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COMMENTARY

A Framework for a Marine Biodiversity Observing Network Within Changing Continental Shelf Seascapes

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Continental shelves and the waters overlying them support numerous industries as diverse as tourism and recreation, energy extraction, fisheries, transportation, and applications of marine bio-molecules (e.g., agribusiness, food processing, pharmaceuticals). Although these shelf ecosystems exhibit impacts of climate change and increased human use of resources (Halpern et al., 2012; IPCC, 2013, 2014; Melillo et al., 2014), there are currently no standardized metrics for assessing changes in ecological function in the coastal ocean. Here, we argue that it is possible to monitor vital signs of ecosystem function by focusing on the lowest levels of the ocean food web. Establishment of biodiversity, biomass, and primary productivity baselines and continuous evaluation of changes in biological resources in these economically and ecologically valuable regions requires an internationally coordinated monitoring effort that fully integrates natural, social, and economic sciences to jointly identify problems and design solutions. Such an ocean observing network is needed to protect the livelihoods of coastal communities in the context of the goals of the Future Earth program (Mooney et al., 2013) and of the Intergovernmental Platform on Biodiversity and Ecosystem Services (http://www.ipbes.net). The tools needed to initiate these assessments are available today.

IMPORTANCE OF MARINE MICROBES

Microorganisms form the base of the marine food web, play critical roles in global biogeochemistry, and are highly sensitive to ecosystem perturbations both at the bottom and the top of the trophic structure. The timing, duration, intensity, and type of blooms of photosynthetic microorganisms are essential in determining recruitment of organisms at higher trophic levels (Platt et al., 2003). Bacteria play a central role in nutrient remineralization; as marine organisms die, their remains are returned to the water mostly in dissolved form. This dissolved matter has a wide variety of important consequences for aquatic life, including fertilization of the ocean and consumption and production of oxygen and CO_2 that, over time, contribute to defining the chemical composition of various ocean water masses. There are beneficial, toxic, and pathogenic microorganisms. Some produce metabolites that may have as yet undiscovered pharmaceutical, agricultural, growth regulating, or other applications (Hay and Fenical, 1996; Mimouni et al., 2012). Some algal blooms may cause harm through the production of toxins, or simply by their accumulated biomass; they can alter food web dynamics, cause illness or mortality, and lead to substantial economic losses. Climate change will likely cause shifts in the diversity and productivity of these organisms due to the expansion of subtropical conditions and the simultaneous shrinking of polar environments (Sarmiento et al., 2004; Polovina et al., 2011; Chust et al., 2014). These changes are expected to lead to profound alterations in bottom-up and top-down controls on marine ecosystems (Frank et al., 2005; Casinia et al., 2009; Doney et al., 2009; Hofmann et al., 2011; Mozetič et al., 2012; Friederike Prowe et al., 2012).

Many of the ecosystem services supporting human activities in coastal ocean waters depend on microorganisms; however, indirect and direct human pressures are significantly impacting these microbial assemblages. These changes can affect fishery catch potential (Glantz, 1992; Cheung et al., 2013),

