Pelagic, shallow benthic substrata
Animal-carried sampling	Position-only tags, environmental sampling, diving and behavior, multisensor tags with acoustics or video	Large vertebrates	Pelagic

Note: See supplemental table S2, available online at *http://dx.doi.org/10.1525/bio.2013.63.5.8*, for further details.

Box 1. Central themes and potentially transformative approaches to a marine biodiversity observation network (MBON).

Crowdsourcing an MBON. Existing regional and global observation systems constitute a wealth of experiments testing network models, infrastructure, technology, and sampling approaches. Learning from such experiments will greatly streamline the development and maximize the cost-effectiveness of a comprehensive MBON.

An MBON should be designed by nature, not by people. Biodiversity observation sites should be selected on the basis of oceanographic forcing factors, biogeographic provinces, and the distribution of water masses, rather than on the basis of political boundaries, in order to ensure that insights into global marine biodiversity change and its causes are environmentally relevant.

It's a small world after all. Connections among pelagic, benthic, and adjacent terrestrial systems (including human activities) are crucial to understanding the temporal scales and driving forces of marine ecosystem processes and their impacts on society. Similarly, comprehensive biodiversity inventories should incorporate state-of-the-art assessment techniques from molecular and organismal to community and seascape scales. Standardization of taxonomy and data infrastructure will facilitate making the necessary connections.

We have the technology. Effective employment of autonomous underwater vehicles, remotely operated vehicles, drifters, and observatory platforms to complement ship-based activities will enhance flexibility and range in sampling, will expand the range of accessible habitats and data, and will streamline costs.

The past is the key to the present. Precise, accurate, and useful marine biodiversity observations will require making legacy data readily accessible online, enhancing tools for automated specimen identification using both morphology and DNA, and developing predictive models based on empirical research.

An MBON should roll with the punches. Adaptive monitoring, with empirical data and models, will ensure that biodiversity research evolves to answer unforeseen questions. Determining which parameters should be monitored will require determining whether and how proxies can be effective.

Power to the people. Developing human resources is as important as technical innovation in creating a successful MBON. To maximize participation and accessibility, MBONs should require depositing voucher specimens (where practical and ethical) in publicly accessible repositories and should result in products that are widely usable. Creative use of citizen science could also broaden support for, engage the public with, and reduce the costs of sustaining an MBON.

Recommendation 1: Coordinate biodiversity sampling and integrate methods across taxa, habitats, and hierarchical levels. The functioning of marine ecosystems and of the services they provide are mediated by complex interactions among a wide range of living organisms. Understanding these interactions requires knowledge of a broad range of taxa and a coordinated sampling effort with standardized methods. Many components of such an effort can be implemented immediately (tables 2 and S2). A common theme is the need to link molecular data, classical specimen-based approaches, and optical or acoustical images. Sharing solutions for sampling designs and data handling with other efforts, including NEON, which has similar aims in the terrestrial realm of the United States, and GEO BON (Scholes et al. 2008), which is a global environmental monitoring network, will help avoid duplication of effort, will ensure that the data are compatible and comparable, and will add value to all of the involved parties' efforts.

Recommendation 2: Maximize compatibility of an MBON with legacy data. The central questions motivating the establishment of an MBON involve trends through time, including responses of biodiversity and ecosystems to climate change, fishing pressure, and pollution. Addressing such questions requires that data from an MBON be maximally comparable with historical biodiversity data, such as those from fisheries surveys and other long-term time series, and museum collections. Such legacy data are invaluable as indicators of former conditions but are also highly diverse and idiosyncratic. Therefore, an MBON should invest in digitizing historical marine biodiversity data (e.g., unpublished environmental impact reports, specimen collections) and in generating new data that are maximally compatible with existing data.

