Attaining an Operational Marine Biodiversity Observation Network (BON) Synthesis Report

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EXECUTIVE SUMMARY

Humans depend on the health of the ocean's ecosystems and associated biogeochemical cycles for food, jobs, and long-term benefits which result in carbon sequestration and oxygen production. Yet many marine habitats are threatened by impacts such as climate change, pollution, overfishing, habitat destruction, and invasive species. A growing body of research demonstrates that the maintenance of marine biodiversity may be key for sustained ecosystem health and resilience against global change, suggesting that managing for marine biodiversity may help resolve conflicting management objectives, and enhance the nation's biosecurity. Thus, biodiversity might serve as a master variable in evaluating both the health of marine ecosystems and the success of management efforts. Yet there is no rigorous, standardized, coordinated approach to monitoring biodiversity in a way that produces a coherent picture of status and trends in the 90% of the Earth's habitable volume that is the ocean.

Developing a marine Biodiversity Observing Network (BON) to understand human impacts on marine systems and predict their consequences should be a national priority. Doing so requires overcoming both the common misperception that the ocean is vast enough to absorb all impacts, and major logistical challenges to access and observe marine biodiversity. Quantifying biodiversity status and trends in a standard, proactive manner will safeguard biodiversity and be less expensive than a reactive response to loss of biodiversity and associated ecosystem resources. With the goal of designing a BON to fill knowledge gaps and provide a sound basis for informing scientific, government, industry, and public decisions, the Interagency Working Group on Ocean Partnerships Ad Hoc Group on Biodiversity convened a three-day workshop in May 2010 to develop a plan for implementing a sustainable marine BON. A Steering Committee of nine academic scientists (seven of whom attended) developed the agenda, which included plenary and break-out sessions. Participants included 35 invited scientists spanning a breadth of expertise and 13 representatives of seven federal agency sponsors.

Overarching components of the BON that were discussed involved 1) integrating across levels of biodiversity from intraspecific genetic variation through species to remotely sensed habitat-level diversity – microsatellites to macrosatellites, 2) linking observations on biodiversity to observations on abiotic environmental variables, 3) siting BON projects to emphasize environmental forcing factors and biogeography, and 4) incorporating adaptive monitoring to make it possible to address unforeseen questions. Workshop discussions focused on priorities for taxonomic range and resolution, target habitats, and appropriate methodologies. They culminated in recommendations for implementing a marine BON, which would advance most of the National Ocean Policy (NOP) Priority Objectives identified by the Interagency Ocean Policy Task Force (OPTF). The recommendations include activities that are possible with existing technology and infrastructure, as well as those requiring substantial investment and/or more development. In addition to recommendations, case studies illustrating practical pathways of leveraging existing data and infrastructure to realize the recommendations were assembled for deep-sea, continental shelf, coral reef, and Great Lakes ecosystems. For reasons of logistics and maturity of systems and technology on which to build, nearshore and estuarine sites are prime candidates for the first end-to-end integrated marine BON demonstration projects.

Recommendations

1. Coordinate biodiversity sampling across taxa, habitats, hierarchical levels, and methods from microbes to mammals.
2. Maximize compatibility of BON with legacy data.
3. Establish one or more Biodiversity Observation Center(s) to coordinate sample processing, including taxonomic identifications, data management, and training and invest in the computational expertise to handle large datasets in an open access environment.
4. Synthesize and make accessible marine taxonomic resources.
5. Invest in developing new approaches for automated sample processing.
6. Modernize and enhance the nation's physical infrastructure for marine exploration.
7. Initiate an integrated marine BON demonstration project soon.

INTRODUCTION

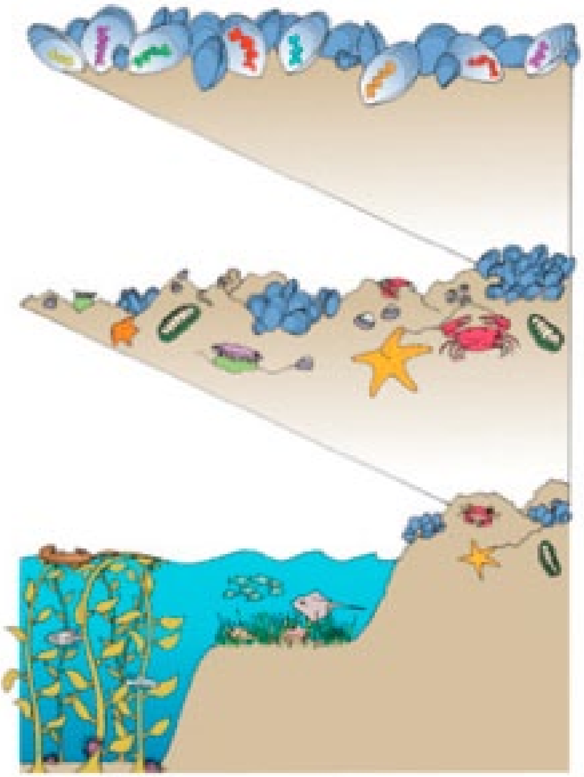

Figure 1. The lower level includes habitat types within a region; the middle level includes species diversity; and the upper level includes genetic diversity within species (from Palumbi et al.[1], with permission).

Biological diversity, or biodiversity, is defined as the variety of life, encompassing variation at levels of complexity from within species to across ecosystems (Figure 1). Humans depend on biodiversity for food, medicines, recreation, biosecurity, and much more[2]. There are also important ethical, cultural and moral justifications for protecting biodiversity. In recognition of the importance of biodiversity for human well-being, 2010 was proclaimed the International Year of Biodiversity by the United Nations.

Biodiversity is no less important in the ocean than on land. Humans depend on the health of the ocean's ecosystems and associated biogeochemical cycles for food, jobs, and long-term benefits that result in carbon sequestration and oxygen production. In its final recommendations to the President, made on 19 July 2010, the Interagency Ocean Policy Task Force declared "It 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" [3]. We note that the recommendations emerging from this workshop include specific measures that address several of the Interagency Ocean Policy Task Force's National Ocean Policy Priority Objectives (see Appendix 6), as detailed below.

A growing body of experimental research demonstrating that the maintenance of biodiversity – and thus the provision of some of these services – may be key for sustained ecosystem health and resilience in the face of environmental change[4] has led to the suggestion that managing for marine biodiversity may help resolve otherwise conflicting management objectives[1, 5]. Thus, biodiversity might be a key master variable useful for determining the health of ecosystems and the success of management efforts.

Surveys and extrapolations based on remotely-sensed habitat loss have produced staggering estimates of the rate of biodiversity loss in many terrestrial habitats[6]. By comparison, few data are available to assess how diversity is changing in the 90% of Earth's habitable volume that is the ocean[7, 8]. The paucity of long-term records that hampers our ability to understand exactly how biodiversity in the seas is responding to human activities is largely due to technical challenges, and to a shortage of taxonomic resources. Diversity of some groups has been measured in some places and at some times, but there is no rigorous, standardized, coordinated approach to monitoring marine diversity that could produce a coherent picture of current status and trends. While we can produce convincing data to quantify the increased concentrations of greenhouse gases in our atmosphere over the past 50 years[9], data do not exist to produce graphs tracking marine biodiversity. So, while Earth is undergoing major changes as a result of human activities, we have little sense of the consequences of these changes for the diversity of plant, animal, fungal, and microbial life in the ocean, although well-developed techniques now exist for assessing and quantifying marine diversity at all levels.

Maintaining biodiversity requires knowing its components; to manage for diversity requires understanding its current status and trends over space and time. Knowledge of biodiversity is also essential for monitoring biosecurity – that is, guarding against threats posed by the introduction of infectious agents, pests, invasive alien species, and the like. A BON can help alert us to the presence of invasive organisms at an early stage, while eradication is still possible. For example, in 2000, divers monitoring the growth of eelgrass in a lagoon near San Diego, California, discovered the highly invasive seaweed *Caulerpa taxifolia*, a native of tropical seas, which had caused widespread ecological damage in the Mediterranean Sea. In California it was eradicated before it spread because, when detected, the seaweed was restricted to patches within a single cove.

Even well known, large, mobile conspicuous members of the biota such as turtles and mammals must be monitored for effective conservation and management. Recent developments in telemetry and electronic tag technology have greatly enhanced knowledge of their movements and behavior, allowing them to be enlisted in sampling the environment. Such "animal oceanographers" can be instrumented to identify their critical foraging habitats, migration corridors, and regions of high occupancy, providing critical knowledge about how components of the variable marine habitat influence their distribution, survival, growth, and reproduction. Oceanographic data provided by these animal-borne sensors could also increase data for understanding other aspects of ecology, including climate change and ocean acidification.

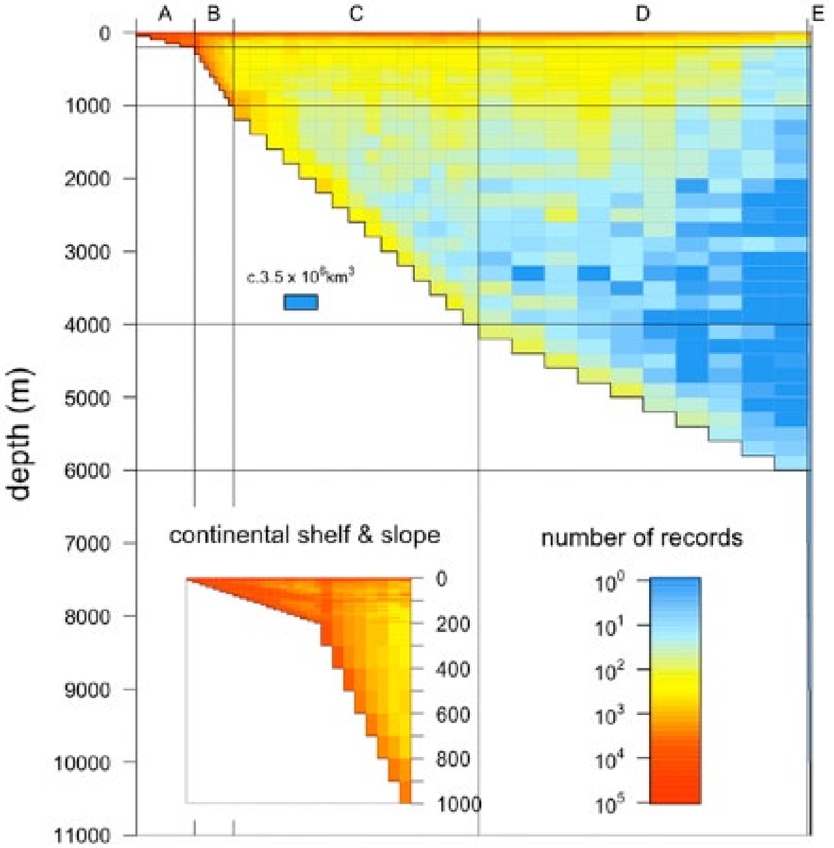

Figure 2. Number of observations of biodiversity with depth and distance from shore for pelagic organisms (A = continental shelf, B = continental slope / mesopelagic, C = continental slope / bathypelagic , D = abyssal plain , E = hadal zone) (from Webb et al. [14]).

Understanding changes in biodiversity is vital given mounting evidence of the critical role that diversity plays in maintaining marine ecosystem function[3, 10]. Several well-documented ecological mechanisms contributing to this effect include: complementarity in the use of resources among species and their responses to environmental variation; positive interactions among species; an increased likelihood of key species being present when species diversity is high; and redundancy, which can provide biological insurance against changes in ecosystem function because species that are similar in many ways may be differentially susceptible to environmental change. It is now clear that in the same way that long-term financial health is bolstered by a diversified portfolio, ecosystem health and resilience are enhanced by the maintenance of biodiversity[11].

Many marine habitats are under threat from climate change, pollution, overfishing, habitat destruction, and invasive species[12, 13]. The resulting changes will undoubtedly have implications for both biodiversity and the services it provides. Thus, developing an observing network for biodiversity to understand the magnitude of these effects and predict their consequences should be a national priority. Some challenges associated with conceptual and practical design of a marine Biodiversity Observing Network (BON) are unique to operating in the ocean. In particular, it is essential to overcome barriers associated with the misperception that the ocean is so vast that it can absorb insults, and, especially for the deep and open ocean areas, the tendency to regard these insults as out of sight, out of mind. These characteristics also present major logistical challenges for access to and observation of biodiversity. As a consequence, current knowledge about marine biodiversity and ecosystem function declines with distance from land and the ocean surface (Figure 2).

A three-day workshop sponsored by seven federal agencies had the explicit goal of confronting these challenges by providing practical guidance on the way forward to implement a sustainable marine BON (see Appendix 1, the Workshop agenda). A major outcome was the insight that we are not limited by ideas nor even by technology — expertise and devices exist to monitor marine biodiversity. Significant barriers, however, are lack of coordination and human resources.

TOWARD AN OPERATIONAL MARINE BIODIVERSITY OBSERVATION NETWORK

The Workshop

The workshop concept arose from discussions among members of the Interagency Working Group on Ocean Partnerships Ad Hoc Group on Biodiversity, which convened a Steering Committee of nine academic scientists, seven of whom attended the workshop. Workshop participants were invited to span a breadth of expertise in taxonomy, experience in various marine environments, and familiarity with technological solutions. A high acceptance rate to invitations (73%, resulting in 35 attendees: Appendix 2) indicated the interest and importance felt by the scientific community for this endeavor. Representatives of the federal agency sponsors (Appendix 2) NOAA, NASA, MMC, ONR, NSF, BOEMRE (formerly known as MMS), and the Smithsonian Institution (for abbreviations and acronyms, see Appendix 3) participated in plenary discussions and attended some break-out sessions as observers.

