Assessing the Global Distribution and Abundance of Marine Life:

Summary of a Workshop Sponsored by the Sloan Foundation and the Office of Naval Research, January 13-15, 1998, Monterey, California

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Abstract

In January, 1998, the Alfred P. Sloan Foundation and the Office of Naval Research sponsored a workshop organized by the Ocean Studies Board of the National Research Council[1], which brought together ecologists, oceanographers, fisheries scientists, and modelers to discuss the value, timeliness, and feasibility of assessing the global distribution and abundance of marine life, with emphasis on higher trophic levels. A global assessment of marine life would aid in predicting the causes of ecosystem change and resulting consequences to fisheries, trophic structure, and dynamics of marine systems. The workshop identified 3 goals: to determine the biomass of marine biota, especially the higher trophic levels; to determine how this biomass is distributed spatially and by size and taxon and; to investigate how these distributions are maintained or changed. Significant advances toward these ambitious goals were considered possible on a 10-year time frame using an iterative process of modeling and observation which estimated global abundance through understanding of the trophic structure, population sizes, and flow of matter through the food webs of major biogeographic zones in the ocean. A pilot observation program would focus on areas of greatest uncertainty identified to be the abundances, distributions and rates of trophic transfer of poorly known open ocean animals, primarily cephalopods, mesopelagic animals, macrocrustaceans, gelatinous zooplankton, epipelagic fish and small cetaceans. Assessment of open ocean taxa requires significant technological development, including acoustical, optical, genetic, and chemical approaches. A global assessment program based on a trophic dynamics/modeling approach presented the prospect of significant scientific and societal benefits but would require the mobilization of a multiagency and multinational effort.

General Focus of the Workshop

Put a man on the moon by 1970. This was the "Grand Challenge" that mesmerized the public and galvanized much of the scientific community in the US during the 1960's. Yet the goal itself (a man standing on the moon) was in many ways secondary to the advances accomplished by the effort. The meaning behind the challenge came from the tremendous technological progress required to achieve it, from its motivating influence on science and technology, and from the way it inspired and riveted the imagination of an entire nation, if not the world.

In January, 1998, the Alfred P. Sloan Foundation, with additional support from ONR, sponsored an informal workshop in Monterey, California, that brought together scientists representing benthic ecology, marine policy, acoustics, optics, fisheries and stock assessment, marine ecology, vertebrate and invertebrate biology, modeling, and physical and biological oceanography (Table 1), to address a similar type of Grand Challenge: "How many fish are in the sea?" While the initial response of most participants was skeptical regarding the value of such a question or of its answer, it quickly became obvious that the question itself had the potential to both inspire the scientific community and captivate the public. The fact that estimates of absolute abundance are relatively uncertain even for the most intensively monitored marine populations, despite the importance of higher trophic levels both as food sources and as major components structuring marine ecosystems, highlights major gaps in our knowledge of marine systems. These gaps include a predictive understanding of complex food web interactions and trophic transfer, the impacts of nutrients and physical processes on higher trophic levels, the magnitude and nature of nekton populations beyond the edge of the continental shelf and in the deep sea, the role of top-down control in regulating ocean food webs, accurate descriptions of the distribution and diversity of marine organisms, and the impact of energy flow through the food web on global carbon and nutrient cycling. Moreover, the decline of many marine fisheries (see Knauss, 1994), the recent suggestion of a long-term gradual decline in the average trophic level of harvested marine fish (Pauly et al., 1998), and possible population increases of medusae (Mills, 1995) and cephalopods

Table 1: Participants in the Global Assessment of Marine Life Workshop Monterey, 1998