Recommendation 3: Establish one or more biodiversity observation headquarters to coordinate sample processing, including taxonomic identifications, data management, and training. A comprehensive MBON will ultimately require sustained long-term support both for the personnel to process large volumes of samples and observations (e.g., molecular data, physical specimens, images) and for the requisite information technology infrastructure. This could be achieved most efficiently and economically by combining in at least one physical center a cadre of mission-oriented master taxonomists and parataxonomists who have expertise covering a wide range of marine organisms, with information technology personnel and infrastructure equipped to handle large volumes of molecular, specimen, image, and acoustic data. Data should be managed across scales of time, space, and organism size and made available in a timely manner, in user-friendly formats, following standards set by the relevant scientific community (Yilmaz et al. 2011). One potential model that achieved some of these goals was the Smithsonian Oceanographic Sorting Center, a unit of the US National Museum of Natural History from 1962 until 1992, which employed resident taxonomists to process, sort, and provide preliminary identification of specimens received from expeditions. An important addition would be parataxonomists trained to make routine identifications, which would free professional taxonomists to assist with difficult identifications and to develop taxonomic resources for nonspecialists, which would make taxonomy more accessible and efficient. The United States lags behind several other nations in developing such a marine biodiversity infrastructure. For example, New Zealand's National Institute of Water and Atmospheric Research produces taxonomic manuals, conducts coastal and oceanic habitat and biodiversity surveys, and monitors invasive species. Most of these efforts, however, are aimed at specialists and do not provide user-friendly identification materials.

The design of an MBON should carefully balance the benefits of centralization with those of a more dispersed network. The latter include wider availability of taxonomic expertise, training, and research opportunities. Similarly, it is impractical and unwise to have a single central repository for specimens; instead, enhancing existing natural history collection resources—both personnel and publicly accessible physical facilities—would strengthen biodiversity infrastructure to collectively accommodate the many specimens to be archived. Importantly, collection infrastructure to house and care for the volume of voucher specimens generated by surveys must be enlarged, improved, and adequately staffed.

Recommendation 4: Produce a comprehensive checklist and identification guide to the marine organisms of US waters. A key requirement for an effective MBON is an accurate and up-to-date checklist of US marine biota, along with user-friendly identification tools. A major impediment to studying and monitoring US marine biodiversity is that existing taxonomic resources are scattered in the specialized and gray literature and are often narrow in taxonomic or regional scope. This situation contrasts with the organized efforts by other nations, including New Zealand (Hewitt et al. 2004) and the European Union (Costello et al. 2006). Organizing and synthesizing such resources would greatly streamline and enhance the capacity for a biodiversity inventory. This process has already begun with efforts such as the Encyclopedia of Life, the Biodiversity Heritage Library, OBIS, and the World Registry of Marine Species (tables 1 and S1). The taxonomy of the macroflora and macrofauna of US waters is relatively well known, so assembly of a comprehensive checklist and guide would involve mostly coordination and synthesis, with select revisionary efforts for poorly understood taxa. We estimate that a small group of mission-oriented master taxonomists could produce a checklist and assemble identification tools for US marine biodiversity in about a decade, enhanced with images and DNA sequences as they become available. Such a United States–focused effort must coordinate with global efforts in order to facilitate and enhance the taxonomy, as well as to provide context for the recognition of invasive organisms (Costello et al. 2010).

Recommendation 5: Invest in developing new approaches for automated sample processing and biodiversity informatics curation. A major frontier in implementing an integrated MBON is the development of systems to automate processing, organizing, and archiving the rapidly growing stream of biodiversity data. Innovations might include image recognition systems, automated processing of genetic samples, and algorithms for species recognition (Sosik and Olson 2007). It is crucial that investments be made to develop informatics tools that efficiently link large data sets (Howe et al. 2008), including molecular, morphological, image, acoustic, and taxonomic data from both new surveys and legacy sources. Strategic investment in these areas would probably pay for itself by reducing the labor involved in processing the large data streams expected from an MBON and by increasing the extent to which data can be made available in real time. Another key challenge in curating biodiversity data involves developing rigorous, standardized systems (*ontologies*) for organizing phenotypic information, including the vast legacy of traditional taxonomic descriptions (Deans et al. 2012) and building a cyberinfrastructure for organizing species-distribution information (Jetz et al. 2012).

Recommendation 6: Initiate an integrated MBON demonstration project as soon as is possible. A comprehensive MBON will mature gradually. An important early step will be to prove the concept of an end-to-end observation program—from the intraspecific genetic variation important to ecosystem functioning (Hughes et al. 2008) to species diversity and remotely sensed habitat-level variation—at one or more sites, preferably by leveraging well-developed existing programs and infrastructure. The project or projects would serve to field test and compare proposed methodological approaches to an MBON (tables 2 and S2) and to evaluate the feasibility and cost of integration across scales and methods in the same system. The latter goal includes linking the catalog of molecular diversity to organism morphologies by means of specimens and images—and in turn to valid taxon names—and ground truthing remotely sensed habitat-level data (through the collection of both specimens and data from the abiotic environment) to coincide with satellite observations. This recommendation could be achieved by a targeted call for proposals of projects to be supported by federal agencies with interests in marine biodiversity (e.g., through the National Oceanographic Partnership Program process; NOPP 2010). In the next section, we offer some suggestions for regions in which such a demonstration project might be feasible.