Workshop discussions focused on priorities for taxonomic range and resolution, target habitats, and appropriate methodologies. The format included presentations of current knowledge by Steering Committee members, small break-out sessions to consider emerging ideas, and plenary discussions to synthesize findings. Themes included how best to produce concrete BON recommendations, questions of scientific and societal concern that should guide BON design and implementation, integration of observations and understanding across spatial and temporal scales, and merging knowledge from various methods. Recommendations were compiled throughout the workshop, which culminated in the development and discussion of preliminary case studies demonstrating application of recommendations to the deep sea, continental shelves (wide and narrow), coral reefs, estuaries, and the Great Lakes.

Structure and major outcomes of break-out groups

Some break-out groups focused on how to determine which habitats and taxa would best characterize the full scope of biodiversity in a marine BON. Habitat types were divided into pelagic and benthic, and the benthic further divided among hard, soft, and biogenic substrata. Taxa were divided mostly by size and whether photosynthetic or habitat-creating. Break-out discussions set the stage for consideration by the entire group of methods to quantify diversity for each habitat and taxon combination derived from a survey of existing methods provided by workshop participants prior to the meeting (Appendix 4). After voting on methods favored, participants discussed the results of the vote in break-out groups. Conclusions from these discussions were that many methods are: 1) currently available to capture diversity at multiple levels and across taxa and spatio-temporal scales (Figure 3), although improvements are possible in most, if not all, approaches, and new technologies will certainly be developed; and 2) appropriate for multiple habitat x taxon approaches (Appendix 4). For example, methods used in shallow water can be adapted to deep habitats, and similar sampling approaches can capture pelagic diversity for a range of microbes, as well as metazoans including zooplankton. A recurring theme was the need to link sampling approaches across scales of space and time. The survey of existing methods suggests that this is possible, but will require significant coordination.

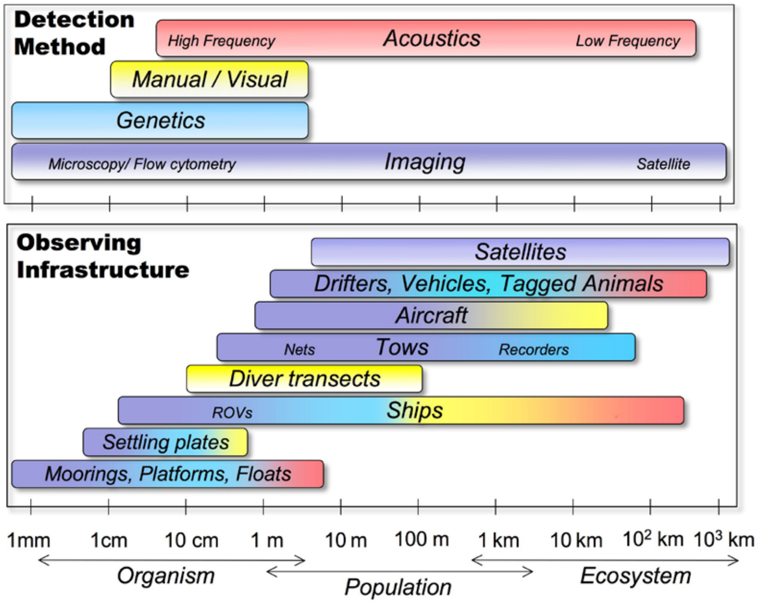

Figure 3. Aquatic biodiversity can be assessed over spatial scales from millimeters to thousands of kilometers using a combination of detection methods (top panel) and observing infrastructures (bottom panel). Some observing infrastructures can accommodate multiple detection methods, indicated here by different colors: e.g. 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.

A marine BON will be critically useful for establishing status and trends in marine biodiversity. In addition, such a network will advance both fundamental and applied knowledge for a range of users. Most of the many possibilities for ancillary benefits raised at a break-out session devoted to the matter fell into the following categories: 1) understanding long-term cyclic changes; 2) providing the baseline for detecting acute human impacts; 3) assessing the effects of multiple stressors on ecosystem health; 4) understanding the causes of diversity differences across water masses (for both species and communities); and 5) defining links between ecosystem services and biodiversity at large scales to complement insights from small-scale studies. These were similar to the results of the break-out session devoted to synthesizing ideas about issues marine BONs should be designed to address (Box 1).

Recommendations

Quantifying biodiversity status and trends in a standardized, proactive manner will foster safeguarding biodiversity, will enhance biosecurity, and will be less expensive than a reactive and curative response to loss of biodiversity and associated ecosystem resources. A central goal of the workshop was to design an operational, marine US BON to fill knowledge gaps and provide a sound basis for informing science, government, industry, and public decisions.

The BON must integrate observations across hierarchical levels of biodiversity from intraspecific genetic variation through species and functional groups to remotely sensed habitat-level diversity. Biodiversity observations must be systematically linked to and interact with appropriate abiotic environmental variables.

Members of the Steering Committee synthesized these and other themes from the Workshop into specific recommendations for implementing a marine BON. Recommendations include actions that members of the Committee judged could be implemented now or in the near future with existing technology and infrastructure, as well as actions that will require substantial investment and/or development. Besides recommending particular technologies and locations, the committee offered insights for guiding the assembly and implementation of a coherent marine BON that it considered transformative (Box 2).

1. Coordinate biodiversity sampling across taxa, habitats, hierarchical levels, and methods from microbes to mammals. Workshop participants came to some consensus on preferred sampling and observing components of marine biodiversity that should serve as the standard for integrated marine biodiversity observation programs. The many components that can be implemented immediately are listed in Appendix 4. Briefly, they include primarily molecular approaches for sampling microbes; optical

Box 1. Top Issues for a BON (Biodiversity Observation Network) to Address *(Numbers in parentheses indicate links to National Ocean Policy (NOP) Priority Objectives of the OPTF)*

- How does biodiversity vary among habitats or water masses, and how is biodiversity in habitats or water masses linked? What processes lead to hotspots in biodiversity? Answering these questions requires baseline spatial and taxonomic assessments of US waters, including mobilizing legacy data. (NOP objectives 3,6,9)
- How do composition and distribution (including geographic and physiologic ranges) of organisms respond to global changes such as warming, altered water carbon chemistry (including acidification), invasive species, deoxygenation, and modified circulation? Do the effects on ecosystem health differ in the face of multiple stressors as compared to a single stressor? (NOP objectives 1,3,5,6,7,9)
- What can we learn about biodiversity and the function of whole systems beyond what we know from studying the parts in isolation? Do diverse and non-diverse systems respond similarly to perturbation, and do they differ in resilience? (NOP objectives 1,5,6)
- What are the consequences of these changes for ecosystem goods and services? What is the relationship between biodiversity and ecosystem health and ecosystem goods and services, especially in sensitive areas and economically important systems (e.g. how do changes in upwelling affect fisheries)? Do insights from small-scale studies allow us to understand links between ecosystem services and biodiversity at large scales? (All NOP objectives)
- What drives changes in the state of ecosystems (e.g. alternate states, regime shifts) and what is the relative importance of physical forcing, biotic interactions, and hysteresis? Are there alternate stable states of marine ecosystems? This requires distinguishing long-term cyclic changes from directional signals as a result of global change, as well as characterizing the current disturbance state to detect human impacts (e.g. bottom trawling, oil spills, invasion by alien species, pollution, overfishing). (NOP objectives 1,2,3,5,6,7,8)
- How can areas at risk for loss of biodiversity be detected? How can recovery from loss of biodiversity be detected? How can we understand and reduce the threats to biodiversity? (NOP objectives 2,3,6)
- How do we leverage existing programs and protocols to monitor biodiversity? (NOP objectives 4,9)
- What information is needed to improve ecosystem models that include biodiversity? (NOP objectives 1,2,3,5,6,7,8)

imaging and/or collection of specimens for smaller invertebrates and photosynthetic microbes (i.e. algae, including cyanobacteria and phytoplankton); transect- or quadrat-based sampling for sessile habitat-forming taxa; a range of optical imaging, electronic tagging, and acoustic methods for large, free-ranging animals; and airborne hyperspectral and other remote-sensing methods for assessing biogenic habitat-scale diversity. A common thread is linking molecular to classical specimen-based approaches and images. A range of pelagic and benthic ecosystems can be sampled with minor variations on this approach. Sharing solutions for, e.g., sampling regimes, and for data handling with NEON[15], which has similar aims in the terrestrial realm of the US, and GEO BON[16], which is a global environmental monitoring network, will help avoid duplication of effort and ensure data are compatible and comparable, while advancing the OPTF National Ocean Policy Priority Objectives 4 (Coordination and Support) and 9 (Mapping and Infrastructure).

2. Maximize compatibility of BON with legacy data. Some central questions motivating establishment of a comprehensive marine BON involve trends through time, including responses of biodiversity and ecosystems to climate change, fishing pressure, and pollution. Addressing such questions requires that data from a BON be maximally comparable to historical biodiversity data like those from fisheries surveys and marine bird and mammal surveys, the Continuous Plankton Recorder, and museum collections. Such legacy data are invaluable as indicators of former conditions, but are also highly diverse and idiosyncratic. Thus, recommendations for a marine BON include designing sampling schemes that, where possible, produce data that can be meaningfully compared with historical data, and investing in rescuing historical marine biodiversity data (e.g. unpublished environmental impact reports and associated specimen collections) by digitizing and organizing them into user-friendly electronic formats that are made publicly available. Because analysis of environmental change depends on comparisons across time, this recommendation advances OPTF National Ocean Policy Priority Objectives 3 (Inform Decisions), 5 (Climate Change), and 8 (Changing Arctic).

3. Establish one or more Biodiversity Observation Center(s) to coordinate sample processing, including taxonomic identifications, data management, and training. Workshop participants emphasized that a comprehensive marine BON will not be viable without sustained long-term support for both the personnel to process large volumes of samples and observations (molecular data, physical specimens, images, etc.), and the requisite

Box 2. Transformative approaches to implementing a marine BON (Biodiversity Observation Network)

- A coordinated network that integrates existing marine research efforts will greatly improve understanding of the status and trends in biodiversity of US waters at relatively modest cost.
- Biodiversity observation sites should be selected based on oceanographic forcing factors, biogeographic provinces, and water masses to assure insights into global marine biodiversity change and its causes are contextually relevant.
- Elucidating connections among pelagic, benthic, and adjacent terrestrial systems (including human activities) is critical to understanding temporal scales and driving forces of marine biological cycles and ecosystem processes.
- Increased use of AUVs, ROVs, drifters, observatory platforms, animal-borne sensors, etc. to complement ship-based activities will enhance flexibility in sampling through time and space; their use will increase the types and quantities of data gathered, and probably will reduce costs.
- Adaptive monitoring, which uses both empirical and model-based data, will allow biodiversity research to evolve, and thus to answer unforeseen questions that cannot be addressed adequately with existing technologies and approaches. Part of deciding which parameters should be monitored should involve determining if proxies can be effective.
- Comprehensive biodiversity inventories should 1) incorporate state-of-the-art assessment techniques from molecular and organismal to community and seascape scales, 2) require depositing voucher specimens (where practical and ethical) in publicly-accessible repositories, and 3) result in products that are widely usable.
- Capturing and making legacy data readily accessible on line, enhancing tools for automated specimen identification using both morphology and DNA, and developing predictive models based on empirical research all must be integrated for precise, accurate, and useful marine biodiversity observations.
- Developing human resources is as important as technical innovation in creating a successful BON.

information technology infrastructure. Such a facility would ideally combine, in one or more physical centers, a cadre of mission-oriented master taxonomists and parataxonomists who have expertise covering a wide range of marine organisms with IT personnel and infrastructure equipped to handle a huge volume of data, e.g. molecular, image, acoustic, and tagging. The data, managed across scales of time, space, and organism size, would be made available in a timely manner, in user-friendly formats, following community standards[17]. A model for part of this goal is the Smithsonian Oceanographic Sorting Center (SOSC, a unit of the US National Museum of Natural History from 1962 until 1992[18]), which employed taxonomists to process and sort specimens received from expeditions; the taxonomists identified what they could, and involved other experts for the rest. An important addition to what the SOSC provided would be parataxonomists, trained to make routine identifications, leaving professional taxonomists to assist with difficult identifications, engage collaborating specialists, and develop taxonomic resources for non-specialists, rapidly making taxonomy more accessible and efficient. Workshop participants noted that the US is well behind some other developed nations in having such a marine biodiversity infrastructure (an example is the Aquatic Biodiversity and Biosecurity unit of New Zealand's National Institute of Water and Atmospheric Research)[19]. This recommendation is key to advancing OPTF National Ocean Policy Priority Objective 9 (Infrastructure), which underpins most of the other Objectives.

4. Synthesize and make accessible marine taxonomic resources. A major impediment to studying and monitoring biodiversity is that the extensive taxonomic resources that do exist are both scattered and incompletely coordinated. Organizing and synthesizing the taxonomic resources would greatly enhance capacity for a biodiversity inventory, speeding identification of organisms sampled and observed. Among the needs is an accurate and up-to-date checklist of the US marine biota, along with identification tools. The macrobiota is taxonomically relatively well known, so assembly of such a resource would involve mostly coordination and synthesis. A small group of mission-oriented master taxonomists – including those at the Biodiversity Observation Center(s) – could produce a checklist and assemble identification tools in about a decade, enhancing them with images and DNA sequences as they become available. But it is essential to the US to help compile global checklists and identification tools so that invasive organisms can be recognized and identified, a task that should involve all taxonomists of marine organisms in the US. Linking such resources with initiatives like the Encyclopedia of Life, OBIS, and WoRMS would improve the usefulness of them all. Importantly, collection infrastructure to house and care for the volume of voucher specimens generated by surveys must be enlarged and improved. It is impractical and unwise to have a single central repository for these specimens; rather, enhancing existing natural history collection facilities in the US that are publicly accessible (including both personnel and physical facilities) would strengthen another vital component of the biodiversity infrastructure so these facilities could collectively accommodate the many specimens to be archived. Making biodiversity data accessible and user-friendly is central to advancing all of the OPTF National Ocean Policy Priority Objectives, but is particularly relevant to Objectives 3 (Improve Understanding), 6 (Ecosystem Protection), and 9 (Infrastructure).

