Abstract
The Sloan Foundation sponsored a workshop in January 1998, to discuss the value, timeliness, and feasibility of stimulating and organizing a period of intense, comprehensive oceanic observation whose purpose would be to assess and explain 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, species interactions, and the population and community dynamics of marine systems. The major goals generated by the workshop were to determine the biomass of the marine biota, especially higher trophic levels, on a global scale, to determine how this biomass is distributed spatially and by size and taxon, and to investigate how these distributions are maintained or changed.

While these goals were acknowledged by all to be extremely ambitious, significant advances toward attaining them were considered possible on a 10-year time frame. An iterative process of modeling and observation was proposed aimed at developing an increasingly more accurate global assessment of the abundance of marine life based on an understanding of the trophic structure, population sizes, and flow of matter through the food webs of major biogeographic zones in the ocean. Existing data on species distributions, species richness and relative abundance, trophic dynamics, and environmental parameters would be used to identify these biogeographic regions. A pilot observational program would focus primarily on filling in large unknowns in our existing global ecosystem models. The largest gap appeared to be information on the abundances, distributions and rates of trophic transfer of poorly known open ocean animals, primarily cephalopods, mesopelagic animals, euphausiids and macrocrustaceans, zooplankton, especially fragile gelatinous forms, macro-sized epipelagic fish and small cetaceans.

Assessment of the biomass, abundance, and size distribution of open ocean taxa requires both significant advancements in new technology and better application of existing technologies, including acoustical, optical, genetic, and chemical approaches. Participants, who included a broad suite of ecologists, oceanographers, fisheries scientists, and modelers, felt that a global assessment program based on a trophic dynamics/modeling approach presented the prospect of significant scientific and societal benefits but would require the organization of a multiagency and multinational effort.
General Focus of the Workshop

Put a man on the moon by 1970. This was the "Grand Challenge" (Briscoe, pers. com.) that mesmerized the public and galvanized much of the scientific community of the US in the 1960s. Yet the goal itself (a man standing on the moon) was actually relatively meaningless. The meaning behind the challenge came from the tremendous technological advances required to achieve it, from its motivating influence on American science and technology, and from the way it inspired and riveted the imaginations of an entire nation.

On January 13-15, 1998, the Sloan Foundation, with additional support from ONR, sponsored an informal workshop in Monterey, California, that brought together scientists representing benthic ecology, marine policy, acoustics, fisheries and stock assessment, marine ecology, vertebrate and invertebrate biology, modeling, and physical and biological oceanography, to address a similar type of Grand Challenge: "How many fish are in the sea?" While the initial response of most participants was skepticism about the value of such a question or of its answer, were it attainable, it became quickly obvious that the question itself had the potential to both inspire the scientific community and captivate the public. The fact that we do not reliably know how many fish are in the sea, 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 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 recent report of a long-term gradual decline in the average trophic level of the fish being removed from the sea by man (Pauly, et al, 1998), of possible expansions of gelatinous planktonic predator populations (Mills), and of the decline of many marine fisheries, suggest some urgency in searching for a quantum leap in our knowledge of the abundances, 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 its 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 major goal, which unites 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. The workshop participants redefined the original charge of the Sloan Foundation 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 determine the global patterns of life in the ocean, the mechanisms that maintain and change these patterns, and the amount of life the ocean can sustain.
This challenge was made more concrete and attainable by focusing it primarily on higher trophic levels, with some emphasis on economically important species. However, the distribution, abundance and productivity of lower trophic levels and the biological, chemical, and physical processes affecting ecosystem structure were also 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?
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, discussion made clear that our present knowledge was not trivial. 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 (ECOSIM- others?). The accuracy with which these models predict global distributions of biomass and abundance are constrained by a few large gaps in our knowledge, especially information on the abundance and distribution of animals in the open ocean and mesopelagic zone. These models constitute puzzles with a relatively small number of very large pieces missing. The generation of information with which to fill these major gaps could result in a quantum leap forward in the accuracy of our estimates of the global abundance of marine life, especially that of higher trophic levels, and was seen as the first step in any observation program.

The major questions posed 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. Equally important, the workshop participants were able to identify the beginnings of a path toward achieving these goals with identifiable benchmarks for success in the short-term future of about 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 very 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 only biological parameter at present. Moreover, the patchy distributions of all organisms and the high motility of most nekton make it very difficult to generalize local distributions and abundances to broader regional or global scales.
The most tractable approach to access the biomass and abundance 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 trophic 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. Models already exist which 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. 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 of providing continually improving reiterative 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 generated. Such an approach can also be tailored for each differing region of the ocean. Moreover, this approach allows the global assessment of marine life to move far beyond a simple census of species abundance 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
Several components were seen as essential for an initial global assessment program. In general these components fell into three phases. During Phase I biogeographic zones would be defined and extensive review of existing data and models undertaken. The goal of the latter would be to clearly define major gaps in our knowledge. Development of important technology for population assessment would also begin in this phase. During Phase 2, important gaps in the models would be filled by specific studies, both observational (population parameters of targeted functional groups measured in situ) and experimental (growth rates, reproductive rates etc.). In Phase III the models would be improved and tested during an iteration of Phase II.