PARTICIPANT	*AFFILIATION*	*EXPERTISE*
Alice Alldredge	University of California, Santa Barbara, USA	biological oceanography, zooplankton
Jesse Ausubel	Alfred P. Sloan Foundation, USA	program manager
Peter Boyle	University of Aberdeen, Scotland	cephalopod population dynamics
Dave Bradley	University of Pennsylvania, USA	marine acoustics
Mel Briscoe	Office of Naval Research, USA	physical oceanography
Doug Butterworth	University of Cape Town, South Africa	fisheries science, statistics
Villy Christensen	ICLARM, Philippines	multi-species modeling
Morgan Gopnik	National Research Council, USA	Director, Ocean Studies Board
Zeke Grader	Pacific Coast Federation of Fishermen's Associations, USA	fishery management
Fred Grassle	Rutgers University, USA	benthic ecology, biodiversity
Ray Hilborn	University of Washington, USA	fishery dynamics and assessment
Eileen Hofmann	Old Dominion University, USA	biological oceanography
D. Van Holliday	Tracor, USA	marine acoustics
John Horne	GLERL, University of Michigan, USA	physical oceanography, acoustics
Michael Jech	GLERL, University of Michigan, USA	acoustics, fisheries assessment
Jules Jaffe	Scripps Institution of Oceanography, USA	biological oceanography, acoustics, optics
Tony Koslow	Division of Fisheries CSIRO, Australia	marine acoustics
Carolyn Levi	New England Aquarium, USA	biological oceanography
Glenn Merrill	National Research Council, USA	Staff, Ocean Studies Board
Ole Misund	University of Bergen, Norway	fishery biology, marine acoustics
Claudia Mills	University of Washington, USA	gelatinous zooplankton
Don Olson	RSMAS ,University of Miami, USA	physical oceanography, modeling
Daniel Pauly	ICLARM, Philippines/University of British Columbia, Canada	ecosystem modeling, fisheries
Julia Parrish	University of Washington, USA	marine ecology and behavior
Marjorie Reaka-Kulda	University of Maryland, USA	biodiversity, coral reef ecology
Bruce Robison	Monterey Bay Aquarium Research Institute, USA	deep-sea pelagic organisms
John Shepherd	Southampton Labs, UK	stock assessment, ocean observation
Bob Smith	Oregon State University, USA	physical oceanography
Michael Smith	Center for Marine Conservation, USA	ichthyology
Andy Solow	Woods Hole Oceanographic Institution, USA	statistics, marine policy
Donna Turgeon	NOAA, USA	marine ecology
John Steele	Woods Hole Oceanographic Institution, USA	oceanography and marine policy
Dan Walker	National Research Council, USA	Staff, Ocean Studies Board

[1] Although this workshop was organized by the National Research Council (NRC), this summary is not a NRC report. Responsibility for this document rests solely with the authors who helped plan and were present at the workshop.

(Caddy, 1995) suggest some urgency in improving our knowledge of the abundance, distribution, and diversity of higher trophic levels in the ocean. Greater understanding of these topics might aid in predicting the causes of ecosystem change and resulting consequences for fisheries, mammal populations, species and trophic interactions, and ecosystem structure.

Redefinition of the Question

Determining how many fish are in the sea is a subset of the much broader goal uniting all ecological research. That broader goal is to describe and understand the patterns of distribution and abundance of organisms and to predict the impact of change on those patterns. Participants redefined the original charge of the workshop in a way that could provide an overarching and unifying umbrella capable of encompassing the diverse interests of the biological community and which expressed a "Grand Challenge" in its most comprehensive and inspiring sense. Thus, the final "Grand Challenge" articulated by the workshop was to answer the question, "How much life can the ocean sustain?"

This challenge was made more concrete and attainable by focusing on the biomass and biological diversity of higher trophic levels, including but not confined to economically important species. However, the distribution, abundance and productivity of lower trophic levels and the biological, chemical, and physical processes affecting ecosystem structure were recognized as necessary to generate global estimates. The major questions thus became: 1) What is the biomass of the marine biota, especially higher trophic levels, on a global scale? 2) How is this biomass distributed spatially and by size and taxon? and 3) How are these distributions maintained or changed?

These were clearly questions of enormous scope, which would require immense resources, major technological advances, and decades of research to answer fully. However, the discussion made clear that our present knowledge was not trivial. Global maps of the chlorophyll biomass supporting higher trophic levels are being continually refined. Reasonable estimates of population parameters and distributions for many species, especially commercially valuable nekton, already exist for certain areas (North Sea, many coastal regions). Moreover, global models that estimate the abundances of higher trophic levels based largely on trophic relationships and transfer efficiencies of biomass through the food web also exist (Christensen and Pauly, 1992; Pauly and Christensen, 1995). Increasing the accuracy and precision with which these models predict global distributions of biomass and abundance is constrained by a few large gaps in our knowledge, especially information on the abundance and distribution of animals by size and taxon in the open ocean and mesopelagic zone. The generation of information with which to fill these major gaps could result in a quantum leap in the accuracy of our estimates of the global abundance and productivity of marine life, especially that of higher trophic levels, and was seen as one of the first steps in any observation program.