Photo by: Mary Lou Frost

5. Invest in developing new approaches for automated sample processing. Molecular sequencing and optical and acoustic imaging, as well as traditional specimen-based sampling, result in volumes of data and samples that can rapidly overwhelm the existing capacity of personnel to process and organize. Workshop participants recommended that, in implementing an integrated marine BON, major effort should be devoted to developing systems that can automate processing and organization of biodiversity observations to eliminate this bottleneck. Innovations might include image recognition systems, including automated processing of genetic samples, algorithms for species recognition, and informatics tools to efficiently link molecular data,

morphological data, images, and taxonomic data from new surveys and legacy data. Strategic investments in this area will likely pay for themselves in relatively short order by reducing the labor involved in processing the large streams of data expected from a BON. This recommendation is key to advancing OPTF National Ocean Policy Priority Objective 9 (Infrastructure), which underpins most of the other Objectives.


Photo by: Paulo Maurin

6. Modernize and enhance the nation's physical infrastructure for marine exploration. The US fleet of marine vehicles capable of working at depths greater than 4500 m was judged inadequate to achieve a basic assessment of deep-sea biodiversity even in US territorial waters. The cost of using most such vehicles for federally funded projects (not including ship costs and mobilization/demobilization) is so high as to make their use prohibitively expensive for most purposes by members of the scientific community. Workshop participants recommended support for an expanded—and affordable—fleet of ROVs and AUVs suited for deep-water deployment, with capacity for event sampling, automated image processing, and other types of modern data-gathering currently available; flexibility is essential for accommodating technologies currently in development or to come during the lifetime of the vehicle. This recommendation is key to advancing OPTF National Ocean Policy Priority Objective 9 (Infrastructure), which underpins most of the other Objectives.
7. Initiate an integrated marine BON demonstration project as soon as possible. The goal is to prove the concept of an end-to-end observation program — from intraspecific genetic variation through species to remotely sensed habitat-level diversity — at one or more sites, preferably by leveraging existing programs and infrastructure that are particularly well developed. This project will serve to field-test and compare several proposed methodological approaches to a BON (Appendix 4) in the same system, and to evaluate the feasibility and cost of integrating across scales and methods in a single system. The latter goal includes 1) linking the catalog of molecular diversity to organism morphologies by means of specimens and images, and linking them, in turn, to valid taxon names; and 2) ground-truthing remotely sensed habitat-level data (which involves collecting both specimens and information on the abiotic environment) to coincide in time and space 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 (through the NOPP process). This recommendation is key to advancing OPTF National Ocean Policy Priority Objective 9 (Infrastructure), which underpins most of the other Objectives.

CASE STUDIES

Case studies, which were assembled by break-out groups, were meant to outline realistic models of marine BONs by habitat, including specific suggestions for siting and for building on existing facilities and programs. Among the common themes to emerge from these deliberations was the observation that the results of the considerable effort already being expended on monitoring efforts related to marine biodiversity studies and resource management are not integrated. A marine BON must integrate existing programs with new approaches at all levels, explicitly including incentives and resources for coordinating and standardizing. In addition, considerable legacy data exist. Assembling and synthesizing the existing programs and data is necessary to identify trends, as well as gaps in taxonomic, spatial, and temporal coverage. Over all, linking biodiversity surveys that capture data at all scales – from microbes to whales, from instants to centuries, and from bottles that sample water to entire ecosystems – is essential, as is determining the scale for monitoring to address particular questions. Initially, sampling will have to be frequent and intensive; as knowledge of an area grows, it can focus on particular places, taxa, or times of year.

Comprehensive understanding will require use of conventional and new technologies. Extending operational systems is a practical way to capitalize on existing logistics, so planned and recently-launched observing sites and systems should be extended to include additional types of observations and data. Extending these systems will also allow identification of methodologies that can be adapted to study taxa, regions, or processes other than those for which they were designed. In particular, routine automation of some new acoustic and imaging technologies could expand the spatial and temporal ranges and the resolution of the systems.

A notable gap is in understanding the spatial and temporal patterns of diversity not only of small organisms such as archaea, bacteria, protists, and viruses, but also of large, mobile predators like turtles, birds, and marine mammals. The small organisms, which are far less well known taxonomically, are likely to be easiest to sample and to characterize (by molecular methods), and may, coincidentally, be the best indicators of rapid change in habitats and biomes as well. However, although well known taxonomically, the large organisms are more difficult to sample. Electronic logging tags permit understanding of their spatial and temporal distribution, leading to knowledge of multi-species aggregations or 'biodiversity hotspots'. For example, areas of high productivity that attract northern elephant seals also are important to a variety of sharks, fishes, turtles, seabirds, and mammals[20]. Both unstudied areas and those that have been subject to research should be included in a marine BON, the former in part to assess representativeness of the studied areas, the latter providing an information base. Prime theoretical considerations in selecting sites include richness and representativeness of both taxa and habitats, likelihood of threat by pollution (including noise), and sensitivity to climate forcing (sites located at the periphery of physico-chemical realms should be targeted). Logistical feasibility is also key to siting decisions.

Understanding biology is strongly contingent on a knowledge base being built, including fostering of taxonomic expertise and resources (guides, museum collections, databases of molecular sequences and geospatial distributions, sampling and data-management protocols, etc.) at appropriate scales of space, time, and taxonomic resolution. To coordinate and help build these, a central facility is needed that would also function as an archival repository for data and for voucher specimens, and where trained professionals routinely identify specimens (based on molecular sequence analysis or morphology, as appropriate). Not only would this be efficient, it would help standardize identifications and procedures across studies and habitats.

Photo by: NOAA

The Deep Sea

The deep sea is the largest part of the biosphere, consisting of two very different, linked habitats, the pelagic and the benthic realms. For the purposes of a BON, the pelagic realm includes waters from the surface to the bottom that overlie the seabed (the benthic realm) beyond the shelf. A major challenge is determining interactions (including spatial and temporal variability) between sea floor biota and that of the water above it. Because much of the deep sea lies outside national boundaries, international and industry collaborations are essential.

Leveraging existing data sets and observing systems – Because research in the pelagic realm is very sparse except relatively near the surface, little guidance and history are available for it. Repositories of such data as are available (e.g. those assembled by the California Current Ecosystem Long-

Term Monitoring Project (LTER)) should be mined as part of the planning process. Although the utility of data collected thus far may be limited (e.g. the long-term CalCOFI dataset are restricted to the epipelagic), it may take relatively little effort and expense to increase diversity of biological data collected at long-term stations.

Reliable, long-term research on the biology of the deep benthos extends back only a few decades. Places studied include Site M at 4100 m off southern California, Davidson Seamount, and the Monterey Canyon (deep locations off the east coast, being far off shore, are logistically difficult to study). Systems to which biological sensors may be added include those in place or planned for studying physical phenomena such as earthquakes or volcanoes (e.g. NeMO). Some examples of technologies being used to study biology in shallower water that could be modified for use in the deep sea are Widder's "eye in the sea" [21] for visualizing bioluminescent organisms and motion-activated imaging at bait stations.

Integration and implementation – To include major water masses, an ideal US system would have sites on the upper and lower Atlantic seaboard of the US, along the coast of the Gulf of Mexico, on the Pacific coast of the continental US, and in the Arctic, the Aleutian Islands, and the tropical Pacific. To promote inter-regional comparisons, sites within regions would include canyons, oxygen-minimum zones, seamounts, and vents and/or seeps.

Practically, to begin to obtain comparative data, priority should be given to one Atlantic and one Pacific system along the US coast, and one in the tropical Pacific. A cabled observing network could be tied to the Discovery Corridor in the Atlantic that extends from the Fundy Isles region of Canada, and in the Northeast Pacific, a network could be tied to the planned Neptune Observatory (which should extend to the Columbia River to encompass a canyon). The passive and active listening posts recently built along the Pacific coast of North America should be linked to this system; additional ones might be sited at depth, and acoustic sensors might be added to the Argo network. A prime location for a replicate site in the tropics is the Marianas islands, with its history of research on physical and biological aspects of the Mariana Trench and associated environments; logistical support is accessible from extensive facilities in Guam.

Transformative ideas – Two possibilities for continuous sampling are autonomous collectors (such as sediment traps that periodically shift preservative-laden containers) for small organisms and images for larger ones. Both are most practical on the sea floor associated with moorings, where physico-chemical data are being collected, and AUVs and gliders dock. Samples and images could be retrieved as the vehicles are serviced and data from them are downloaded. In the pelagic realm, drifters and floats might be designed to gather smaller amounts of similar data, but ships will also be needed. As patterns and relationships are uncovered, times and places of sampling can be dictated by proxies such as climatologies. Inferences to be made from legacy data concern trends such as the similarities and differences among Bear Seamount, Davidson Seamount, and seamounts in Hawaii, and changes in the Gulf of Mexico using BOEMRE data collected in connection with mineral exploration.

Continental Shelves

US Northeast Shelf – The US northeast shelf is a highly productive large marine ecosystem influenced by prevailing advection from subpolar regions, dynamic exchanges across coastal and offshore boundaries, and proximity to dense human population centers. Some information about biodiversity status exists but knowledge is uneven and incomplete.

Leveraging existing data sets and observing systems – Long-term monitoring efforts in the region include fisheries stock assessments and protected resource surveys; sampling techniques having included nets, trawls, acoustics, aerial and shipboard observers, and more recent efforts have included acoustics, aerial survey, animal tagging, and some benthic imaging. Process studies such as the GLOBEC Georges Bank program and routine environmental monitoring by national weather buoys are also important assets. Most biological data focus taxonomically on organisms larger than macrozooplankton and spatially on areas shallower than approximately 350m.

Integration and implementation – Extending spatial, temporal, and taxonomic coverage to fill gaps in current observing programs will lead to a comprehensive BON with modest additional ship time. This will, however, require major enhancements in human capital and resources for data analysis and synthesis. Routine survey cruises (for assessment of managed stocks and resources, and environmental monitoring) should be supplemented with automated organism imaging and classification systems for plankton, continuous acoustic measurements for zooplankton and fish, grab sampling for benthic infauna, and enhanced water sampling for microscopic and molecular analyses of microbes. Readily-accessible near-shore sites can contribute to detailed characterization of shelf biodiversity; importantly, they can help ground-truth innovative developments in ship-free offshore sampling, including use of automated underwater vehicles, floats, or moorings for passive acoustic sampling of mammals, and unmanned aerial vehicles for surface surveys of seabirds, mammals, and some turtles.

Image by: Monterey Bay National Marine Sanctuary

Transformative ideas – Focus should be on intense biodiversity monitoring along selected cross-shelf transects – new Discovery Corridors - in light of historical information that cross-shelf variations in water masses profoundly affect biodiversity. These transects could be done in conjunction with upgraded resources management surveys that span the entire region multiple times per year. The intense surveys would require state-of-art biodiversity assessment techniques ranging from molecular to organism and community scales. Discovery Corridors could be located to leverage existing near-shore 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 NSF's Ocean Observatories Initiative, and the slope-to-deep sea time series provided by long term occupation of the Line W moorings. Combining such sea-based sampling approaches with remote sensing observations would bridge scales of spatial, temporal, and taxonomic variation.

US West Coast Shelf – The narrow continental shelf and slope associated with the California Current large marine ecosystem is highly productive and influenced by a seasonal coastal upwelling that can have large implications for both benthic and pelagic ecosystems and their coupling. The steepness of the slope and its proximity to shore means that habitats from intertidal to coastal to open ocean exist within a relatively small area.

Leveraging existing data sets and observing systems – Currently, clusters of activity in ocean monitoring activities are centered in Oregon, Monterey / San Francisco Bays, and Southern California, each spanning a range in latitude, upwelling influence, and degree of human impact / urbanization. For example, the quarterly CalCOFI cruises off southern and central California collect data on phytoplankton biodiversity and zooplankton biomass and biodiversity, as well as a suite of physical parameters. PISCO surveys intertidal and shallow subtidal diversity. Additional sampling of phytoplankton from piers occurs as part of monitoring for harmful algal blooms. The TOPP program has approximately 2,500 datasets from electronic tags for 23 species of sharks, turtles, seabirds, and marine mammals[22]. Thus, pieces of the infrastructure of a BON are already in place.

Integration and implementation – Among gaps to be filled are those concerning offshore benthic biodiversity. PacOOS and/or the West Coast Governors' Agreement on Ocean Health might be used to facilitate integrating projects in Oregon, California, and Washington to produce a coast-wide BON. Integrating pelagic and benthic and nearshore and offshore observations will be key to developing a comprehensive understanding of biodiversity trends.

Transformative ideas – A coordinated network integrating existing efforts with some new ones would permit addressing such fundamental problems as how biodiversity responds to climate fluctuations on scales from interannual to decadal associated with El Niño / La Niña Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) cycles. A range of locations would allow understanding of how variation in diversity affects resilience of regional assemblages to perturbation. The explicit linking of observing systems across habitat types (benthic-pelagic or nearshore-offshore) would also raise the possibility of assessing whether patterns of mass or energy transfer across ecosystems are paralleled by gradients in diversity.