Designing an MBON: Candidate regions

The design of a comprehensive MBON should carefully balance the representation of unstudied areas with the representation of those that have been subject to intensive prior research. The former provide breadth and assess representativeness of the studied areas, whereas the latter provide depth through a higher-resolution and more integrated picture. The prime theoretical considerations in selecting sites include the richness and representativeness of both taxa and habitats, the likelihood of local and regional threats, and sensitivity to global climate forcing (boundaries between physicochemical realms should be targeted). Logistical feasibility is also important to siting decisions. The examples outlined below are intended to provide realistic models of MBON nodes that take advantage of existing resources for several habitats in US waters. The United States also has an opportunity (and a responsibility) for a more global focus on marine biodiversity, given its administration of dependent territories in the Pacific and the Caribbean, its presence in the Arctic and Antarctic, and its maritime commercial activities.

Estuaries and nearshore regions. Estuaries and nearshore coastal regions are some of the most productive aquatic habitats, generating a wide array of goods and services. They are the aquatic regions most affected by human activities, including entry points for invasive species (Ruiz et al. 2000). Nearshore environments provide ideal opportunities to test several proposed MBON approaches because of their relative ease of access, long history of study, and rich databases available from conservation and monitoring programs, which are reflected in comparatively well-known taxonomy and ecology and a well-characterized baseline. This also makes them ideal for the early detection of invasive species; a thorough and responsive MBON could detect new arrivals, which would support attempts to eradicate them before they establish.

A central feature of coastal regions is that many habitat formers are emergent or shallow-water plants (e.g., marsh grasses, mangroves, seagrasses) that are amenable to observation by remote sensing and, therefore, to linking biodiversity observations from microscales to regional scales. Such components of habitat biodiversity can be surveyed over large scales using air- or space-borne platforms, including satellite and aircraft imagery and LIDAR (light detection and ranging; Chust et al. 2008, Vierling et al. 2008). On-the-ground sampling for morphological and genetic identification of species composition must then complement aerial surveys. Deeper waters can be sampled semicontinuously with buoy-based instrumentation, passive imaging, and gliders. Environmental data from these platforms would be supplemented by periodic cruises to collect biological specimens and by acoustic mapping of bottom landscapes and habitat diversity, ground truthed with collections. This general approach could be adapted to many nearshore marine and freshwater habitats.

The US continental shelf. Geologically, the US continental shelf comprises two distinct entities: the narrow, steep, and geologically active rocky West Coast and the broad, geologically passive sediment shelves of the East and Gulf Coasts. These margins host a dramatic range of habitats with very different biological communities and ecologies, from subtropical coral reefs in Florida to the upwelling zone along the narrow shelf of the North Pacific and the broad, shallow sediment plains of the southeastern United States, the Bering Sea, and the Arctic Ocean. Here, we focus on two end members that span this range.

The US Northeast shelf is a highly productive and well-studied region influenced by prevailing advection from subpolar regions, dynamic exchanges across coastal and offshore boundaries, and proximity to dense human population centers. The layout for a Northeast continental shelf MBON should include selected transects to capture cross-shelf variation in water masses that profoundly affects biodiversity and could be designed to complement and upgrade the National Oceanic and Atmospheric Administration's (NOAA) existing fisheries stock assessments, protected resource surveys (e.g., the Marine Resources Monitoring, Assessment, and Prediction Program), and its Ecological Monitoring Program, which span the entire region multiple times per year. For example, selected transects could be located in order to leverage existing nearshore observing systems such as the Martha's Vineyard Coastal Observatory and the New Jersey Shelf Observing System, planned shelf-break observing infrastructure that is part of the US National Science Foundation's Ocean Observatories Initiative, and the slope-to-deep-sea time series provided by long-term occupation of the Line W moorings. Building on these existing pieces, a comprehensive MBON for the US Northeast shelf could be achieved with modest additional ship time by extending spatial, temporal, and taxonomic coverage to fill the gaps in current observing programs. Combining such sea-based sampling approaches with remote-sensing observations would bridge scales of spatial, temporal, and taxonomic variation (see tables 2 and S2).