The major questions had the characteristics of a Grand Challenge in that they were broad and integrating, bold and motivational, compelling, and of use in providing a strategy for long term focus for scientific research. Moreover, they encompassed issues immediately recognizable as being of value to policy makers and the general public. World demand for marine food resources is expected to far exceed availability in the next several decades. Hence there is a critical need to address current perceptions regarding the size of sustainable yields from the world's oceans in the foreseeable future. The workshop participants were able to identify the beginnings of a path toward achieving these goals with identifiable benchmarks for success in a time frame of 10-15 years.

General Approach

Technological barriers prohibit the direct enumeration of most types of life in the ocean, except at very local scales. Sampling systems such as nets, and acoustical and optical instruments, which capture or count individual animals directly, can be deployed only over small areas of the ocean at any one time using ships, mooring, or airplane overflights. Larger scale synoptic systems, such as satellites, are limited in the types of life they can detect, with phytoplankton pigments being the primary biological parameter presently quantifiable with these techniques. Moreover, the patchy distributions of all organisms and the high motility of most nekton make it difficult to generalize local distributions and abundances to broader regional or global scales.

The most tractable approach to assess the biomass and productivity of higher trophic levels at a regional scale was identified as a trophic dynamics approach. The abundance of higher trophic levels is constrained by the biomass at lower levels available for consumption, the efficiencies of energy transfer at each link in the food web, and population parameters, including rates of reproduction, growth, and mortality, which alter population sizes and rates of trophic transfer. Existing models estimate the biomass and abundance of higher trophic levels based on the sizes of the populations of different functional groups throughout the food web and the rates at which biomass is transferred among them. Continued development and improvement of these models could greatly increase the predictive capability of this and similar approaches. Outputs of such models adapted for each major region of the ocean could be cumulated to achieve global estimates.

A trophic dynamics approach has the potential to provide iterative estimates of the distribution and abundance of higher trophic levels as new observational data are generated. Models can be tested against new information as it is obtained. Such an approach can also be tailored to specific regions of the ocean. Moreover, this approach allows the global assessment of marine life to move far beyond a simple census of species abundance, biomass, and distribution. Information of vital interest to biologists on the life histories and rates of growth, mortality, reproduction, and feeding of organisms becomes essential for such an approach to succeed. It requires an extensive understanding of biological processes and energy flow. It also relies on investigations of lower trophic levels and ecosystem processes. Thus the approach has the advantage of providing a unifying theme for a full range of biological questions that would rely heavily upon both modeling and observation for success.

Participants discussed the relative roles of observation and modeling extensively throughout the meeting. Many suggested that the most appropriate approach would be to compile existing data and review current ecological models, then focus any new observational efforts specifically on those processes and taxonomic groups that the models do not describe well. The incorporation of existing and new observations into a framework of ecological theory and modeling was viewed as the approach most likely to generate cohesive conclusions on an attainable time scale.

Components of a Global Assessment Program

An initial global assessment program targeted to last roughly 10 years was outlined in three phases. This program was envisioned as a multi-national effort on the scale of the larger global change programs.

Phase I (years 1-4, technology development, planning and site selection)

1. *Defining biogeographical zones:* Trophic structure varies considerably across regions of the ocean. Splitting the globe into biogeographic regions based on commonalties in trophic structure was advocated so as to expand from local to regional and global scales and to attain the necessary level of detail at a global level. Biogeographic zones should be as large as possible while maintaining approximately the same trophic web structure. The same kinds of functional groups, as well as similar species, should exist within regions placed in the same biogeographic zone. Biologically significant characteristics such as depth, latitude, bottom topography, and oceanographic characteristics would also be used in defining biogeographic zones. Two or more schemes for partitioning the global ocean might be devised based on different criteria. Several schemes for identifying marine biomes already exist which could provide a basis for further advancement. The scheme that presently offers the best hope of generating consensus is that of Longhurst (1996). It consists of 56 "biochemical provinces", some overlapping with the large ecosystems of Sherman et al. (1993).