Nearshore Regions, Estuaries, and Great Lakes

Estuaries, near-shore coastal regions, and the Great Lakes are some of the most productive aquatic habitats in the US, generating a wide array of goods and services. They are also the aquatic regions most impacted by human activities, including being entry points of non-indigenous, invasive organisms.

Leveraging existing data sets and observing systems – A proposed marine BON would make use of the background data available in many near-shore locations and from conservation and monitoring programs such as the National Estuary Research Reserve System[23]. Among many long-term monitoring programs are two in Narragansett Bay that have documented decade-scale changes in nutrient cycling, phytoplankton, zooplankton, and fish community dynamics[24]. Chesapeake Bay is the site of several long-term studies on plankton and nutrient dynamics (e.g. LMER/LTER, ECOHAB, national and state monitoring programs); approximately 50 years of collated biological and physical data are publicly available[25]. Other LTER sites on the east coast with aquatic elements – in Massachusetts, Virginia,

Photo by: Claire Fackler

Georgia, and Florida (see MIRADA-LTERs[26] for some examples) – have biodiversity observations that could become part of integrated long-term studies of ecosystem change, trophic dynamics and biogeochemical processes. In Lake Michigan, long-term seasonal plankton and benthos monitoring programs are run by the NOAA Great Lakes Environmental Research Laboratory, the US EPA makes semi-annual observations of the offshore region of the entire lake, and annual lake-wide fisheries surveys are made by the USGS. Several programs aimed at preventing aquatic invasive organisms (Marine Invasions Research Lab, NEMESIS, NBIC, etc.) are located on estuaries and the Great Lakes. The BON could also leverage the Great Lakes Observing System (GLOS[27]).

Integration and implementation – Marsh/intertidal and shallow vegetated regions can be surveyed for components of plant or habitat biodiversity over relatively large scales using air- or space-borne platforms (e.g. satellite and aircraft imagery, LIDAR). Aerial surveys would be complemented by on-the-ground transects for visual assessment of species composition and collection of specimens for morphological identification and genetic analyses. Deeper waters would be surveyed through a combination of buoy-based instrumentation for semi-continuous sampling (using, e.g., passive imaging, gliders). Data on environmental forcing from such a moored platform would be supplemented by periodic cruises to collect specimens for biotic inventories (bottom grabs for microbes and invertebrates, net tows for bottom and mid-water fishes and zooplankton, and Niskin bottles for microplankton). Cruises should include acoustics for mapping bottom landscapes and habitat diversity, which would be ground-truthed by the collections. The approach described here for estuaries could be adapted to many near-shore marine and freshwater habitats.

Transformative ideas – Near-shore environments provide ideal opportunities for initial tests of several proposed marine BON approaches because of their relative ease of access and long history of exploration, resulting in comparatively well-known taxonomy and ecology, and a good baseline to extend. This aspect also makes them ideal for perceiving aquatic invasive organisms; a thorough and responsive BON could detect new arrivals, supporting attempts to eradicate them before they establish. Many key habitat-formers are emergent plants (for example, marsh grass and mangroves) that are amenable to observation by remote sensing and thus to linking biodiversity observations from regional to micro-scales.

Coral Reefs

Coral reefs are arguably the most diverse and among the most imperiled of marine ecosystems, so a BON focused on reefs is essential as well as challenging. On an areal basis, reefs are minor in the continental US, but vast areas are under US jurisdiction in Micronesia, Samoa, the central Pacific, and the Caribbean, and 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 study and monitoring of reefs, which have a long history, encompass broad spatial, temporal, and taxonomic scales, providing proof of concept for a marine BON extending from intraspecific genetic variation through species to remotely sensed habitat-level diversity.

Leveraging existing data sets and observing systems – Coral reefs are most prevalent in shallow, clear waters, so multi- and hyper-spectral imagery from aircraft and satellites can provide local to global coverage, differentiating habitat and community types, including sea-grass beds, coral rubble, and various types of coral communities. The Millennium Coral Reef project, a collection currently numbering about 1500 Landsat-acquired multispectral images, provides a baseline for assessing current reef status around the globe. Aircraft-based hyperspectral coverage, with some field spectroradiometric ground-truthing, is also available for large reef tracts including the Florida Keys, Puerto Rico, and the US Virgin Islands.

Well-established monitoring programs that survey reefs, most with transects and quadrats using observers and video and still imagery, include Australia's Long Term Monitoring Project of the Great Barrier Reef and NOAA's Reef Assessment and Monitoring Program of US Pacific Islands. Because they typically focus on fishes and corals, these surveys miss the bulk of reef diversity, which comprises other invertebrates and microbes. ARMS devices[28], which sample sessile and sedentary reef organisms by mimicking the structural complexity of hard bottom habitats, were developed to address this taxonomic gap in monitoring. Next-generation sequencing methods that target single gene loci (e.g. 18S, 28S, and 16S mitochondrial ribosomal RNA, COI) are being tested for environmental barcoding to characterize organisms that have colonized ARMS.

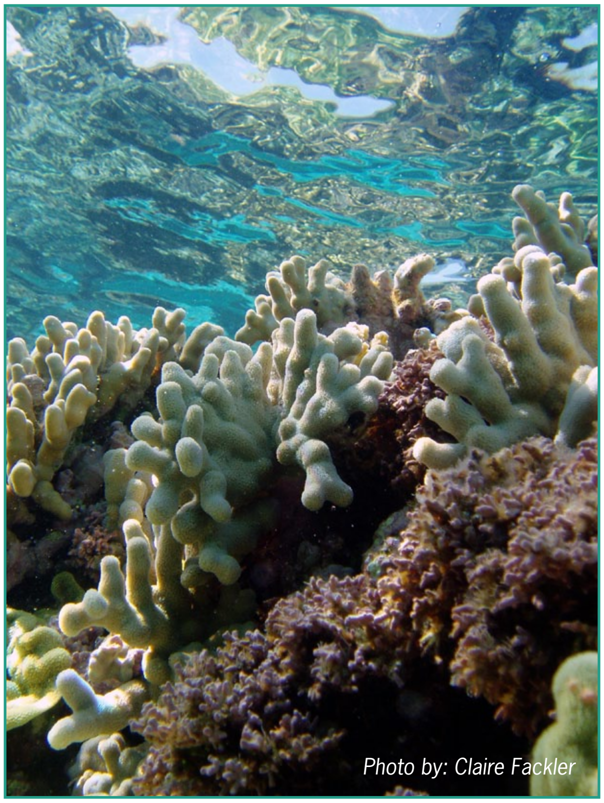
Photo by: Claire Fackler

Integration and implementation – The components of a marine BON could be readily linked for coral reefs; many are already in place for the French Polynesian island of Moorea. The Moorea Biocode project intends to document and characterize all species on the island, based on collecting voucher specimens from which images and genetic barcodes have been obtained, and including ARMS, to sample quantitatively the reef cryptobiota for the first time. The CRIOBE field station has 40 years of reef monitoring data, and the recently-established LTER site (through the University of California Gump field station) is collecting geochemical and physical oceanographic measurements, as well as characterizing ecological communities in depth. MIRADA-LTER is also conducting an inventory of microbial diversity in Moorea's waters.

Transformative ideas – The broad range of methods available makes coral reefs an excellent proof of concept habitat for a marine BON, allowing capture of data at all scales from microbes to the entire coral reef ecosystem. Remote sensing could monitor ecosystem response over large spatial scales, with triggers when observations or models predict major stresses having potential for drastic impacts, as is done by the NESDIS Coral Reef Watch Satellite Monitoring program[29], which monitors and models ocean temperature data to warn of warming events that could cause coral bleaching. Genetic characterization of some reef biotas would allow applications of environmental DNA sampling such as sequencing gut contents (for study of food webs) or plankton samples (to understand recruitment dynamics).

REFERENCES AND WEBSITES CITED

1 Palumbi, S. R., P. A. Sandifer, J. D. Allan, M. W. Beck, D. G. Fautin, M. J. Fogarty, B. S. Halpern, L. S. Incze, J. A. Leong, E. Norse, J. J. Stachowicz, and D. H. Wall. 2009. Managing for ocean biodiversity to sustain marine ecosystem services. Frontiers in Ecology and the Environment 7:204-211.

2 MEA. 2005. Ecosystems and Human Well-being: Biodiversity Synthesis. World Resources Institute, Washington, DC.

3 http://www.whitehouse.gov/files/documents/OPTF_FinalRecs.pdf

4 Stachowicz, J. J., J. F. Bruno, and J. E. Duffy. 2007. Understanding the effects of marine biodiversity on communities and ecosystems. Annual Review of Ecology Evolution and Systematics 38:739-766.

5 Foley, M. M., B. S. Halpern, F. Micheli, M. H. Armsby, M. R. Caldwell, C. M. Crain, E. Prahler, N. Rohr, D. Sivas, M. W. Beck, M. H. Carr, L. B. Crowder, J. Emmett Duffy, S. D. Hacker, K. L. McLeod, S. R. Palumbi, C. H. Peterson, H. M. Regan, M. H. Ruckelshaus, P. A. Sandifer, and R. S. Steneck. 2010. Guiding ecological principles for marine spatial planning. Marine Policy 34:955-966.

6 Pimm, S. L., G. J. Russell, J. L. Gittleman, and T. M. Brooks. 1995. The future of biodiversity. Science 269:347-350.

7 Hendriks, I. E., C. M. Duarte, and C. H. R. Heip. 2006. Biodiversity research still grounded. Science 312:1715-.

8 Sala, E. and N. Knowlton. 2006. Global marine biodiversity trends. Annual Review of Environment and Resources 31:93-122.

9 IPCC. 2007. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland.

10 Worm, B., E. B. Barbier, N. Beaumont, J. E. Duffy, C. Folke, B. S. Halpern, J. B. C. Jackson, H. K. Lotze, F. Micheli, S. R. Palumbi, E. Sala, K. A. Selkoe, J. J. Stachowicz, and R. Watson. 2006. Impacts of biodiversity loss on ocean ecosystem services. Science 314:787-790.

11 Schindler, D. E., R. Hilborn, B. Chasco, C. P. Boatright, T. P. Quinn, L. A. Rogers, and M. S. Webster. 2010. Population diversity and the portfolio effect in an exploited species. Nature 465:609-612.

12 Lotze, H. K., H. S. Lenihan, B. J. Bourque, R. H. Bradbury, R. G. Cooke, M. C. Kay, S. M. Kidwell, M. X. Kirby, C. H. Peterson, and J. B. C. Jackson. 2006. Depletion, degradation, and recovery potential of estuaries and coastal seas. Science 312:1806-1809.

13 Halpern, B. S., S. Walbridge, K. A. Selkoe, C. V. Kappel, F. Micheli, C. D'Agrosa, J. F. Bruno, K. S. Casey, C. Ebert, H. E. Fox, R. Fujita, D. Heinemann, H. S. Lenihan, E. M. P. Madin, M. T. Perry, E. R. Selig, M. Spalding, R. Steneck, and R. Watson. 2008. A global map of human impact on marine ecosystems. Science 319:948-952.

14 Webb, T. J., E. Vanden Berghe, and R. O'Dor. 2010. Biodiversity's big wet secret: the global distribution of marine biological records reveals chronic under-exploration of the deep pelagic ocean. PLoS One 5(8): e10223.

15 http://www.neoninc.org

16 http://www.earthobservations.org/geobon.shtml

17 Yilmaz, P. et al. 2010. The "Minimum Information about a MARKer gene Sequence" (MIMARKS) specification. Nature Preceedings. doi:10.1038/npre.2010.5252.2

18 http://siarchives.si.edu/findingaids/FARU0610.htm

19 http://www.niwa.co.nz/our-science/aquatic-biodiversity-and-biosecurity

20 http://seamap.env.duke.edu

21 http://www.pbs.org/wnet/nature/episodes/the-beauty-of-ugly/interview-dr-edith-widder/426/

22 http://www. topp.org

23 http://www.nerrs.noaa.gov

24 http://www.gso.uri.edu/phytoplankton, http://www.gso.uri.edu/fishtrawl

25 http://www.chesapeakebay.net/dataandtools.aspx?menuitem=14872

26 http://amarallab.mbl.edu

27 http://glos.us

28 http://www.pifsc.noaa.gov/cred/arms.php

29 http://coralreefwatch.noaa.gov/satellite/index.html

APPENDIX 1. WORKSHOP AGENDA

Attaining Operational Marine Biodiversity Observations: A Workshop to Determine the Status of Current Abilities and Scope Future Solutions

Consortium for Ocean Leadership
1201 New York Avenue NW, Fourth Floor, Washington, DC
May 24–27, 2010

GOAL: Identifying the BEST OPTIONS for IMPLEMENTING a Local, National and Global Biodiversity Observing Network (BON)

Monday, 24 May

8:30–9:00	Assemble/Breakfast
9:00–9:20	Opening Remarks – Welcome Ocean Leadership, Federal Sponsors

I. INTRODUCTION

9:20–9:40	Introduction to the Overarching Goal Regarding Marine Biodiversity Monitoring *– J. Stachowicz*

II. HABITATS

9:40–10:10	Overview of Benthic Habitats: Shallow/ Deep *– E. Duffy*
10:10–10:30	Q&A
10:30–10:45	Break
10:45–11:15	Overview of Pelagic Habitats: Shallow/ Deep *– T. Rynearson, H. Sosik*
11:15–11:45	Q&A
11:45–12:15	Lunch
12:15–1:15	(No. 1) Breakout Groups to Discuss Major Challenges and Opportunities by Habitat *– Facilitated by SC members*
1:20–1:50	Breakout Summaries (10 minutes per group) *– SC members*

III. TAXONOMY

1:50–2:20	Overview of Taxonomy Issues: Microbes to Metazoa *– G. Paulay, L. Amaral–Zettler*
2:20–2:40	Q & A
2:40–2:55	Break
2:55–3:55	(No. 2) Breakout Groups to Discuss Major Taxonomic Challenges and Opportunities *– Facilitated by SC members*
4:00–4:30	Breakout Summaries (10 minutes per group) *– SC members*
4:30–5:00	Day 1, Wrap–up Discussion / Review *– SC Chairs*

Tuesday, 25 May

8:00–8:30	Breakfast

IV. METHODS

8:30–9:00	Overview of Existing and Anticipated Biodiversity Observing Methodologies *– T. Rynearson*
9:00–9:20	Q&A
9:20–10:20	Breakout Groups to Identify Major Methodological Challenges and Opportunities *– Facilitated by SC members*
10:20–10:35	Break
10:35–11:20	Breakout Groups continued *– Facilitated by SC members*
11:25–11:55	Breakout Group summaries *– SC members*
11:55–12:25	Lunch
12:25–1:25	Small groups to Review Objectives of the BON, formulate 5 most–important questions a BON could address *– Facilitated by SC members*
1:30–2:00	Plenary to discuss top 5 questions from each group
2:00–2:15	Break
2:20–4:20	Breakout Groups to Discuss Habitats, Taxa, Methods that would Best Address Objectives *– Facilitated by SC members*
4:20–5:00	Breakout Summaries (10 minutes per group) *– SC members*
5:05–5:30	Wrap–up Discussion / Review *– Steering Committee Chairs*
6:30–9:00	Joint reception with the Revolution of Science through Scuba Symposium at the Smithsonian National Museum of Natural History Ocean Hall.

