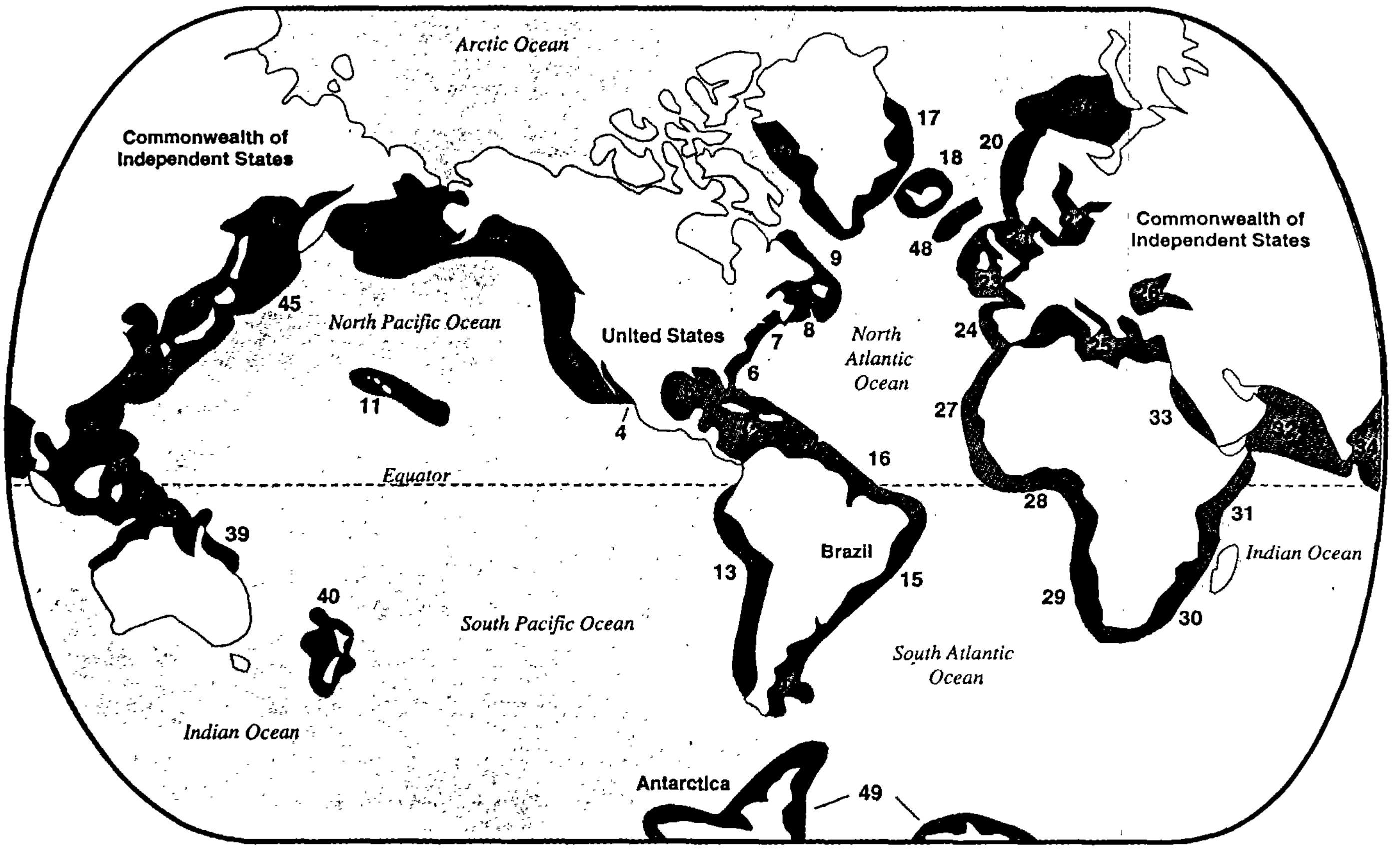
INTERGOVERNMENTAL OCEANOGRAPHIC COMMISSION

ASSESSMENT AND MONITORING OF LARGE MARINE ECOSYSTEMS



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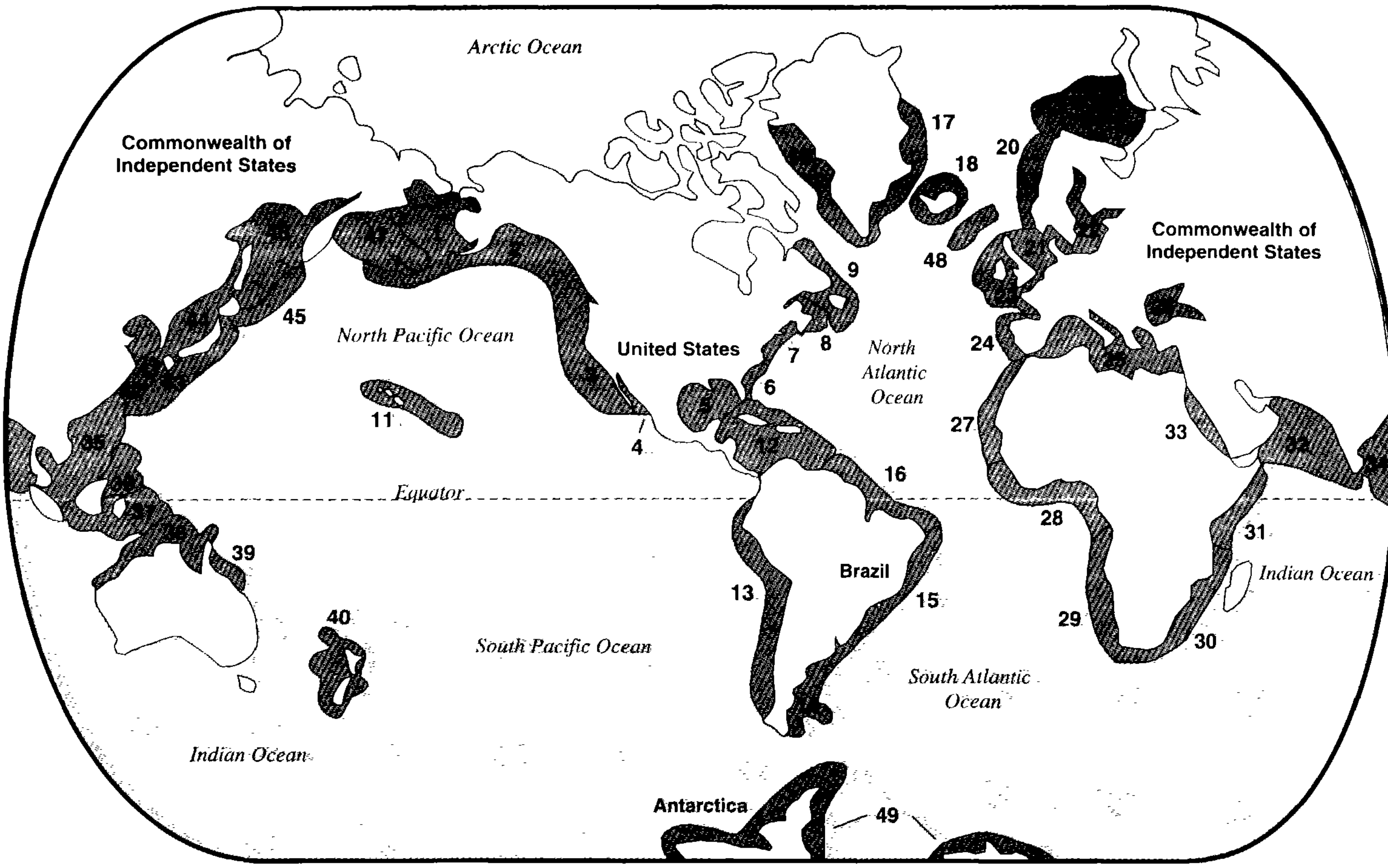

WORLD MAP OF LARGE MARINE ECOSYSTEMS

1. Eastern Bering Sea
2. Gulf of Alaska
3. California Current
4. Gulf of California
5. Gulf of Mexico
6. Southeast U.S. Continental Shelf
7. Northeast U.S. Continental Shelf
8. Scotian Shelf
9. Newfoundland Shelf
10. West Greenland Shelf
11. Insular Pacific-Hawaiian
12. Caribbean Sea
13. Humbold Current
14. Patagonian Shelf
15. Brazil Current
16. Northeast Brazil Shelf
17. East Greenland Shelf
18. Iceland Shelf
19. Barents Sea
20. Norwegian Shelf
21. North Sea
22. Baltic Sea
23. Celtic-Biscay Shelf
24. Iberian Coastal
25. Mediterranean Sea
26. Black Sea
27. Canary Current
28. Guinea Current
29. Benguela Current
30. Agulhas Current
31. Somali Coastal Current
32. Arabian Sea
33. Red Sea
34. Bay of Bengal
35. South China Sea
36. Sulu-Celebes Seas
37. Indonesian Seas
38. Northern Australian Shelf
39. Great Barrier Reef
40. New Zealand Shelf
41. East China Sea
42. Yellow Sea
43. Kuroshio Current
44. Sea of Japan
45. Oyashio Current
46. Sea of Okhotsk
47. West Bering Sea
48. Faroe Plateau
49. Antarctic

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Foreword

A significant milestone in marine resource development was achieved in July 1992 with the adoption by a majority of coastal countries of follow-on actions to the United Nations' Conference on Environment and Development (UNCED). The UNCED declarations on the ocean explicitly recommended that nations of the globe: (1) prevent, reduce, and control degradation of the marine environment so as to maintain and improve its life-support and productive capacities; (2) develop and increase the potential of marine living resources to meet human nutritional needs, as well as social, economic, and development goals; and (3) promote the integrated management and sustainable development of coastal areas and the marine environment. UNCED also recognized the general importance of capacity building, as well as the important linkage between monitoring and the achievement of marine resource development goals.