   An important aspect of defining biogeographic zones and trophic structure included developing accurate maps of biodiversity, species richness, relative abundance, species/area relationships, species ranges, and habitats of key fish and benthic taxa. GIS databases and maps of environmental parameters could be used to test hypotheses on biogeographic distributions, species richness, and other ecological components. Participants at the workshop felt that historical and recent information on several major taxonomic groups was sufficient to develop reasonably accurate maps of the global biodiversity of these groups within the first year of the program. Taxa for which this was judged possible included fish, corals, anemones, decapods, mollusks, and bryozoans. Many institutions and agencies are presently involved in biodiversity issues. The Living Marine Resources (LMR) module of the international Global Ocean Observing System (GOOS) program has proposed similar goals. NOAA has been developing a taxon database and information on cnidarians, mollusks, decapods, ctenophores and annelids which is nearing completion. A Scientific Committee on Ocean Research (SCOR) working group on biogeography will report soon and 30 to 40 national museums are presently working on greater coordination of their programs internationally. Databases such as FishBase (Froese and Pauly, 1998) and Species 2000 (Bisby and Smith, 1996) are under development to provide uniform nomenclature and basic biological information on described species. Protocols for ensuring data quality, coordinating reporting mechanisms, and other input controls would be critical for compiling more extensive databases.

2. *Assembly of Historic Data:* A necessary component of a global assessment program would be to coordinate and review historical and existing data sources. Initiation of a new program without reviewing existing data, would be a poor use of funds and may not provide a comparative context for new observations. Compilation and evaluation of historical survey, catch, and biological data on major nekton, especially the rich international literature on many species, would be crucial. Development of databases such as FishBase for other higher trophic level organisms, including micronekton and squid, would be extremely beneficial.

   The workshop participants favored using existing data on better known systems while focusing new observational efforts on less well-known regions. This approach would provide some knowledge about many oceanic regions rather than in depth knowledge of only a few regions. Areas such as upwelling zones, coral reefs, the North Sea, and many coastal zones are relatively well known. These biogeographic regions could be modeled based on existing data and observational efforts focused on the larger, open ocean areas. Compilation of historical data would facilitate ongoing modeling effort.

3. *Modeling:* Numerous models of trophic structure and energy transfer exist. However, existing models need to be coordinated and new models developed which use the same currency units (carbon, mass etc.). This modeling effort could help identify the types of information most needed to reduce uncertainties in prediction of the abundance of higher trophic levels and thus, provide focus for the observational program.

4. *Technology Development:* Assessment of the biomass, abundance, and size of open ocean taxa requires both significant advances in new technology and better application of existing technologies. The vast potential of existing acoustic and optical technology has yet to be fully utilized for fisheries and ecosystem assessment. Thus, a program to assess marine life could serve as a stimulus for major development and application of assessment technology. Remote species identification was noted to be a central requirement for any significant effort to assess the biomass of single species. Participants actively involved in developing acoustical, optical, and other monitoring technologies felt that the integration of various sensors and platforms that currently exist could be valuable for addressing many of the observational needs of a potential program.

   Technologies that show promise include use of LIDAR to detect pelagic fish from aircraft, sheet laser methods, long-range, low frequency back and forward scattering sensor systems, horizontal multi-frequency sonar, and multi beam and multifrequency acoustics. Acoustical signals offer the capability to assess the distribution of fish in reasonably large volumes of water (0.1 to 100 km^3). The most modern acoustical tools employ both multibeam echosounders and wide frequency-bandwidth sonar, which have the ability to count and size individuals and, to some degree, discriminate among species. More extensive calibration and ground-truthing of these signals with actual species abundances and taxonomic affiliations would permit extrapolation of this technology to a larger suite of animals. The field of passive acoustics is underutilized for species that generate sound (e.g. reef fishes, marine mammals) and could be exploited. Finally, inexpensive, calibrated acoustic technology should be adapted for use aboard commercial vessels and other ships of opportunity.