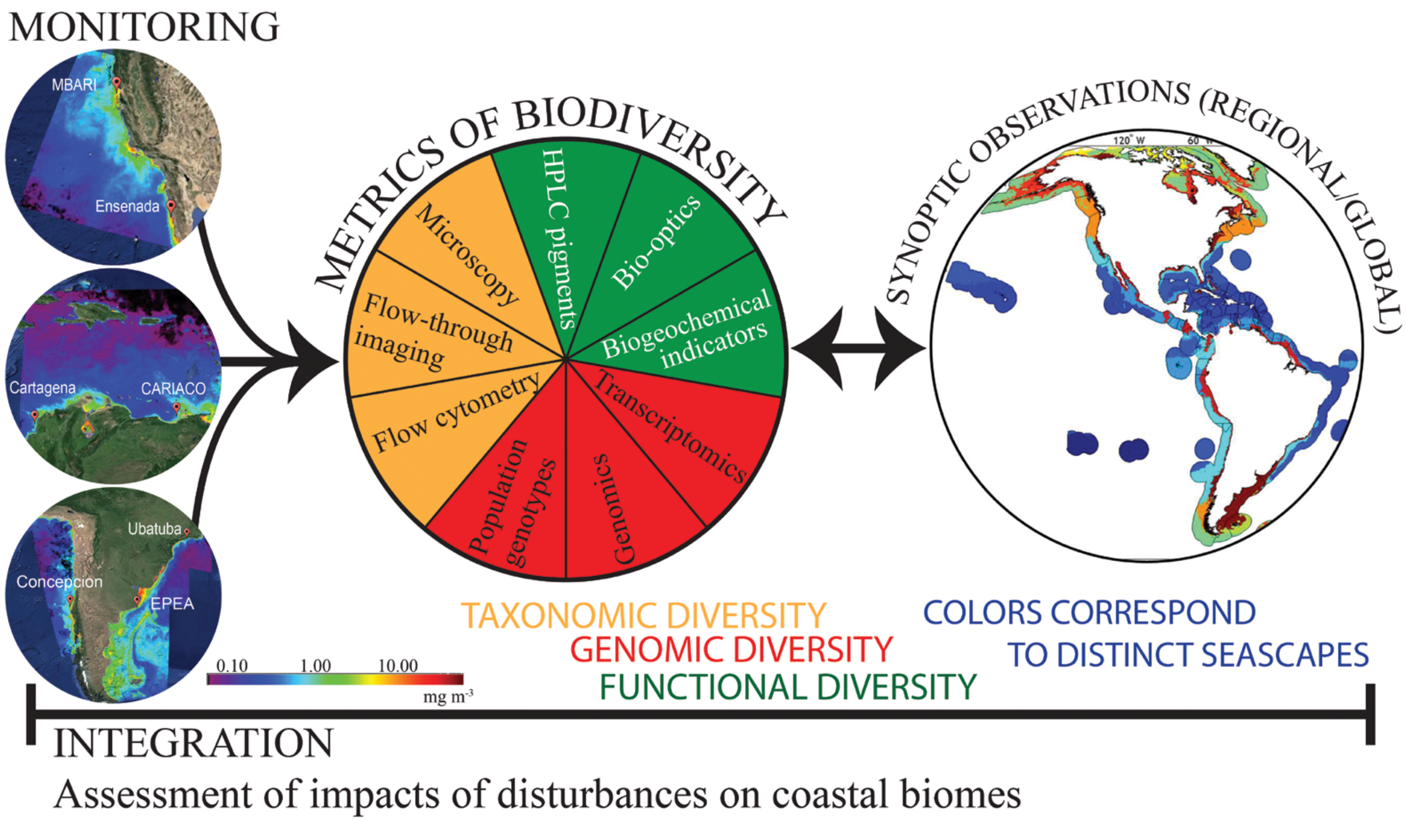

Figure 1. Examples of coherent biogeographical seascapes that extend across Exclusive Economic Zones (EEZs). Dynamic seascape maps can today be built at monthly or higher temporal resolutions by integrating satellite observing technologies, in situ monitoring systems, and statistical assessments implemented through computer models (Kavanaugh et al., 2013). Historical maps can be derived from measurements collected over recent decades. (left) Examples of chlorophyll-*a* concentration images derived from the NASA MODIS-Aqua satellite sensor highlight the locations of some long-standing ocean biogeochemistry and ecology time-series stations. (middle) The circular panel lists some of the technologies currently available for collecting a minimum set of observations to define different types of biological diversity in continental shelf ecosystems. (right) Seascape classifications shown were derived from sea surface temperature, chlorophyll-*a* concentration, and photosynthetically active radiation (PAR) images from the MODIS sensor (annual mean for 2012, 9 km resolution). These types of maps can be overlaid on geopolitical jurisdictions and combined with other data on particular uses of the ocean to inform decisions of both managers and users.

patterns of harmful algal bloom occurrence (Paerl and Huisman, 2009), and dispersal of invasive species (Hellmann et al., 2008; Rahel and Olden, 2008), and it is likely that they cause other shifts in marine habitats on continental shelves around the world that are not yet identified. These changes may affect the jobs, economy, and well-being of coastal communities, in particular, those of "low-income food-deficit countries" whose populations obtain > 20% of their protein from local fisheries (FAO, 2012). Sustaining such valuable ecosystem services is thus at the core of every coastal nation's security. Proactive efforts to inform mitigation and adaption policy must be based on scientific insight and technological inventiveness so that nations around the globe can more effectively monitor their Exclusive Economic Zones (Figure 1).