Phase I

1. Defining Biogeographical zones
Trophic structure varies considerably across various regions of the ocean. Splitting the globe into biogeographic regions based on commonalities in trophic structure was advocated in order to accurately expand from local to regional and global scales and to attain the necessary
level of detail at a global level. Biogeographic zones should be defined to be as large as possible while maintaining approximately the same trophic web structure. The same kinds of functional groups, rather than the same 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 systems of partitioning the global ocean might be devised based on different criteria. Several systems identifying marine biomes already exist which could provide a basis for further advancement.

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, including surface productivity, could be used to test hypotheses on biogeographic distributions, species richness etc. Participants at the workshop felt that historical and recent information on several major taxonomic groups was sufficient to develop global maps of the biodiversity of these groups within the first year of the program. Benthic taxa for which this was judged possible included corals, anemones, decapods, mollusks, and bryozoans. Many institutions and agencies are presently involved in biodiversity issues. NOAA has been developing a taxon database and information on cnidarians, mollusks, decapods, ctenophores and annelids is nearly ready. A 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 and Species 2000 are under development to provide uniform information on described species. Protocols for ensuring data quality, coordinating reporting mechanisms, and other input controls would be critical for compiling databases.

2. Assembly of Historic Data
A necessary component of a global assessment program would be to catalyze the coordination and review of historical and existing data sources. Initiation of a new program without reviewing the existing data would be a less efficient 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 levels, including squid, and micronekton, would be extremely beneficial.

The workshop participants favored use of existing data on better known systems while focusing new observational efforts on less well-known regions. From the modeling perspective it was wiser to know a little about a lot of oceanic regions than to know one or two areas completely. 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 have to be tightly coupled with the 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 units of currency
(carbon, mass etc.). This modeling effort would help guide the observational program and insure that data are collected in units appropriate for the models.

4. Technology Development
Assessment of the biomass, abundance, and size of open ocean taxa requires both significant advancements in new technology and better application of existing technologies. The vast potential of existing acoustic and optical technology has yet to be fully tapped 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, PIV and sheet laser methods, acoustic tomography, long-range, low frequency back and forward scattering sensor systems, horizontal multi-frequency sonar, and multi beam acoustics. Acoustical signals offer the capability to assess the distribution of fish in reasonably large volumes of water (0.1 to 100 km³). The most modern acoustical tools employ both multibeam echosounders and wide band sonar, which have the ability to count and size individuals and, to some degree, discriminate type. More extensive calibration and ground-truthing of these signals with actual animal 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 noise (reef fishes, marine mammals) and could be exploited.

Optical and bio-optical techniques are crucial for an assessment program. Continued miniaturization of archival and pop-up tags suggests that tagging technology holds promise, particularly for marine reptiles and marine mammals. A wealth of new approaches is opening up through the use of genetic markers and means of assessing populations through chemical markers and tracers also has 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 including ships, large marine animals, open-ocean moorings, bottom-mounted moorings, nets, submersibles, neutrally buoyant floats, drifters, autonomous underwater vehicles, ROV’s, 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 serial changes in our capability for oceanic estimation are possible on a short (5-10 year), medium (10-15 yrs) or long (15-25yr) time horizon.
Phase II.

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 observational program needed to focus on obtaining that 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. Especially lacking is good information on the abundances, distributions and rates of trophic transfer for oceanic cephalopods, mesopelagic animals, euphausiids and macrocrustaceans, zooplankton, especially fragile gelatinous forms, 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 the logical first 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 are conspicuously sparse. Research would focus on the assessment of population sizes, where possible, and on trophic dynamics, rates of trophic transfer, and population parameters including growth rates, feeding rates, mortality, reproduction, survivorship etc. Field observations would be augmented with laboratory-base experimental approaches where possible.

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 - 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 this period with strong and iterative interaction

10-year Program

A very rough outline of a potential 10-year program was generated. This program was envisioned as a multi-national effort costing on the order of 50 million per year. The program consisted of a number of concurrent activities:

PHASE I (Years 1-4): Planning, technology development and consolidation of existing knowledge
   A. Develop global maps of biodiversity and define the biogeographic zones
B. Assemble the relevant existing ecological knowledge of each zone, which would allow identification of the major gaps in knowledge.

C. Refine modeling efforts using available information. Use the models in planning of the observational phase.

D. Develop technologies likely to provide the greatest benefit during the observational phase.

**PHASE II (Years 4-8): Observational Program**

A. Investigate one representative open ocean region.

B. Conduct modest investigation of better known regions

The observational program was viewed as a pilot study. Research would focus both on improving population and biomass assessment directly, and on obtaining appropriate population and community parameters to better assess distributions and abundances through trophic dynamics. 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 little interest or potential role in regional assessments and significant coordination between the various nations would be required.

**PHASE III (8-10 years): Improve Models and Modeling Estimates**

**Participation and implementation**

The workshop participants suggested that, in addition to the Sloan Foundation, 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. These might include the fishing industry, the International Monetary Fund (IMF), the Food and Agriculture Organization (FAO), or other governmental sources, particularly in the 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, participants felt that unless the broader ocean science community can be convinced of the value of the project, it is likely to face significant difficulties.