   Optical and bio-optical techniques are crucial for an assessment program. The recent development of a method for the in situ measurement of animal acoustic target strength with concurrent species identification via optical imaging provides important calibrating information which can be extrapolated to larger scale surveys of animals (Jaffe et al., in press). Continued miniaturization of archival and pop-up tags suggests that tagging technology also holds promise, particularly for marine reptiles and marine mammals. The use of genetic markers and the assessment of populations through chemical markers, scents, and tracers may have potential. Multidisciplinary approaches which combine two or more sensor technologies to achieve better measurement resolution and accuracy need to be developed. Finally a variety of platforms could be exploited such as ships, large marine animals, open-ocean moorings, bottom-mounted moorings, nets, submersibles, neutrally buoyant floats, drifters, autonomous underwater vehicles (AUVs), remotely operated vehicles (ROVs), aircraft, and satellites (especially for phytoplankton biomass) to realize the full potential of a global assessment program.

   Clearly these technologies cannot all be developed fully in the short term, but major changes in our capability for oceanic estimation are possible on a short (5-10 years), medium (10-15 years) or long (15-25 years) term time horizon.

Phase II (years 4-8, observational program)

1. *Pilot Observational Program at Representative Open Ocean Zones:* Given the ambitious nature of assessing marine life on a global scale, the workshop consensus was that any pilot observation program needed to focus on obtaining information that would result in the largest leap forward in our ability to assess higher trophic levels globally. Thus, the most pressing need was to augment information on the large, less well-known biogeographical regions. The modelers participating in the workshop felt that these major gaps centered on estimates of the abundance and distribution of open ocean nekton and macrozooplankton. Often real mismatches exist between estimates of organisms obtained using standard oceanographic biological sampling and abundances estimated from indirect methods such as assessment of top predator diets (Clarke, 1996). Such contradictory evidence clearly highlights the level of our uncertainty and the need for information on trophic interactions as well as species abundance. Especially lacking is good information on the abundances, distributions and rates of trophic transfer for oceanic cephalopods, mesopelagic animals, euphausiids and macrocrustaceans, gelatinous zooplankton, macro-sized epipelagic fish and small cetaceans in the open oceans. Investigation of these taxa would produce a major step forward and appeared to be a logical place on which to focus a coordinated observational effort in meeting the Grand Challenge. While phytoplankton, microbes, and certain taxa of zooplankton are reasonably well known for these regions, data on higher trophic levels is conspicuously sparse. Research would focus on the assessment of population sizes, where possi-

ble, and on trophic dynamics, rates of trophic transfer, and population parameters including growth rates, feeding rates, mortality, reproduction, survivorship and other parameters. Field observations would be augmented with laboratory experiments where possible. Criteria for site selection would need to consider international participation and relevancy for the national science and resource management programs of participating nations. Many countries would have an interest and potential role in regional assessments and significant coordination between the various nations would be required.

2. *Filling Major Gaps in Better Known Zones:* Trophic dynamics and important population parameters of key organisms in other biogeographic regions could also be a focus of some observational work where such data would correct major deficiencies in our ability to make predictions regarding better known regions. Moreover, some assessment in well known regions could serve to verify model findings in an iterative process, thus increasing confidence in modeling results.

Phase III (years 8-10, Improve Models and Modeling Estimates)

Both newly generated observations and historical data would be used to improve the modeling estimates. The improved models would be verified with additional observation. Thus modeling and observation would continue simultaneously throughout the program with intensive activity in years 8-10.

Participation and implementation

The workshop participants suggested that, in addition to support from foundations, typical funding sources such as the National Science Foundation (NSF) and the National Oceanic and Atmospheric Administration (NOAA) should be augmented by additional non-traditional sources of either support or advice. These might include the fishing industry, non-government organizations, the Global Environmental Facility (GEF), the Food and Agriculture Organization (FAO), or other governmental sources, particularly in developing countries. The participants recognized that "selling the idea" to the public as well as program officers at government agencies and elsewhere would require a clear, concise message with strong societal and scientific relevance. Furthermore, the support and enthusiasm of the broader ocean science community would be essential for successful development and implementation.

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