MONITORING MARINE BIODIVERSITY

Today, it is still impractical to monitor the number and diversity of organisms in mid to upper trophic levels of the food web. We suggest instead focusing on understanding ecosystem function (Cleland, 2012)—the array of biogeochemical and ecological interactions that take place within a system, as well as the services that ecosystems may provide. By targeting the dynamics of microorganisms within seascapes spanning the world's continental shelves, an operational Marine Biodiversity Observation Network (MBON) can achieve regular assessments of ecosystem diversity and function (Biodiversity Ad Hoc Group, 2010; Duffy et al., 2013).

Measuring Ecosystem Function in a Dynamic Environment

There are several challenges in defining an MBON to achieve regular assessments of ecosystem diversity and function. One challenge is establishing an accurate baseline of ecosystem diversity from which to detect and quantify changes. This task requires developing indices that integrate long historical time series of environmental and biological data into synthetic "mean" conditions (i.e., a biodiversity climatology) and choosing a particular reference timeframe. The purpose of these indices is to facilitate calculation of biodiversity "anomalies" to evaluate quantitatively population shifts that may result from changes in tides and currents, transformations mediated by biological activity, or human interventions that enhance or diminish particular ecosystem services. The lack of firmly defined habitat boundaries also presents a challenge, as dynamic changes in ecosystems disregard geopolitical jurisdictions. How do we address this complexity in a way that is useful to resource managers and other decision makers?

Making Observations in a Dynamic Seascape Context

Understanding ecosystem responses to climate and system feedbacks requires an objective framework to (1) scale local observations to their regional context, (2) objectively delineate the regional boundaries that define unique water masses, and (3) determine how these boundaries shift in space and time. In defining such a system, it is important to find properties that can be measured quickly, economically, and over large areas. One advantage of measuring tiny microorganisms is that their number in the ocean is orders of magnitude larger than that of consumers, and their total biomass is far larger than that of all metazoans combined (Pomeroy et al., 2007). Furthermore, the various functional groups of microorganisms are typically associated with different chemical and physical ocean properties. Because of their large numbers, they change the color of the ocean, and these colors can be used as a characteristic index of the biodiversity of these groups. Subtle changes in color, along with other variables, including temperature, salinity, and wind and current speed and direction, can be measured from space using specialized satellite sensors.

Currently, we can track physical features such as eddies and water masses in the ocean, basic biological patterns of chlorophyll and productivity, and simple measures of biological ecosystem function over scales of hundreds of meters to global by using a combination of methods that include satellite observations, ship-based surveys, moored instruments, measurements from networks of drifting buoys, autonomous platforms such as unmanned aerial and underwater vehicles, and computer simulations (Talley et al., 2010; Chelton et al., 2011; Muller-Karger et al., 2013). A system that integrates these technologies provides the capability to measure changes in large dynamic and coherent biogeographical regions or "seascapes" (Reygondeau et al., 2013; Kavanaugh et al., 2013).

TWO ESSENTIAL STEPS TOWARD ESTABLISHING AN MBON

We recommend the following specific actions to construct an effective MBON:

1. Determine the minimum set of observations needed to define ocean biodiversity.

Methods to quantify the diversity of marine microorganisms are still largely isolated within scientific disciplines, including biogeochemical oceanography and molecular biology. We envision an approach that includes the systematic linking of in situ observations of phytoplankton via traditional microscopy-based measurements, automated cell imaging and classification (e.g., Sosik and Olson, 2007), High Performance Liquid Chromatography (HPLC) for pigment analysis, hyperspectral optical measurements, and satellite imagery. This MBON vision can benefit from the following recent scientific advances at both micro- and macroscales:

- *Microscale:* Advances in genomics now enable sequence-based identification of phytoplankton and analysis of gene expression and functionality. Environmental DNA (eDNA) techniques now promise insights into the dynamics and relative abundance of species across trophic levels without having to actually capture organisms

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(Lodge et al., 2012; Thomsen et al., 2012; Taberlet et al., 2012).