Wednesday, 26 May

8:30–9:00	Breakfast

VI. Synthesis

9:00–11:00	(No. 5) Breakout Groups Condense and Prioritize Taxa and Methods, Address BON Questions – How often to sample as a function of habitat, taxa and methods? – *Facilitated by SC members*
11:00–11:15	Break
11:15–12:15	Breakout Group Summaries/Plenary Review of BON Options – *SC members*
12:15–12:45	Lunch
12:45–2:30	Breakout Groups Discuss Linking Spatial, Temporal, and Taxonomic Scales – What might be transformative? Existing Programs–What makes them successful? Legacy data? OOI? – *Facilitated by SC members*
2:30–3:00	Break
3:00–4:00	Case Study Examples by Participants – *SC members, Participants*
4:00–4:30	Identify Action Items (Online Forum for Comments) – Participants, Community, Federal – *SC members, Participants*

Thursday, 27 May

Steering Committee Wrap–Up

9:00–2:30	Steering Committee Workshop Synthesis

VII. TIMELINE

June–Dec.	Workshop Synthesis Posted to Online Forum for Public Comments, Moderated by the Steering Committee; Workshop Results Presented at Major Conferences
Jan. 2011	Workshop Summary, and Online Forum Comments, Presented to Interagency Working Group on Ocean Partnerships Ad Hoc Group on Biodiversity
Feb. 2011	Ad Hoc Group on Biodiversity to Consider BON Implementation Steps

APPENDIX 2. PARTICIPANT LIST

Steering Committee

Amaral-Zettler, Linda	Marine Biological Laboratory
Duffy, J. Emmett	Virginia Institute of Marine Science
Fautin, Daphne	University of Kansas
Paulay, Gustav	University of Florida
Rynearson, Tatiana	University of Rhode Island
Sosik, Heidi	Woods Hole Oceanographic Institution
Stachowicz, John	University of California-Davis

Workshop Participants

Best, Ben	Duke University
Bowen, Don	Fisheries and Oceans Canada
Caley, Julian	Australian Institute of Marine Sciences
Caron, David	University of Southern California
Clark, Chris	Cornell University
Costa, Dan	University of California-Santa Cruz
Diaz, Bob	Virginia Institute of Marine Science
Etter, Ron	University of Massachusetts-Boston
Fogarty, Mike	National Marine Fisheries Service
Frank, Ken	Dalhousie University
Galagan, James	Boston University
Geller, Jon	Moss Landing Marine Laboratory
Guild, Liane	National Aeronautics and Space Administration
Guinotte, John	Marine Conservation Biology Institute
Haddock, Steve	Monterey Bay Aquarium Research Institute
Jaffe, Jules	Scripps Institution of Oceanography
Lawson, Gareth	Woods Hole Oceanographic Institution
Levin, Lisa	Scripps Institution of Oceanography
Meyer, Chris	Smithsonian Institution
Ohman, Mark	Scripps Institution of Oceanography
Reid, Philip	University of Plymouth
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Workshop Sponsors

Beach, Reginald	National Oceanic and Atmospheric Administration / Office of Oceanic and Atmospheric Research
Breuer, Eric	National Oceanic and Atmospheric Administration / National Marine Fisheries Service
Canonico, Gabrielle	National Oceanic and Atmospheric Administration / National Ocean Service
Eckman, Jim	Office of Naval Research
Garrison, Dave	National Science Foundation / Geosciences
Gisiner, Bob	Marine Mammal Commission
Lindstrom, Eric	National Aeronautics and Space Administration / Earth Science Division
Meyer, Chris	Smithsonian Institution
Snyder, Scott	National Science Foundation / Biological Sciences
Ticco, Paul	National Oceanic and Atmospheric Administration / National Ocean Service
Turner, Woody	National Aeronautics and Space Administration / Headquarters Science Mission Directorate
Valdes, Sally	Bureau of Ocean Energy Management, Regulation, and Enforcement
Weise, Michael	Office of Naval Research

Additional Attendees

Armaiz-Nolla, Kamil	Consortium for Ocean Leadership
Bohan, Margot	National Oceanic and Atmospheric Administration
Decker, Cynthia	National Oceanic and Atmospheric Administration
Feldman, Michael	Consortium for Ocean Leadership
Ford, Michael	National Oceanic and Atmospheric Administration
Goodwin, Hilary	Consortium for Ocean Leadership
Innes, Mina	Marine Mammal Commission
Moustahfid, Hassan	National Oceanic and Atmospheric Administration
Simmons, Samantha	Marine Mammal Commission
Wolfe, Bret	US Fish and Wildlife Service
Zimmermann, Leigh	Consortium for Ocean Leadership

APPENDIX 3. ACRONYMS AND ABBREVIATIONS

ARMS	Autonomous Reef Monitoring System
AUV	Autonomous Underwater Vehicle
BOEMRE	Bureau of Ocean Energy Management, Regulation and Enforcement
BON	Biodiversity Observing Network
CalCOFI	California Cooperative Oceanic Fisheries Investigations
CRIOBE	Le Centre de Recherches Insulaires et Observatoire de l'Environnement de Polynésie Française
DNA	Deoxyribonucleic Acid
ECOHAB	Ecology and Oceanography of Harmful Algal Blooms
ENSO	El Niño / La Niña Southern Oscillation
EPA	Environmental Protection Agency
GEO BON	Group on Earth Observations Biodiversity Observation Network
GLOBEC	Global Ocean Ecosystem Dynamics
GLOS	Great Lakes Observing System
IPCC	Intergovernmental Panel on Climate Change
IT	Information Technology
IWG	Interagency Working Group
IWG-OP	Interagency Working Group on Ocean Partnerships
JSOST	Joint Subcommittee on Ocean Science and Technology
LIDAR	Light Detection And Ranging
LMER	Land Margin Ecosystem Research
LTER	Long Term Ecological Research
MEA	Millennium Ecosystem Assessment
MIRADA	Microbial Inventory Research Across Diverse Aquatic
MMS	Minerals Management Service
NASA	National Aeronautics and Space Administration
NBIC	National Ballast Information Clearinghouse
NEMESIS	National Exotic Marine and Estuarine Species Information System
NEON	National Ecological Observatory Network
NeMO	New Millennium Observatory
NESDIS	National Environmental Satellite, Data, and Information Service
NOAA	National Oceanic and Atmospheric Administration
NOP	National Ocean Policy
NOPP	National Oceanographic Partnership Program
NSF	National Science Foundation
OBIS	Ocean Biogeographic Information System
OPTF	Ocean Policy Task Force
ONR	Office of Naval Research
PacOOS	Pacific Coast Ocean Observing System
PDO	Pacific Decadal Oscillation
PISCO	Partnership for Interdisciplinary Studies of Coastal Oceans
RNA	Ribonucleic Acid
ROV	Remotely Operated Vehicle
R/V	Research Vessel
TOPP	Tagging of Pacific Predators
USGS	United States Geological Survey
WoRMS	World Register of Marine Species

APPENDIX 4. MONITORING APPROACHES AND METHODS

Preliminary list of approaches and methods considered potentially useful in monitoring marine biodiversity, as well as existing monitoring programs, providing a flavor for the feasability of biodiversity monitoring across a range of spatial and taxonomic scales using currently available technologies. The list was compiled with input from various sources and is not exhaustive. Comments from the community that wil be useful in expanding and filling in the table are welcome.

	System/Program Name	Taxa Monitored	Environment	Purpose	Analyses	Description
1	**Colonization-trap methods**					
1.01	**Autonomous Reef Monitoring System (ARMS)**	Epifaunal macroinvertebrates: diversity and abundance of colonists	Benthic hard substrata, shallow (Coral Reefs)	Designed to systematically assess and compare indices of invertebrate biodiversity across gradients of biogeography, environmental conditions, and anthropogenic stress over time.	Morphological taxonomy; Barcode of Life DNA; Mass parallel sequencing (454) proposed for large-scale efforts.	Long-term devices designed to mimic the structural complexity of benthic habitats for collecting colonizing invertebrates (following Martin et al).
1.02	**Sediment trays**	Infaunal macroinvertebrates: diversity and abundance of colonists	Benthic soft substrata, deep sea	To quantify recruitment and the assembly of of soft-sediment communities under different flow regimes and sediment characteristics. Can be used at various temporal and spatial scales	Invertebrate diversity, Community structure and temporal dynamics	Trays are used to mimic specific sediment substrates and sample the natural communities.
1.03	**Granite blocks**	Epifaunal macroinvertebrates: diversity and abundance of colonists	Benthic hard substrata, shallow	Designed to mimic rock wall habitats to quantify community assembly and to experimentally manipulate biotic and abiotic forces. Can be oriented vertically or horizontally	Invertebrate diversity, Community structure and temporal dynamics	Long-term blocks designed to mimic rock wall habitats (Miller and Etter 2008)
1.04	**Disc rack - Virtue Project**	Epifaunal macroinvertebrates: abundance and diversity of colonists	Marine Environment	Educational tool, standardized method to look at communities. Apparently widespread in the EU	Invertebrate diversity, Community structure and temporal dynamics	A simple rack hung or suspended with CDs separated from one another (thus providing upper and underside surfaces)
1.05	**Settlement plates**	Epifaunal macroinvertebrates: abundance and diversity of colonizing recruits	Benthic substrata, shallow	monitor recruitment	sessile fauna diversity and ecological interactions	Old-fashioned, "2D ARMS"
2	**Field survey methods**					
2.01	**Photoquadrats/rock walls**	Epifaunal macroinvertebrates: abundance and diversity	Benthic hard substrata, shallow	To monitor changes in community dynamics, biodiversity and the impacts of climate change and invasive species. Can be used on larger scales to explore regional and global biogeographic forces.	Community structure and temporal dynamics	Long-term quadrats on existing rock walls that are visited on a regular basis. Diversity and temporal dynamics can be easily quantified from photos.
2.02	**MARINe (Multi-agency Rocky Intertidal Network: www.marine.gov)**	Epifaunal macroinvertebrates and algae: abundance and diversity	Benthic hard substrata, shallow	Designed to assess population and community dynamics as well as size structure over time	Population and community metrics, Size structure analyses (all over time)	Marine Rocky reefs along west coast of NA (since 1992 in many sites)
2.03	**CBS (Coastal Biodiversity Surveys: http://cbsurveys.ucsc.edu/)**	Epifaunal macroinvertebrates and algae: abundance and diversity	Benthic hard substrata, shallow	Designed to provide spatially explicit maps of species distribution at sites across the intertidal gradient	Biogeographic analyses of biodiversity and community composition	Marine Rocky reefs along west coast of NA; Spatially explicit (X,Y,Z) assesment of biodiversity
2.04	**Long-Term Monitoring Program**	fishes and macrobenthic invertebrates: diversity, long-term temporal and spatial dynamics	coral reefs	long term monitoring of the GBR	standardized reporting, various scientific papers	
2.05	**SeagrassNet**	Seagrasses: diversity and abundance. Environmental parameters	Benthic soft substrata, shallow (also some hard, and coral reef)	Designed to statistically sample seagrass habitats of all species with repeated measures to detect change over time and identify trajectories	Seagrass specied ID, percent cover, biomass, canopy height, density, change in seagrass bed size, plus temperature, light, salinity and sediment	Trained monitoring teams collecting date 4x/yr at fixed transects and reporting to a common database via the internet