On the US West Coast, the narrow continental shelf and slope associated with the California Current Large Marine Ecosystem is influenced by a seasonal coastal upwelling, with large implications for both benthic and pelagic ecosystems and their coupling. The steepness of the slope and its proximity to shore mean that habitats from intertidal to open ocean exist within a relatively small area, which offers a relatively efficient and economical approach to a comprehensive MBON. A Pacific Coast MBON could leverage and build on the considerable resources already devoted to clusters of ocean monitoring activities centered in Oregon, Monterey Bay, and Southern California, each spanning a range in latitude, upwelling influence, and degree of human impact and urbanization. For example, the quarterly cruises off Southern and Central California organized by California Cooperative Oceanic Fisheries Investigations currently collect data on phytoplankton biodiversity and zooplankton biomass and biodiversity, as well as a suite of physical parameters. The Partnership for Interdisciplinary Studies of Coastal Oceans supports surveys of intertidal and shallow subtidal diversity. Additional sampling of phytoplankton from piers occurs as a part of monitoring for harmful algal blooms. Southern California also provides an excellent model for integrating the taxonomic component of a biodiversity monitoring system, through voluntary standardization of methods and taxonomies by workers at regional municipalities and agencies (Cadien and Lovell 2011). The Southern California Association of Marine Invertebrate Taxonomists integrates data from 20 programs focused on infaunal and epibenthic monitoring, using grabs and trawls, covering hundreds of sites from nearshore to 1000 meters and including data on more than 3000 species. Coordinating across existing locations would facilitate the understanding of how variation in diversity, interacting with physical forcing, affects the resilience of regional assemblages. Explicitly linking observing systems across habitats would also allow assessment of whether patterns of mass and energy transfer across ecosystems are paralleled by gradients in diversity. A coordinated MBON built out from existing efforts on the West Coast would be especially well poised to address how biodiversity and ecosystem functioning respond to climate fluctuations on the interannual to decadal scales associated with the El Niño Southern Oscillation and Pacific Decadal Oscillation cycles. The Pacific Coast Ocean Observing System or the West Coast Governors' Agreement on Ocean Health might be used to facilitate integration of projects in Oregon, California, and Washington to produce a coastwide MBON.

Coral reefs. Coral reefs are among the most diverse and imperiled marine ecosystems, with vast areas under US jurisdiction in Micronesia, Samoa, the central Pacific Ocean, the Caribbean, Hawaii, and Florida. Reefs are important components of one of the largest marine protected areas in the world, the Papahānaumokuākea Marine National Monument in the Northwestern Hawaiian Islands. The long history of study and monitoring of reefs, across broad spatial, temporal, and taxonomic scales, often by national organizations (e.g., NOAA, the Australian Institute of Marine Science), provides an excellent basis for a future reef-focused MBON. Transects and quadrats have traditionally been used in reef-monitoring efforts, with a focus on fishes, corals (and their diseases), algae, and other sessile macrobenthos, so that much of the reef diversity represented by mobile invertebrates and microbes has been missed. Autonomous reef monitoring structures (ARMS) were recently developed to partly fill this gap and can be used in conjunction with DNA sequencing to facilitate identification; ARMS have been used successfully to sample sessile and sedentary reef organisms in a standardized way (Plaisance et al. 2011). Benthic habitat mapping using multi- and hyperspectral imagery from aircraft and satellites is also well established on reefs, including those in the Florida Keys, Puerto Rico, and the US Virgin Islands, and allow substantial differentiation of bottom and community types in clear, shallow waters (Guild et al. 2008). For example, the Millennium Coral Reef Mapping Project, a collection currently including more than

1700 Landsat-acquired multispectral images, provides a baseline for assessing current reef status around the globe (Andréfouët et al. 2008b). Remote sensing can monitor for changing habitat distributions and ecosystem responses over large spatial scales, as is done by the National Environmental Satellite, Data, and Information Service Coral Reef Watch satellite monitoring program, which monitors and models ocean temperature data to warn of warming events that could cause coral bleaching.