- *Macroscale:* Advances in satellite technology include the Ocean and Land Colour Instruments (OLCI) to be flown on the European Sentinel3 satellites, planned for launch in the 2015–2020 timeframe, and the sensors of the Pre-Aerosol, Clouds, and Ecosystem Mission (PACE) Project, under consideration for development by NASA before the end of this decade. These sensors will continue the science-quality ocean color record initiated by SeaWiFS, MERIS, and MODIS-Aqua (see http://oceancolor.gsfc.nasa.gov) but also allow better classification of broad taxonomic or functional groups of phytoplankton.

2. Establish connections between existing international programs and standardize methodologies to enable comparison of data.

Building an MBON requires integration of existing observing systems with broad-scale monitoring capabilities. Though limited in number, existing long-term ocean time series have provided a needed perspective on how coastal and ocean biodiversity and biogeochemistry are changing in response to climate change (Ducklow et al., 2009; Church et al., 2013). An important step will be to strengthen networks of such existing time-series programs and complement their observations with the more advanced technologies mentioned above.

In the United States, the Integrated Ocean Observing System (IOOS) program is pioneering the implementation of an MBON. IOOS has issued preliminary guidance for biological data services, including core variables such as fish, zooplankton, and phytoplankton species and abundance.

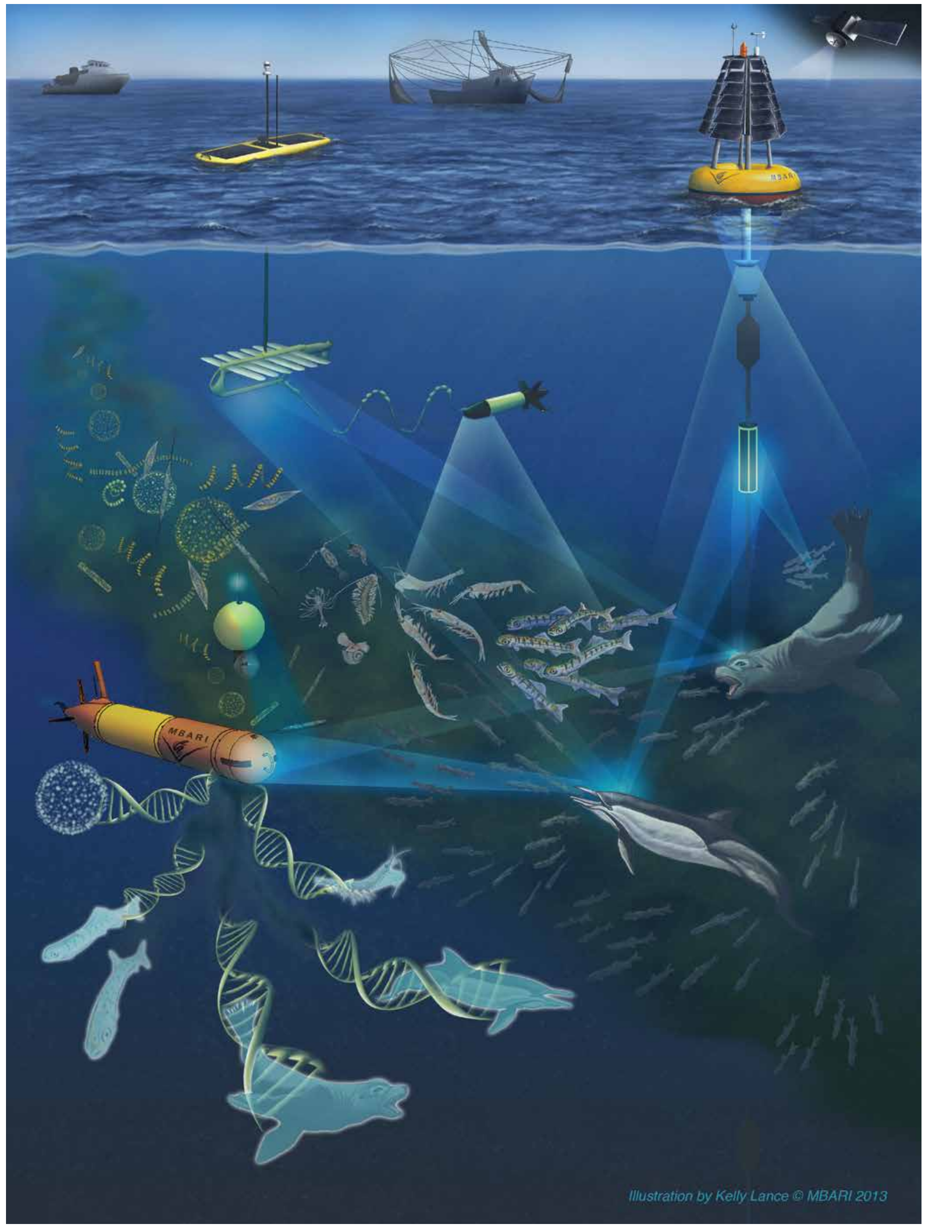

Figure 2. Schematic representation of a pelagic food web and technologies that will support biodiversity assessments in a continental shelf MBON. *Monterey Bay Research Institute/MBARI*

The program has identified 26 core variables to be measured on a national scale to detect ecosystem change and to support ecosystem modeling. This basic MBON hopes to benefit from assessment data of marine fauna (fish, reptiles, birds, and mammals) collected by federally supported infrastructures (e.g., US National Oceanic and Atmospheric Administration [NOAA] National Marine Fisheries Science Centers, NOAA National Marine Sanctuaries, and the US Fish and Wildlife Service), as well as from scientific initiatives led by academia (e.g., Tagging of Pacific Predators), and state-level regulatory agencies.