Construction Cost	Deployment Method	Recovery Method	Pros	Cons	Employment Duration / Shelf Life of Materials Collected	Distribution of the Technique (How Widely Used?)	POC
~$100 in materials, 3 hours labor.	Diver	Diver	Simplicity of design, low cost; Mass parallel sequencing: Quicker (minimal sorting of sample just grind up and sequence), Cost effective for large volume surveys.	Not representative of all species; Technology not yet optimized for sequencing most invertebrates yet. Genetic databases often not to species level yet.			
$300 but can vary depending on size and style	ROV/Submersible	ROV/Submersible	Important for quantifying community development in remote settings	Usually isolated from surrounding sediments precluding colonization through sediments.			
$100	Diver	Diver	Good for setting up experimental manipulations (flow, cages, etc) on hard substrates. Can be placed in specific microhabitats and can be monitored photographically.	Can be labor intensive to install and some may be removed by storms.			
Probably < $10/rack	Diver in shallow water, hang from pier? ROV or sub in deep water	Diver, ROV or SUB	Simple, useful educational tool, can engage school children, college students. Can be used globally due to ready materials and low cost	CD surfaces may only attract a subset of the hard substrate fauna. Isolation from natural substrate may create artifacts	uncertain. Probably 1-2 years	apparently wisespread in Scandinavia, Europe	
$5	manual	manual	simple, very widely used, cheap	ID of recruits challenging morphologically if fauna not well known		very widely used, especially in intertidal and harbors	
$10 material, 1 hr labor	Diver	Diver	Fast, relatively easy and cheap. Can be easily replicated in space and time.	Some of the community might be obscurred in photos by luxuriant growth (macroalgae) or overgrowing epifauna			
Many different pieces of equipment	Field sampling by people	Field sampling by people	Very detailed and accurate assessments	Cost of personel, need for experts	NA	Along the whole Western coast of US	
Many pieces of equipment	Field sampling by people	Field sampling by people	Very detailed and accurate assessments	Cost of personel, need for experts		Along much of Western coast of North America	
	diver	n/a	long term monitoring	much is not ampled	n/a	standardized for GBR and other AIMS monitoring	
	Intertidal or diving		Standardized protocol, works for all species in the world, trains local scientists and managers, comparable date	Start up costs for site location and training required		114 sites worldwide	

	System/Program Name	Taxa Monitored	Environment	Purpose	Analyses	Description
3	**Sample-based methods**					
3.01	**Continuous Plankton Recorder**	Phytoplankton, mesozooplankton, smaller organisms: diversity and abundance. Chlorophyll, physico/chemical parameters	Epipelagic	Quantitative sampling of mesozooplankton (including meroplankton), semi-quantitative for phytoplankton and smaller constituents and fish larvae, presence/absence for coelenterates and some other planktonn on a moving band of silk of 270um mesh. One sample on silk represents 10 nautical miles of tow and 3 m3 filtered water. Production of a visual estimate of chlorophyll into 4 categories (Phytoplankton Colour index). Has been intercalibrted with SeaWifs satellite measurments.	Morphological taxonomy, DNA anlyses, photography, biomass,. Long-term changes, interocean comparisons, SEM and EM. Used to measure biodiversity, non-natives species, biomass, phenology, growing season, HAB species. Used in studies of eutrophication, ecosystem stability, ocean acidification, conservation, carrying capacity, trophic mismatch, pelagic benthic coupling.	The Continuous Plankton Recorder is an approximately 900cm long machine that samples plankton on a moving band of 270um silk at a rate that is proportional to the speed of the tow ship. A cassette system is used; one cassette equals ~500 nautical miles of tow. The machines are towed by voluntary merchant ships (Ships of Opportunity, SOOP).Survey started in June 1931, stopped during the Second World War and has sampled using Merchant ships on their regular routes each month since January 1946 in the North Sea and North Atlantic,from 1997 in the North Pacific expanding more recently into other areas of the world. >500 taxa of phytoplankton and zooplankton identified, half to species level; North Atlantic Ocean and adjacent shelf of NW Europe and part east coast USA and Canada, North Pacific, Japan to Canada and Alaskan waters, some sampling in the South Atlantic and sister surveys in the Southern Ocean,
3.02	**Multiple Opening and Closing Net and Environmental Sensing System (MOCNESS)**	Mesozooplankton, Micronekton, Nekton: diversity and abundance	Pelagic (Epi, Meso, Bathy, Abysso)	Quantitative sampling of target size class using various sized systems (1/4-m, 1-m, 10-m) and nets (100 um - 2mm)	Morphological taxonomy, DNA barcoding, live photography, biomass, silhouette photography, 454 pyrosequencing (proposed)	Stratified oblique tows with real-time environmental data (T/S/D, fluorescence, etc)
3.03	**Ship-board DNA sequencing**	All taxa: diversity	Pelagic	Accurate DNA-based species identification; species diversity (presence / absence)	DNA barcodes from Identified specimens: PCR and DNA sequencing of target gene region	ABI Automated DNA Sequencer (4-capillary GeneScan)
3.04	**Classical biological oceanographic sampling**	Phytoplankton, zooplankton: abundance (and diversity?). Chlorophyll, physico-chemical parameters	Pelagic (epi)	time series	microscopy for cell counts and spp id	tranditional time series program
3.05	**Lake Michigan Pelagic and Benthic Monitoring Program**	Phytoplankton, zooplankton, benthos, fishes: diversity and abundance. Nutrients, physical parameters	Pelagic and benthic soft substrata	Designed to describe seasonal dynamics of plankton and benthos in nearshore and offshore waters and to serve as foundation for process studies to understand the causes of changes in the ecology of the lake	Morphological taxonomy	Standard plankton and benthos monitoring using nets and benthic grab samples (ponar)
3.06	**Predator diet sampling**	Fishes and their prey: diversity and abundance	Pelagic, demersal on continental shelf	interannual and seasonal	morphological taxonomy, fatty acid signature analysis	seasonal sampling of predator diets
3.07	**Groundfish trawl survey**	Fishes: diversity and abundance	Demersal on continental shelf	spatial and temporal indices	community analyses	stratified random trawl surveys
3.08	**Research Vessel (RV) Bottom Trawl Survey**	Fishes, benthic macroinvertebrates, (recently added: zooplankton): diversity and abundance. Bottom-water temperature, (recently added: oxygen, chlorophyll)	Demersal on continental shelf	Designed to provide annual, fishery-independent indices of abundance of commercially exploited species over large spatial scales. All species are assessed, including non-commercial providing useful information on species diversity, dominance and changing compositional patterns over time.	All species are identified and measured (lengths and weights). For a sub-set of species, aging information is obtained.	For the Scotian Shelf, the RV survey was intiated in 1970 and continued un-interrupted to present. Bottom waters of the Northwest Atlantic Ocean at depths ranging from 50 to 200-300 m
3.09	**HPLC pigment analysis**	phytoplankton: abundance and higher-taxon diversity	Pelagic (epi)	phytoplankton biomass and pigment types	decomposition into class-specific pigments through optimization (e.g. Chemtax)	discrete water samples, filtered, extracted in organic solvent and analyzed with high pressure liquid chromatography

Construction Cost	Deployment Method	Recovery Method	Pros	Cons	Employment Duration / Shelf Life of Materials Collected	Distribution of the Technique (How Widely Used?)	POC
1CPR + 1Cassette and 1 Ship requiring fitting with a davit. Cost for 1 CPR/Cassette $19,000, Davit construct and instal $11,000 (varies with ship, not needed on 30% of ships) . Cable and block $500 (varies with ship). Set up costs for new route - assume 500nm tow x 12 tows per annum,	CPRs sent to ships in a standard yellow box using a normal carrier. The machine is unloaded and deployed from the stern of the vessel by the ship's crew using the normal winch and equipment on the vessel or when necessary via a small davit or in one case from an articulated arm. A 100m cable is used, marked so 22m is between the surface and the CPR.	CPR recovered by the ship's crew, If the tow is longer than 500 nautical miles the cassette system is changed by them. When tow completed the CPR is loaded in the box and returned to the laboratory for sample analysis and machine servicing. Relatively inexpensive for detail obtained.	Extensive and well proven methodology. Used extensively, more than 200,000 samples processed. Large standardised computer database of historical data. Large archive of historical samples preserved in formalin from ~1998 that are available for further analysis. No cost for the ship platform. voluntary help by ship's officers and crew. Develops a centre of expertise in plankton taxonomy.	Only samples near surface. Shipping routes can change. Some regions of the world rarely traversed by merchant ships. Some species may be selectively sampled. Laour intensive use of parataxonmists. Some organisms not preserved in formalin and disintegrated.	Can be deployed on short coastal to trans-ocean routes. Operates remotely behind the ship for days. Samples are preserved in excellent condition for many decades.	Now extensively used througout the globe, but still only covering a small area of the global oceans.	Director SAHFOS, Prof Peter Burkill. Or Philip (Chris) Reid
$50,000 - $100,000	Coastal to Ocean-Class Research Vessel	Coastal to Ocean-Class Research Vessel	Quantification and verification of valid sampling, high-volume sampling for rare species, recovery of living specimens	Deployment from research vessels	Tow length dependent on depth sampled: 2-3hrs for surface samples; 24+ hrs for deep tows (to 5000m); archived samples preserved in formalin (no end date), alcohol (2-5 years for DNA), liquid nitrogen (no end date)	MOCNESS or similar instrumented multi-net systems used world-wide	Erich Horgan (BESS) or Peter Wiebe (WHOI)
$75,000	Coastal to Ocean-Class Research Vessel	Coastal to Ocean-Class Research Vessel	Rapid at-sea confirmation of species identification	Currently done on individual specimens (labor-intensive; expensive)	Appropriate for cruises lasting weeks to months; DNA data permanent record	Not usual yet	Ann Bucklin (UConn)
combination of moorings and ships	CTD casts/ship	CTD casts/ships	well defined methods, long running sereis	limited coverage		common	Francisco Chavez
N/A	Shipboard	Shipboard	The methods are standard and seasonal sampling (if samples are processed immediately) will allow identification of invading species.	Season sampling at inshore and offshore sites is expensive. Phytoplankton taxonomy is difficult and time consuming.	Zooplankton and benthos samples have indefinite shelf life. Phytoplankton samples last only a year or two unless slides are made.	Standard. Zooplankton and benthos taxonomy is simple. Phytoplankton and microzooplankton taxonomy is difficult.	
$120/sample	live-capture	live-capture	relatively inexpensive, consistent temporal sampling, may sample some species better than research trawl surveys	may not reflect changes in prey field; subject ot bias by changing foraging distribution of predator	~20 yr	broadly	
	ship	ship	large area of consistent temporal and spatial sampling	low sampling intensity	~40 yr	continental shelves	
A large, science-dedicated vessel deploying a bottom trawl in pre-detemined geographic areas, lasting one month each year during July. The annual cost of the program is $1M CDN.	Ship	Ship	Data on fish stock status and diversity obtained independently from fishery. Standardized sampling in existence since 1970 and cover large spatial scales.	Some species not adequately sampled. High cost.		Similar surveys of exploited fish species are conducted throughout the United States, Canada and the European Seas.	
	ship, boat, pier, etc.	ship, boat, pier, etc.	Wide taxonomic range, in common use and limited taxonomic expertise required	Subject to uncertainty due to species-specific and physiological variability in pigment ratios; no in situ or automated application to date, requires immediate sample handling	indefinite storage in liquid nitrogen	in wide use in biological oceanography	

	System/Program Name	Taxa Monitored	Environment	Purpose	Analyses	Description
3.10	**454-Pyrotag sequencing**	Microorganisms, micrometazoans: diversity, some components of abundance	All environments, in principle	Provides both taxonomic and relative abundance data for Bacteria and Archaea and presence/absence data for Eukarya	rRNA gene hypervariable regions for bacteria, archaea and eukaryotes	Taxonomic resolution to genus or species possible but depends on extent of annotations in database; captures diversity information for both abundant and rare community members; ability to extend this to longer reads and barcoding applications.
3.11	**PhyloChip: Universal 16S rRNA Gene Microarray**	Microorganisms, micrometazoans: diversity (and abundance?)	All environments, in principle	The Phylochip is a microarray that uses genetic probes on the chip to match gene sequences in a water, air, or soil sample.	Microarray uses genetic probes (rRNA gene fragments) on chip to match gene sequences in water or sediment sample	The GeneChip Phylochip Manufactured by Affymetrix Corporation ® can detect up to 32,000 unique versions of the bacterieal 16S RNA gene.
3.12	**Lab-on-a-chip**	Microorganisms, micrometazoans: diversity and abundance	Pelagic		Lab-on-a-chip (LOC) probes for any gene fragment on single chip mm to a few cm square. Can be applied to real-time qPCR to detect	
3.13	**Hand-held Nucleic Acid Sequence Based Amplification (NASBA) sensor**	Microorganisms, micrometazoans: diversity (and abundance?)	Pelagic			prototype hand –held reverse-transcription Nucleic Acid Sequence Based Amplification sensor.
3.14	**Autonomous Microbial Genosensor**	Microorganisms: diversity (and abundance?)	Pelagic			in situ sensor for marine microbe detection. Based on NASBA as well.
3.15	**Environmental Sampling Platform**	Microorganisms, micrometazoans: diversity (and abundance?). Proteins and biotoxins	Pelagic	Can archive and detect in situ, can be coupled with other equipment to obtain environmental data associated with sampling event. Real-time. Expandable to other techniques.	HABS, and biotoxins DNA and protein array analyses via filtered samples	
3.16	**All Taxon Biodiversity Inventories (ATBI)**	All taxa (potentially)	All environments (potentially)	document "total" biodiversity of area	Taxonomic, genetic	Team of taxonomists and collectors document biodiversity by "saturation" sampling
4	**Mixed sample/video/acoustic methods**					
4.01	**ROV transects: mid-water time series**	Nekton, gelatinous zooplankton: diversity and abundance	Pelagic: mid-water	time series/discovery	Video, various molecular analyses	ROV transcets
4.02	**ROV transects: benthic biology**	Macroinvertebrates and fishes: diversity and abundance	Benthic soft and hard substrata, deep sea	ecology/discovery	video/discrete sampling	ROV
4.03	**Bio-Optical Multi-frequency and Environmental Recorder (BIOMAPER-II)**	Mesozooplankton: diversity and abundance. Temperature, salinity, transmittance, fluorescence	Pelagic	Sample zooplankton diversity, abundance, size		Multi-sensor system including multi-frequency echosounder, VPR, and environmental sensing system (temperature, salinity, transmittance, fluorescence)
5	**Remote sensing (optical / spectral methods)**					
5.01	**Airborne Visible Infrared Imaging Spectrometer (AVIRIS)**	Habitat-forming plants and macroinvertebrates: areal coverage and higher-taxon diversity	Benthic hard and soft substrata, shallow	Designed to support NASA's research programs with airborne measurements of upwelling spectral radiance in 224 contiguous spectral channels from 400 to 2500 nm.	Spectral analysis of shallow water benthic type and coastal vegetation type	Spectral radiance information for terrestrial and shallow water marine ecosystems; Image classification of benthic types, HAB, and coastal terrestrial cover types
5.02	**Customized Headwall Imaging Spectrometer**	Phytoplankton, habitat-forming plants and macroinvertebrates: areal coverage and higher-taxon diversity	Pelagic (epi); benthic hard and soft substrata, shallow	Designed to support NASA's ocean color and marine research airborne missions with measurements of upwelling spectral radiance in 120 contiguous spectral channels from 400 to 1000 nm.	Spectral analysis of shallow water benthic type and coastal vegetation type	Image classification of benthic types, HABs; Spectral radiance information for ocean color and shallow water marine ecosystems
5.03	**Spectroradiometer (GER1500, SpectraVista Corp) and underwater housing**	Habitat-forming plants and macroinvertebrates: areal coverage and higher-taxon diversity	Benthic hard and soft substrata, shallow	Designed to collect field spectroscopy data of terrestrial and marine ecosystem features	Spectral analysis of shallow water benthic type and coastal vegetation type	Spectral radiance curves (spectral library) for terrestrial and shallow water marine ecosystems