A potential model of an MBON that links observations at multiple biological scales has been developed on the coral reefs of the Polynesian island of Moorea. The Moorea Biocode Project (Check 2006) documents and characterizes all species on the island through collection, vouchering, imaging, DNA sequencing, and taxonomic identification. The resulting taxonomic infrastructure and identified genetic sequence library allow quantitative sampling and tracking of biodiversity through novel tools and approaches, including ARMS and sampling of planktonic larvae of benthic species and of the gut contents of targeted species. Monitoring of reef biological communities has also been ongoing on Moorea for 40 years, through the Centre de Recherches Insulaires et Observatoire de l'Environnement field station, and has been enhanced since 2004 by the establishment of a long-term ecological research site that collects geochemical and physical oceanographic measurements and characterizes ecological communities in depth. The Moorea Microbial Inventory Research Across Diverse Aquatic Long Term Ecological Research Sites project has provided a first baseline of microbial diversity in these waters (McCliment et al. 2011).

The deep sea. The deep sea is the largest part of the biosphere and consists of two very different, linked habitats: the pelagic realm—waters beyond the continental shelf from the surface to the bottom—and the benthic seabed. Much of the deep sea lies outside national boundaries and jurisdictions, so international and industry collaborations are essential to implementing an effective deep-sea MBON.

Because research in the pelagic realm is very sparse except near the surface (figure 1), guidance and historical precedents for developing a deep-sea MBON are limited. Reliable, long-term research on the biology of the deep benthos extends back only a few decades. Currently, the best-studied sites include Site M, at 4100 meters off Southern California (Smith et al. 2001); Davidson Seamount; and the Monterey Canyon (Ruhl et al. 2008). Deep locations off the East Coast of North America are farther offshore and are therefore logistically more difficult to study. As part of a first MBON effort, priority might be given to one Atlantic and one Pacific deep-sea system along the North American coast and to one in the tropical Pacific.

Sampling in deep-sea habitats could be leveraged using existing or planned infrastructure. For example, observing networks could be tied to the Discovery Corridor in the Atlantic, which extends from the Fundy Isles region of Canada (Herder and Van Guelpen 2008), and the planned cabled observatories in the Northeast Pacific (the North-East Pacific Time-Series Underwater Networked Experiments Observatory, the Ocean Observatories Initiative, and the New Millennium Observatory). The passive and active listening posts recently built along the Pacific Coast of North America (Payne et al. 2010) should be linked to this system. A prime location for a deep-sea site in the tropics is the Marianas Islands, with its history of research on physical and biological aspects of the Mariana Trench and its associated environments. Acoustic sensors might be added to the Argo Network, and biological sensors could be added to cabled observatories. Automated technologies for studying organisms in shallower water could be modified for use in the deep sea, such as the Ocean Research and Conservation Association's Eye-in-the-Sea camera (Widder et al. 2005), for visualizing bioluminescent organisms, and motion-activated imaging at bait stations. Regular sampling in the remote environment of the deep sea would be best achieved by integrating autonomous collectors with fixed physical observing system stations. For small organisms, these could include sediment traps that periodically shift preservative-laden containers and environmental sample processors (Scholin et al. 2009). For larger organisms, imaging systems would be appropriate. Both are most practical on the seafloor, associated with moorings, where physicochemical data are already being collected. In the pelagic realm, drifters and floats might be designed to gather smaller samples, but ships will also be needed.

Conclusions

A comprehensive MBON is a realistic and feasible goal. It can begin now by building strategically on existing infrastructure, networks, and technology and can then grow gradually. Several themes are central to designing and implementing an effective MBON. First, we have the technology for major advances—the challenges are primarily coordination among existing efforts, standardization, and interoperability, which will require appropriate incentives. Of course, funding will be required for major expansion, but much initial progress is possible with modest additional investment. A second theme is modularity: Many building blocks are already in place, and significant progress can be made by adding biological observations to primarily physical observing systems and linking them. Finally, taking a proactive and flexible approach—adaptive monitoring—from the beginning can save money and can potentially save property and lives by anticipating hazards resulting from a changing ocean. The time required to achieve the goals outlined here will of course depend on political will. But, given a concerted effort, modest funding, and the many pieces already in place, the core of a comprehensive MBON could be achieved within 5 years.

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