Several ongoing international scientific efforts could be engaged to augment the US-focused IOOS initiatives. For example, the Antares network coordinates research and training activities between institutions in Argentina, Brazil, Chile, Colombia, Ecuador, Mexico, Peru, and Venezuela using programs such as the international CARIACO Ocean Time-Series Program. Time-series stations managed by each of these countries can be linked with existing US programs such as those of the Monterey Bay Aquarium Research Institute (MBARI) and the California Cooperative Oceanic Fisheries Investigations (CalCOFI) as well as time series programs located in the Gulf of Mexico, the Florida Keys, on the northwest coast, at the Martha's Vineyard Coastal Observatory (MVCO), in the Gulf of Maine (Gulf of Maine North Atlantic Time Series or GNATS), and elsewhere. Similar networks exist around Europe and off Africa, such as the European Time Series in the Canary Islands (ESTOC), the DYnamique des Flux de mAtière en MEDiterranée (DYFAMED), and the Cape Verde Ocean Observatory (CVOO).

Coordinating across international ocean time series efficiently uses existing infrastructure and helps to establish common sampling protocols, best practices, and internal consistency among observations from different locations (Lorenzoni and Benway, 2013). This action, implemented following the guidelines of the United Nation's Convention on Biodiversity for protocols to collect, process, analyze, and manage samples and information, can help satisfy the critical need for a coordinated capacity-building and education effort among partner nations.

The knowledge generated by an MBON is required to implement an ecosystem-based management approach that works across static political boundaries and that embraces the concept of dynamic natural boundaries. It is needed to collect and analyze information about the relationships between biodiversity and people in order to support "Driver-Pressure-State-Response" analyses (Kelble et al., 2013). Every nation is charged with the protection of the health of its citizenry and the preservation of its cultural and natural heritage, and an MBON is required to enable this effort. We urge our political leaders to establish a Marine Biodiversity Observation Network and the fiscal mechanisms to sustain it.

"ONE ADVANTAGE OF MEASURING TINY MICROORGANISMS IS THAT THEIR NUMBER IN THE OCEAN IS ORDERS OF MAGNITUDE LARGER THAN THAT OF CONSUMERS, AND THEIR TOTAL BIOMASS IS FAR LARGER THAN THAT OF ALL METAZOANS COMBINED."