Construction Cost	Deployment Method	Recovery Method	Pros	Cons	Employment Duration / Shelf Life of Materials Collected	Distribution of the Technique (How Widely Used?)	POC
~30K/per run yielding ~ 1 million sequences			captures diversity information for both abundant and rare community members; ability to extend this to longer reads and barcoding applications.	Currently restricted to labs with available facilities; expensive up-front costs but different platforms promise cost reductions; not available for in situ platforms but resulting data could be adapted for use with in situ instrumentation such as ESP via phylochips, microarrays etc.		ICoMM International Census of Marine Microbes project: (http://icomm.mbl.edu); data are downloadable at the VAMPS website (http://vamps.mbl.edu). Project descriptions, DNA extraction methodology, proposals and associated metadata are found the MICROBIS pages: http://icomm.mbl.edu/microbis/project_pages/pp_by_name/ The MIRADA-LTERS project will soon have data available for fresh water and marine LTERS see http://amarallab.mbl.edu/MIRADA for project details.	Linda Amaral-Zettler
<$1000 a chip			Taxonomic resolution to genus or species possible. Another advantage is that it can be used with RNA to determine the most metabolically active organisms in a sample.	Targets known diversity and will not capture unknown or novel diversity.			
			Requires minimal reagents, fast, high-though-put, cost-effective	Still in development, detection issues, etc.			
			Isothermal amplification does not require thermocycling during the procedure. Has a high sensitivity. Can be used to detect viruses (has been tested with Noroviruses) and other microbes. NASBA assay has also been developed for the detection of rbcL mRNA from the red tide dinoflagellate Karenia brevis by Marine Microbiology Group USF.	No capacity for sample archival.			
				No capacity for sample archival.			
~$190K	Shipboard	Shipboard	real-time monitoring in situ	$$$, coastal deployment challenges, as with all in situ instrumentation – the possibility of vandalism; biofouling			Chris Scholin
reasonable efforts start at $100K	varied	varied	most taxonomically thorough; sets background taxonomic knowledge; creates taxonomic tools	mostly qualitative; relies on taxonomic experts; utility increased over long-term as samples get further studied		examples: CReefs, Biocode, BIOTAS, Bouchet inventories	
very expensive	ship	ship	robust and long running	expensive/limited range	generally hrs -day/DNA can be archived for extended periods	not widely used	Bruce Robison/Steve Haddock
							Jim Barry
~$1M	Towed from vessel		Combination of instruments allows cross-comparison, especially the use of video samples to assist in the interpretation of acoustic data	Large (1 tonne), requires a large vessel and handling system			
	Aircraft	Aircraft		Cost			NASA JPL
	Aircraft	Aircraft	Portable	Cost			NASA Ames Airborne Sensor Facility
	Diver	Diver	Portable	Time in the field			NASA Ames, Guild, PI

	System/Program Name	Taxa Monitored	Environment	Purpose	Analyses	Description
5.04	**Ocean Color Satellites (SeaWiFS, MODIS)**	Phytoplankton: abundance and higher-taxon diversity	Pelagic (deep, shallow) and both Hard and Soft Bottom environments (shallow)	Remote assessment of algal pigment stocks; rates of production; coarse taxonomy	Detect "color" differences in surface ocean via fluorescence signature of pigment, processesd via bio-optical models	Polar-orbitting satellites designed to maximize global coverage and repeat
6	**In situ optical methods**					
6.01	**Video Plankton Recorder (VPR)**	Meso- and macrozooplankton: diversity and abundance	Pelagic	Sample zooplankton diversity, abundance, size	Taxonomy	Image-forming optical system sampling a field of view of 7x7mm to 42x42mm
6.02	**In situ zooplankton imaging systems (VPR, SIPPER, LOPC, ISIIS, Ocean DIVA, UVP, ZOOVIS, etc; plus some holographic systems: Holocamera, eHolocam, Digital Holosub, etc.)**	Meso- and macrozooplankton: diversity and abundance	Pelagic	Sample zooplankton diversity, abundance, size	Taxonomy	video imaging or holographic imaging
6.03	**Flow cytometry (many lab systems, plus in situ systems: Imaging FlowCytobot, FlowCAM, Cytobuoy/Cytosub)**	Phytoplankton, some microzooplankton: diversity and abundance	Pelagic	abundance, cell size, and taxonomic groups	optical signature analysis, image analysis in appropriate cases	scattering/fluorescence and/or video imaging of single cells in flow
6.04	**Absorption spectra (ac-9, ac-s, Optical Plankton Discriminator)**	Phytoplankton: abundance (and higher-taxon diversity?). Other absorbing constituents	Pelagic	Assessment of light absorbing constitutents, potential phytoplankton pigment types	spectral decomposition, derivative analysis	submersible "shiny tube" or liquid waveguide spectrophotometry
6.05	**Fluorescence spectra (FluoroProbe, etc.)**	Phytoplankton: abundance and higher-taxon diversity (pigment types)	Pelagic	assess spectral fluorescence characteristics indicative of group-specific pigments	spectral decomposition, derivative analysis	spectral fluorometer
6.06	**Bathysnap camera system**	Macroinvertebrates and fishes: diversity and abundance	Benthic hard and soft substrata: deep sea	to monitor long term changes in benthic communities	Changes in animals, sediment-water interface (e.g., color indications of timing and duration of settlement of phytoplankton to bottom)	
7	**Animal-carried sampling (tags)**					
7.01	**Position-only/ presence-absence**	Large vertebrates: position and movements.	All environments	track migrations, habitat use, find ecosystem hotspots	Position, movements of tagged animal: track migrations, habitat use, find ecosystem hotspots	could be anything from a microchip sized acoustic fish tag to a cigarette pack sized long term seal or large fish satellite tag (ARGOS)
7.02	**Environmental sampling**	Large vertebrates: position and movements. Temperature, pressure (depth), salinity (conductivity), color (fluorimetry)	All environments	determine physical and biochemical parameters correlated with animal presence, habitat selection	use correlative models to determine physical and biochemical parameters correlated with animal presence, habitat selection: GAM, GLM, EcoSim etc	generally about the size of a cigarette pack or small computer speaker. Potted in material for depth tolerance to 2000+ meters
7.03	**Diving and behavior**	Large vertebrates: position and movements (depth, 3-D accelerometry), feeding biology	All environments	determine how animals sample the water column in 3-D, partitioning of feeding, resting, travelling, energy budgets, more	high resolution 3-D spatial modeling, statistical analyses	as above

Construction Cost	Deployment Method	Recovery Method	Pros	Cons	Employment Duration / Shelf Life of Materials Collected	Distribution of the Technique (How Widely Used?)	POC
several hundred million dollars per satellite	Rocket	None	Global coverage; long term deployment	low spectral resolution; requires ground-truthing	N/A	Relatively common due to centralized processing and distribution	
$75k	Profiled or towed from vessel, mounted on AUVs (eg REMUS), moored		High vertical resolution; processing can be done in real-time	Small sample volumes; sampling efficiency affected by density of organisms and avoidance behavior			
$100K	ship, AUV, mooring		taxonomic resolution to genus or species possible; rapid and quantitative abundance estimates; enables unprecedented space / time resolution and range; automated in situ application possible	Routine operation with taxonomic resolution requires complex data analysis systems (e.g., supervised machine learning algorithms) and manual development of training sets, cost	days to months		
$100K	ship, mooring, large AUV	ship, mooring, large AUV	taxonomic resolution to genus or species possible with imaging systems; rapid and quantitative abundance estimates; enables unprecedented space / time resolution and range; automated in situ applications exist	Routine operation with taxonomic resolution requires complex data analysis systems (e.g., supervised machine learning algorithms) and manual development of training sets, cost	months for in situ instruments, sample storage indefinite in liquid nitrogen for lab analysis	prototype in situ applications in coastal systems, ship-board analysis common for picoplankton	
$20K	ship, AUV, mooring, etc.		Wide taxonomic range within phytoplankton, rapid and relatively inexpensive, no reagents, limited taxonomic expertise required; in situ application	low taxonomic resolution (maybe class level); subject to uncertainty due to species-specific and physiological variability in spectra; confounding signals from non-phytoplankton constituents, bio-fouling	weeks to months	relatively common in marine optics community	
$20K	ship, AUV, mooring, etc.		Wide taxonomic range, rapid and relatively inexpensive, no reagents, limited taxonomic expertise required; in situ applications exist	Subject to uncertainty due to species-specific and physiological variability in spectra; confounding signals from non-phytoplankton constituents, biofouling	weeks to months	small user set to date	
$100K	ship with precise positioning by submersible	ship after acoustic release	gives very good look at long term variation in bottom community	areal coverage quite small	months to year	used rarely	
$10-800	surface or surgically implanted	FM radio, acoustic, satellite, recapture and download	cheap, deployable in large numbers, provides data on migratory routes, habitat usage patterns, ecosystem hotspots	doesn't tell you why the animal is there or what the immediate environment is like - coarse movements only, usually	weeks to years	wide	Dan Costa
$1200-4000	attached to pelage or with suction cops (short term) or barbed attachments (long term)	satellite telemetry, recovery	cheap, deployable in large numbers, can provide as many CTD casts when placed on 10 or more animals as could be obtained in 100 years of ship-based transects. Transport is free.	some sensors, like conductivity, can be sensitive to animal's electric field and must be carefully calibrated. Not programmable: animals go where they want to go. Fortunately they usually go to interesting parts of the ocean	weeks to years	wide	Dan Costa
$800 - 5000	as above	as above	can provide surprisingly detailed data about energy budgets, foraging success, behavior and habitat use	confirmatory sampling of prey fields or other data still requires ship-based sampling. Lab studies often needed to verify caloric costs/benefits	weeks to years	wide	Dan Costa