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REFERENCES

Biodiversity Ad Hoc Group. 2010. *Attaining an Operational Marine Biodiversity Observation Network (BON) Synthesis Report*. Interagency Working Group on Ocean Partnerships, 33 pp., http://www.nopp.org/wp-content/uploads/2010/03/BON_SynthesisReport.pdf.

Casinia, M., J. Hjelm, J.C. Molinero, J. Lovgren, M. Cardinale, V. Bartolino, A. Belgrano, and G. Kornilovs. 2009. Trophic cascades promote threshold-like shifts in pelagic marine ecosystems. *Proceedings of the National Academy of Sciences of the United States of America* 106:197–202, http://dx.doi.org/10.1073/pnas.0806649105.

Chelton, D.B., P. Gaube, M.G. Schlax, J.J. Early, and R.M. Samelson. 2011. The influence of nonlinear mesoscale eddies on near-surface oceanic chlorophyll. *Science* 334:328–332, http://dx.doi.org/10.1126/science.1208897.

Cheung, W.W.L., R. Watson, and D. Pauly. 2013. Signature of ocean warming in global fisheries catches. *Nature* 497:365–368, http://dx.doi.org/10.1038/nature12156.

Church, M.J., M.W. Lomas, and F.E. Muller-Karger. 2013. Sea change: Charting the course for biogeochemical ocean time series research in a new millennium. *Deep Sea Research Part II* 93:2–15, http://dx.doi.org/10.1016/j.dsr2.2013.01.035.

Chust, G., J.I. Allen, L. Bopp, C. Schrum, J. Holt, K. Tsiaras, M. Zavatarelli, M. Chifflet, H. Cannaby, I. Dadou, and others. 2014. Biomass changes and trophic amplification of plankton in a warmer ocean. *Global Change Biology*, http://dx.doi.org/10.1111/gcb.12562.

Cleland, E.E. 2012. Biodiversity and ecosystem stability. *Nature Education Knowledge* 3(10):14, http://www.nature.com/scitable/knowledge/library/biodiversity-and-ecosystem-stability-17059965.

Doney, S.C., V.J. Fabry, R.A. Feely, and J.A. Kleypas. 2009. Ocean acidification: The other CO_2 problem. *Annual Review of Marine Science* 1:169–192, http://dx.doi.org/10.1146/annurev.marine.010908.163834.

Ducklow, H.W., S.C. Doney, and D.K. Steinberg. 2009. Contributions of long-term research and time-series observations to marine ecology and biogeochemistry. *Annual Review of Marine Science* 1:279–302, http://dx.doi.org/10.1146/annurev.marine.010908.163801.

Duffy, J.E., L.A. Amaral-Zettler, D.G. Fautin, G. Paulay, T.A. Rynearson, H.M. Sosik, and J.J. Stachowicz. 2013. Envisioning a Marine Biodiversity Observation Network. *BioScience* 63:350–361, http://dx.doi.org/10.1525/bio.2013.63.5.8.

FAO. 2012. The State of World Fisheries and Aquaculture, 2012. Food and Agriculture Organization of the United Nations, Rome, 209 pp.

Frank, K.T., B. Petrie, J.S. Choi, and W.C. Leggett. 2005. Trophic cascades in a formerly cod-dominated ecosystem. *Science* 308:1,621–1,623, http://dx.doi.org/10.1126/science.1113075.

Friederike Prowe, A.E., M. Pahlow, S. Dutkiewicz, M. Follows, and A. Oschlies. 2012. Top-down control of marine phytoplankton diversity in a global ecosystem model. *Progress in Oceanography* 101:1–13, http://dx.doi.org/10.1016/j.pocean.2011.11.016.

Glantz, M.H., ed. 1992. *Climate Variability, Climate Change and Fisheries.* Cambridge University Press, 420 pp.