	System/Program Name	Taxa Monitored	Environment	Purpose	Analyses	Description
7.04	**Multi-sensor tags with acoustics or video**	Large vertebrates: position, movements, feeding biology	All environments	observe foraging ecology, identify prey species, prey capture behavior. Detect responses to human, conspecifics, predators	Very large data sets (Gb to Tb). Analytic methods are intensive and time consuming, even with automated processing algorithms	devices are generally 1 kg or larger, and therefore usually only attached for hours or a couple days (lg coffee cup to thermos sized)
7.05	**Multi-sensor animal tags**	Large vertebrates: position, movements, physiology. Environmental parameters and acoustics	All environments	sample throughout ocean	position, depth, temperature, oxygen, movement, sound	penetration or suction animal tags
8	**Acoustic methods**					
8.01	**Autonomous Acoustic Habitat Monitoring**	Sound-producing mammals, fishes, and other animals: diversity (and abundance)	All environments	Sample acoustic habitats to quantify spatio-temporal-spectral variability and detect occurrence and distribution of acoustically active marine animals	Noise statistics; spatio-temporal maps; animations tuned to species or groups, location, tracking	Acoustic recorders: ambient noise, species-specific acoustic signals
8.02	**Passive Acoustic Recievers**	Sound-producing mammals, fishes, and other animals: diversity (and abundance)	Pelagic and benthic: continental shelf	temporal indices	community analyses	deploymentof fixed station receivers
8.03	**Mutli-frequency echosounder**	Mesozooplankton, micronekton, fishes: abundance (and diversity)	Pelagic	Sample zooplankton/micronekton/fish diversity, abundance, size	Acoustic inversions of abundance in size/taxonomic categories	Measures acoustic backscattering
8.04	**Passive Acoustic Monitoring - autonomous**	Sound-producing mammals, fishes, and other animals: diversity (and abundance)	All environments	Sample acoustic habitats to quantify spatio-temporal-spectral variability and detect occurrence and distribution of acoustically active marine animals	Noise statistics; species detection, spatio-temporal maps; animations tuned to species or groups, location, tracking	Autonomous seafloor recorders: ambient noise, species-specific acoustic signals
8.05	**Passive Acoustic Monitoring - towed**	Sound-producing mammals, fishes, and other animals: diversity (and abundance)	All environments	Detect occurrence and distribution, and estimate relative abundance of acoustically active marine animals	Beamforming, auro-detection, tracking	Towed hydrophone array
8.06	**Passive Acoustic Monitoring - cabled**	Sound-producing mammals, fishes, and other animals: diversity (and abundance)	All environments	Sample acoustic habitats to quantify spatio-temporal-spectral variability and detect occurrence and distribution of acoustically active marine animals	Noise statistics; species detection, spatio-temporal maps; animations tuned to species or groups, location, tracking	Seafloor, cabled hydrophone arrays
8.07	**Passive Acoustic Monitoring - moored with surface expression**	Sound-producing mammals, fishes, and other animals: diversity (and abundance)	Pelagic and benthic substrata, coastal	Reduce ship strikes and quantify acoustic impacts	Noise statistics, species detection	Moored with satellite links
8.08	**Autonomous glider**	Sound-producing mammals, fishes, and other animals: diversity (and abundance?)	All environments	sample throughout ocean	oceanogrphic productivity variables and acoustics	passive glider that samples acoustics
9	**Potential Future Technologies**					
9.01	**Portable Remote Imaging Spectrometer**	Phytoplankton, habitat-forming plants and macroinvertebrates: areal coverage and higher-taxon diversity	Benthic hard and soft substrata, shallow	Small imaging spectrometer intended to fly on a variety of airborne platforms. Optimized for coastal ocean science	Spectral analysis of shallow water benthic type and coastal vegetation type	
9.02	**Next Generation Airborne Visible Infrared Imaging Spectrometer (AVIRISng)**	Habitat-forming plants and macroinvertebrates: areal coverage and higher-taxon diversity	Benthic hard and soft substrata, shallow	Designed to support NASA's research programs with measurements of upwelling spectral radiance in 224 contiguous spectral channels from 400 to 2500 nm.	Spectral analysis of shallow water benthic type and coastal vegetation type	
9.03	**Autonomous Acoustic Habitat Monitoring**	Sound-producing mammals, fishes, and other animals: diversity (and abundance)	All environments	Sample acoustic habitats to quantify spatio-temporal-spectral variability and detect occurrence and distribution of acoustically active marine animals	Noise statistics, spatio-temporal maps and animations tuned to species or groups	Acoustic recorders w on-board auto-recognition, underwater comms to AUVs and surface buoys
9.04	**imaging AUVs for water column and benthos**					
9.05	**sample collection AUVs for microbial communities (sample return)**					
9.06	**ecogenomic sensors (real-time analyses + sample return)**					

Construction Cost	Deployment Method	Recovery Method	Pros	Cons	Employment Duration / Shelf Life of Materials Collected	Distribution of the Technique (How Widely Used?)	POC
$10k-$30K	usually harnessed, attached to skin/pelage by adhesive or suction cup. Can use skin-penetrating tether (barbs) in some cases.	device must usually be recovered due to the volume and bandwidth of data	combines environmental and biological sensors with broadband stereo acoustics or hi-res video. Usually programmable sampling to prevent memory limits to useful lifespan of tag (memory gets better, smaller, cheaper all the time; 100 Gb solid state memory on small tags is now in reach)	still too large to put on small animals (<50 kg or so). Great sophistication means more things that can go wrong, greater cost, and greater operator expertise required.	usually deployed for days or hours. Data are digital and last indefinitely.	relatively few users (tens)	Dan Costa
$10k	small boats to ships	small boats to ships	small-scale and large-scale sampling to integrate animal activity with ocean ecology and habitat	recovery risk	days to many months	limited	Oregon, UCSC, WHOI, private etc
$8000/ unit	Surface vessel or diver; attach to trees, bury in ground	Surface vessel or diver	one person can deploy and retreive, lots of data	too expensive, deployment too short, data processing intensive	duration - 100+ days10+ years	all oceans, ca. 120years of data collected per year	C.W. Clark
	ship	ship	longer-term continuous monitoring	species must vocalize		continental shelves, basins	
$200k	Profiled or towed from vessel, mounted on AUVs (eg REMUS), moored		High temporal sampling frequency, high range resolution to large range	Provides only indirect measurements of zooplankton/fish, discriminating among species/groups present based on acoustic data along is challenging			
$1000-8000/ unit	Surface vessel or diver; attach to trees, bury in ground	Surface vessel or diver	one person can deploy and retreive, lots of data	too expensive, deployment too short, data processing intensive, species must produce sound	duration - 100+ days10+ years	becoming much more common, all oceans, ca. 120years of data collected per year	C.W. Clark
$400/sensor plus ancillaries	ship	ship	augments other survey methods, provides archived record for post-processing	requiresexperienced analyst, back-deck logistics	duration of cruise, 10+ yrs usage, long-term archive	very limited	C.W. Clark
>$100K	ship	not	Real-time data, beamforming	expensive maintenance and repair, fixed location	decades	very limited	C.W. Clark
>$100K	ship	ship	Near-real-time data for monitoring and mitigation, dual comms for reprogramming	expensive maintenance and repair, fixed location	years	very limited	C.W. Clark
>$25k	ship	ship	spatial sampling coupled with acoustics	glide, not active propulsion	many months	becoming more common	WHOI, SIO, UW, Duke, Industry, military
	Aircraft	Aircraft	Portable				NASA Ames Airborne Sensor Facility
	Aircraft	Aircraft					NASA JPL
$300-400/unit	Surface vessel or diver; attach to trees, bury in ground	Surface vessel or diver; detach, unbury					

	System/Program Name	Taxa Monitored	Environment	Purpose	Analyses	Description
9.07	**OOI/IOOS sustained observatories (e.g., ENDURANCE,NEPTUNE,MARS, VENUS)**	Hydrographic data, currents, DO, sound, Chlorophyll, seismic activity, nitrate, pH, pCO2	shelf, slope, vents, seeps	long term monitoring and research, ecosystem response to climate variability	video and still time series, experiments, acoustics all possible	NE Pacific Margin with nodes at 80 m, 150 m, 500 m, 3000 m; Juan de Fuca Plate
9.08	**DNA probes for invasive species (already used for Asian carp)**	All taxa	All environments			
9.09	**Autonomous Robot Swarms**	Macroinvertebrates and fishes: diversity and abundance. Environmenta parameters	Benthic soft and hard substrata, deep sea	To quantify long (or short)-term changes in deep-sea communities, abiotic environment, and ecosystem processes.	Spatial and temporal dynamics	An autonomous multiple robot system that can recharge while at sea and continue sampling and transmitting data to shore. Will allow us to sample at temporal and spatial scales that would provide novel insights into the functioning of deep-sea ecosystems.
9.10	**Broadband acoustic scattering systems (up and coming)**	Mesozooplankton, micronekton, fishes: abundance (and diversity?)	Pelagic	Sample zooplankton/fish diversity, abundance, size		Active acoustic scattering systems capable of greater species discrimination than traditional narrowband multi-frequency systems
9.11	**Stand-off optical systems (missing?)**	Mesozooplankton, micronekton, fishes: abundance (and diversity?)	Pelagic	Sample zooplankton/fish diversity, abundance, size		Image-forming optical system sampling at a distance far enough away from the instrument to minimize avoidance issues associated with current optical systems that sample some small volume near to the instrument
9.12	**Next Generation Ocean Color satellites (ACE, HySPIRI, HICO, GEO-CAPE)**	Phytoplankton: abundance and higher-taxon diversity	Pelagic (deep, shallow), benthic hard and soft substrata (shallow)	Remote assessment of algal pigment stocks; rates of production; improved taxonomy	Bio-optical models	Satellites in appropriate orbit for monitoring coastal ocean or maximizing coverage of global ocean
9.13	**Wormcam**	Infaunal macroinvertebrates: diversity, abundance, activity	benthic soft substrata (shallow), possibly adaptable to other habitats	Designed to assess rates of bioturbation and other faunal activity.	Analysis of collected images.	Ethernet camera in an underwater housing in the shape of a sediment profile prism (Rhoads and Cande 1971) with water quality sensors. Connected to solar powered surface buoy that telemeters images and data to base station.
9.14	**Ship board continuous flow cytometry**	Phytoplankton: higher-taxon diversity and abundance	Pelagic (epi)	Assess abundance and higher-taxon composition	analysis of optical data	Flow cytometer analyses organisms using the flow-through seawater system on-board a ship so spatial data is recovered.
9.15	**In-situ microscope**	Microorganisms, including phyto- and microzooplankton: diversity and abundance	All environments	to determine size spectra of microbes, to assign phytoplankton to taxa	standard imaging processing methods	on chip microscopes are just starting to emerge. One for in-situ studies that could be put on a mobile platform that would accomplish in-situ studies w/o requiring specimen retrieval would be a major achievement
9.16	**Underwater bathymetric lidar imaging systems**	Habitat-forming plants and macroinvertebrates: areal coverage	Benthic substrata, shallow	to obtain high resolution (~cm) of the sea floor incl topography (~10 cm res)	image and signal processing techniques	bathymetric lidars can be used to construct high res optical images of regions that containt both reflectance and depth data

Construction Cost	Deployment Method	Recovery Method	Pros	Cons	Employment Duration / Shelf Life of Materials Collected	Distribution of the Technique (How Widely Used?)	POC
MEGABUCKS… 210M? (approved)	Permanent Nodes, attach instrumentation	ROV, Submersible	Infrastruture will be in place, with a host of continuous environmental variables measured. Telemetry to shore in real time.	High cost of placement and retrieval. Fouling possible	Unknown	Limited regional access	
	Any ship transiting an area	Any ship transiting an area	Much less expensive than using existing technology (e.g. mounting repeated expeditions). Can be designed for a variety of different tasks. Can work at sea for extended periods without investigator involvement.	Still under development, actual costs and capabilities unknown.			
$150k	Towed from vessel, deployed autonomously (AUV, drifters, moorings)		High temporal sampling frequency, high range resolution to large range, improved species classification relative to traditional acoustic systems	Provides only indirect measurements of zooplankton/fish			
??	Towed from vessel, deployed autonomously (AUV, drifters, moorings)		Ability to sample larger animals currently not well sampled by most gears, especially micronekton				
several hundred million dollars per satellite	Rocket	None	Greater spectral and spatial resolution allows for improved species ID and distribution	Timeline uncertain, subject to funding	N/A	N/A	
Housing ~$1,000. Plus off the shelf camera, electronics, buoy ~$7,000. Electronic tech labor ~$2,000	Surface vessel or diver	Surface vessel or diver	Near real-time insitu imaging of faunal responses to day to day variation in habitat and water quality. Relative low cost and off the shelf components.	Needs frequent maintenance in high fouling areas/seasons. Species identification limited to large fauna.	Days to months	Emerging techniques developed with NSF funding.	Robert Diaz, go to and click on Wormcam: http://www.vims.edu/people/diaz_rj/index.php
	ship	ship	Rela-time in situ analysis of phytoplankton composition	This method can't be used to detect species but can be used to detect classes of phytoplankton (e.g. dinos vs diatoms)	N/A	N/A	Ginger Armbrust
initial: $100k, in large batches, $1-5k	any underwater platform	vehicle recovery	potential high resolution spatial and temporal sampling with multiple systems	extensive digital processing			
$1M-$2M	towed, AUV, ROV	either ship based or land based (AUV from shore)	high resolution optical images have great utility for identifying many benthic features. The addition of sea floor topography lends a quantitative element to placing organisms into a context that considers sea floor surface area	expensive, lots of data			

APPENDIX 5. MAJOR HABITAT DIVISIONS AND TAXA TO BE OBSERVED

Benthic (Biogenic, Hard Bottom and Soft Bottom)

- Sessile Macrobiota
- Demersal Fauna
- Epibiota
- Cryptobiota
- Infauna
- Meiofauna
- Microbes (Bacteria, Archea, Protista and Viruses)

Pelagic

- Microbes (Bacteria, Archea, Protista and Viruses)
- Macrozooplankton
- Mesoplankton
- Gelatinous Zooplankton
- Fish
- Birds
- Mammals
- Turtles
- Squid

APPENDIX 6. NATIONAL OCEAN POLICY PRIORITY OBJECTIVES

1. Ecosystem-Based Management: Adopt ecosystem-based management as a foundational principle for the comprehensive management of the ocean, our coasts, and the Great Lakes.
2. Coastal and Marine Spatial Planning: Implement comprehensive, integrated, ecosystem based coastal and marine spatial planning and management in the United States.
3. Inform Decisions and Improve Understanding: Increase knowledge to continually inform and improve management and policy decisions and the capacity to respond to change and challenges. Better educate the public through formal and informal programs about the ocean, our coasts, and the Great Lakes.
4. Coordinate and Support: Better coordinate and support Federal, State, tribal, local, and regional management of the ocean, our coasts, and the Great Lakes. Improve coordination and integration across the Federal Government, and as appropriate, engage with the international community.
5. Resiliency and Adaptation to Climate Change and Ocean Acidification: Strengthen resiliency of coastal communities and marine and Great Lakes environments and their abilities to adapt to climate change impacts and ocean acidification.
6. Regional Ecosystem Protection and Restoration: Establish and implement an integrated ecosystem protection and restoration strategy that is science-based and aligns conservation and restoration goals at the Federal, State, tribal, local, and regional levels.
7. Water Quality and Sustainable Practices on Land: Enhance water quality in the ocean, along our coasts, and in the Great Lakes by promoting and implementing sustainable practices on land.
8. Changing Conditions in the Arctic: Address environmental stewardship needs in the Arctic Ocean and adjacent coastal areas in the face of climate-induced and other environmental changes.
9. Ocean, Coastal, and Great Lakes Observations, Mapping, and Infrastructure: Strengthen and integrate Federal and non-Federal ocean observing systems, sensors, data collection platforms, data management, and mapping capabilities into a national system, and integrate that system into international observation efforts.

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