Halpern, B.S., C. Longo, D. Hardy, K.L. McLeod, J.F. Samhouri, S.K. Katona, K. Kleisner, S.E. Lester, J. O'Leary, M. Ranelletti, and others. 2012. An index to assess the health and benefits of the global ocean. *Nature* 488:615–620, http://dx.doi.org/10.1038/nature11397.

Hay, M.E., and W. Fenical. 1996. Chemical ecology and marine biodiversity: Insights and products from the sea. *Oceanography* 9(1):10–20, http://dx.doi.org/10.5670/oceanog.1996.21.

Hellmann, J.J., J.E. Byers, B.G. Bierwagen, and J.S. Dukes. 2008. Five potential consequences of climate change for invasive species. *Conservation Biology* 22(3):534–543, http://dx.doi.org/10.1111/j.1523-1739.2008.00951.x.

Hofmann, G.E., J.E. Smith, K.S. Johnson, U. Send, L.A. Levin, F. Micheli, A. Paytan, N.N. Price, B. Peterson, Y. Takeshita, and others. 2011. High-frequency dynamics of ocean pH: A multi-ecosystem comparison. *PLoS ONE* 6(12):e28983, http://dx.doi.org/10.1371/journal.pone.0028983.

IPCC (Intergovernmental Panel on Climate Change). 2013. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, eds, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1,535 pp.

IPCC. 2014. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Working Group II Contribution to the IPCC 5th Assessment Report: Changes to the Underlying Scientific/Technical Assessment*. http://ipcc-wg2.gov/AR5/images/uploads/IPCC_WG2AR5_SPM_Approved.pdf.

Kavanaugh, M.T., B. Hales, M. Saraceno, Y.H. Spitz, A.E. White, and R.M. Letelier. 2013. Hierarchical and dynamic seascapes: A quantitative framework for scaling pelagic biogeochemistry and ecology. *Progress in Oceanography* 120:291–304, http://dx.doi.org/10.1016/j.pocean.2013.10.013.

Kelble, C.R., D.K. Loomis, S. Lovelace, W.K. Nuttle, P.B. Ortner, P. Fletcher, G.S. Cook, J.J. Lorenz, and J.N. Boyer. 2013. The EBM-DPSER conceptual model: Integrating ecosystem services into the DPSIR framework. *PLoS ONE* 8(8):e70766, http://dx.doi.org/10.1371/journal.pone.0070766.

Lodge, D.M., C.R. Turner, C.L. Jerde, M.A. Barnes, L. Chadderton, S.P. Egan, J.L. Feder, A.R. Mahon, and M.E. Pfrender. 2012. Conservation in a cup of water: Estimating biodiversity and population abundance from environmental DNA. *Molecular Ecology* 21:2,555–2,558, http://dx.doi.org/10.1111/j.1365-294X.2012.05600.x.

Lorenzoni, L., and H.M. Benway, eds. 2013. *Global Intercomparability in a Changing Ocean: An International Time-Series Methods Workshop*. Bermuda Institute of Ocean Sciences, November 28–30, 2012, Ocean Carbon and Biogeochemistry (OCB) Program and International Ocean Carbon Coordination Project (IOCCP), 61 pp, http://www.us-ocb.org/publications/TS_Workshop_report_FINAL.pdf.

Melillo, J., T. (T.C.) Richmond, and G.W. Yohe, eds. 2014. *Climate Change Impacts in the United States: The Third National Climate Assessment*. US Global Change Research Program, 841 pp., http://dx.doi.org/10.7930/J0Z31WJ2.

Mimouni, V., L. Ulmann, V. Pasquet, M. Mathieu, L. Picot, G. Bougaran, J.-P. Cadoret, A. Morant-Manceau, and B. Schoefs. 2012. The potential of microalgae for the production of bioactive molecules of pharmaceutical interest. *Current Pharmaceutical Biotechnology* 13:2,733–2,750, abstract at http://www.ncbi.nlm.nih.gov/pubmed/23072388.

Mooney, H.A., A. Duraiappah, and A. Larigauderie. 2013. Evolution of natural and social science interactions in global change research programs. *Proceedings of the National Academy of Sciences of the United States of America* 110(suppl. 1):3,665–3,672, http://dx.doi.org/10.1073/pnas.1107484110.

Mozetič, P., J. Francé, T. Kogovšek, I. Talaber, and A. Malej. 2012. Plankton trends and community changes in a coastal sea (northern Adriatic): Bottom-up vs. top-down control in relation to environmental drivers. *Estuarine, Coastal and Shelf Science* 115:138–148, http://dx.doi.org/10.1016/j.ecss.2012.02.009.

Muller-Karger, F., M. Roffer, N. Walker, M. Oliver, O. Schofield, M. Abbott, H. Graber, R. Leben, and G. Goni. 2013. Satellite remote sensing in support of an Integrated Ocean Observing System. *IEEE Geoscience and Remote Sensing Magazine* 1:8–18, http://dx.doi.org/10.1109/MGRS.2013.2289656.

Paerl, H.W., and J. Huisman. 2009. Climate change: A catalyst for global expansion of harmful cyanobacterial blooms. *Environmental Microbiology Reports* 1:27–37, http://dx.doi.org/10.1111/j.1758-2229.2008.00004.x.

Platt, T., C. Fuentes-Yaco, and K. Frank. 2003. Spring algal bloom and larval fish survival. *Nature* 423:398–399, http://dx.doi.org/10.1038/423398b.

Polovina, J.J., J.P. Dunne, P.A. Woodworth, and E.A. Howell. 2011. Projected expansion of the subtropical biome and contraction of the temperate and equatorial upwelling biomes in the North Pacific under global warming. *ICES Journal of Marine Science* 68:986–995, http://dx.doi.org/10.1093/icesjms/fsq198.

Pomeroy, L.R., P.J. leB. Williams, F. Azam, and J.E. Hobbie. 2007. The microbial loop. *Oceanography* 20(2):28–33, http://dx.doi.org/10.5670/oceanog.2007.45.

Rahel, F.J., and J.D. Olden. 2008. Assessing the effects of climate change on aquatic invasive species. *Conservation Biology* 22:521–533, http://dx.doi.org/10.1111/j.1523-1739.2008.00950.x.

Reygondeau, G., A. Longhurst, E. Martinez, G. Beaugrand, D. Antoine, and O. Maury. 2013. Dynamic biogeochemical provinces in the global ocean. *Global Biogeochemical Cycles* 27:1,046–1,058, http://dx.doi.org/10.1002/gbc.20089.

Sarmiento, J.L., R. Slater, R. Barber, L. Bopp, S.C. Doney, A.C. Hirst, J. Kleypas, R. Matear, U. Mikolajewicz, P. Monfray, and others. 2004. Response of ocean ecosystems to climate warming. *Global Biogeochemical Cycles* 18, GB3003, http://dx.doi.org/10.1029/2003GB002134.

Sosik, H.M., and R.J. Olson. 2007. Automated taxonomic classification of phytoplankton sampled with imaging-in-flow cytometry. *Limnology and Oceanography: Methods* 5:204–216, http://www.whoi.edu/cms/files/Sosik&Olson_LOM2007_35925.pdf.

Taberlet, P., E. Coissac, F. Pompanon, C. Brochmann, and E. Willerslev. 2012. Towards next-generation biodiversity assessment using DNA metabarcoding. *Molecular Ecology* 21:2,045–2,050, http://dx.doi.org/10.1111/j.1365-294X.2012.05470.x.

Talley, L., R. Fine, R. Lumpkin, N. Maximenko, and R. Morrow. 2010. Surface ventilation and circulation. Pp. 38 in *Proceedings of OceanObs'09: Sustained Ocean Observations and Information for Society*, vol. 1. Venice, Italy, September 21–25, 2009, J. Hall, D.E. Harrison, and D. Stammer, eds, ESA Publication WPP-306, http://dx.doi.org/10.5270/OceanObs09.

Thomsen, P.F., J. Kielgast, L.L. Iversen, P.R. Moller, M. Rasmussen, and E. Willerslev. 2012. Detection of a diverse marine fish fauna using environmental DNA from seawater samples. *Plos ONE* 7(8):e41732, http://dx.doi.org/10.1371/journal.pone.0041732.