Achievement of UNCED recommendations will require the implementation of a new paradigm in ocean monitoring and management that can overcome traditional geopolitical and interdisciplinary sectorization. Such an approach should be based on principles of ecology and sustainable development. The large marine ecosystem (LME) concept provides the framework for achievement of UNCED commitments. LMEs are areas which are being subjected to increasing stress from growing exploitation of fish and other renewable resources, coastal zone damage, river basin runoff, dumping of urban wastes, and fallout from aerosol contaminants. The LMEs are regions of ocean space encompassing near-coastal areas from river basins and estuaries on out to the seaward boundary of continental shelves and the seaward margins of coastal current systems. They are relatively large regions on the order of 200,000 km^2 or larger, characterized by distinct, bathymetry, hydrography, productivity, and trophically dependent populations. The theory, measurement, and modelling relevant to monitoring the changing states of LMEs are imbedded in reports on multistable ecosystems, and on the pattern formation and spatial diffusion within ecosystems.

Because LMEs usually subsume the coastal waters of more than one state, coordination between those states in monitoring and resource management is desirable. At present, however, no single international organization is authorized towork with coastal states to monitor the changing ecological states of LMEs and to reconcile the needs of individual nations where mitigation actions are necessary to reverse the deleterious impacts of stress on productivity and biomass yields. The need for a regional approach for implementation of marine research, monitoring, and stress mitigation has been recognized. Of course, coastal states maintain ultimate responsibility for their territorial sea and exclusive economic zone resources. Recognition of the LME concept engenders no legal commitment by coastal states to share their resources, although it is in their enlightened self interest to do so.

It is within the nearshore coastal domains of the LMEs that the human-induced stress on ecosystems requires mitigating actions to ensure the continued productivity and economic viability of marine resources. Although the management of LMEs is an evolving scientific and geopolitical process, sufficient progress has been made to allow for useful comparisons among the primary, secondary, and tertiary driving forces influencing large-scale changes in the biomass yields and long-term sustainability of LMEs. Results from a series of LME studies are presented in this report. They depict a linkage between the efforts of IOC to initiate a Global Ocean Observing System (GOOS) that includes modules for monitoring changes in ocean health and living resources. The report is intended to encourage dialogue and debate on strategies for linking scientific and societal interests. It is aimed at assisting in the short-term and long-term development and sustainability of coastal ocean ecosystems in the post-UNCED decade of the 1990s, bearing in mind the need to meet the objectives of Agenda 21 aimed at reducing the degradation of marine ecosystems and promoting their integrated management and sustainable development. The IOC is pleased to acknowledge the effort of K. Sherman and D. Busch, of the NMFS, NOAA, Northeast Fisheries Science and Research Center, Narragansett Laboratory, in the preparation of this report.

1. Utility of Coastal Ecosystem Assessment and Monitoring

Human intervention and climate change are sources of increasing variability in the natural productivity of coastal marine ecosystems. Within the near shore areas and extending seaward around the margins of the global land masses, coastal ecosystems are being subjected to increased stress from toxic effluents, habitat degradation, excessive nutrient loadings, fallout from aerosol contaminants, and episodic losses of living marine resources from pollution effects, and overexploitation. The growing awareness that the quality of the global coastal ecosystems are being adversely impacted by multiple driving forces has accelerated efforts to assess, monitor, and mitigate coastal stressors from an ecosystem perspective. The Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational, Scientific, and Cultural Organization (UNESCO) is encouraging coastal nations to establish national programs for assessing and monitoring coastal ecosystems so as to enhance the ability of national and regional management organizations to develop and implement effective remedial programs for improving the quality of degraded ecosystems (IOC, 1992a).

For purposes of this report, marine ecosystem monitoring is defined as a component of a management system that includes: (1) regulatory, (2) institutional, and (3) decision-making aspects relating to marine ecosystems, and therefore, would include a range of activities needed to provide management information about ecosystem conditions, contaminants, and resources at risk. Based on successful experiences in North America, Europe, and elsewhere, the core component of a comprehensive ecosystem monitoring system that consists of conceptual and numerical modelling capability, laboratory and field research, time-series measurements, data analysis, synthesis and interpretation, and a capacity for initiating the effort with preliminary or scoping studies is most likely to be successful. The principal characteristic of a comprehensive ecosystem monitoring program is the integration and coordination of the component parts of the effort into a total ecosystems approach designed to produce scientific information in support of coastal resources management.

We provide information and guidelines that focus on an integrated regional and global approach to coastal marine ecosystem assessment and monitoring. The strategy is consistent with the conclusion that monitoring efforts at the regional scale need to be strengthened to improve understanding of broader-scale trends in marine ecosystem quality. In addressing sampling design alternatives for a regional strategy for coastal ecosystem monitoring, we have reviewed options, with respect to: (1) an independent, fixed-station monitoring effort, or (2) an integrated network of monitoring stations based on a statistical design on a regional scale. A regional network that links both strategies and includes areas of special attention is preferred. Among the options to be employed is the use of stratified sampling for long-term trend assessments of ecosystem parameters using standard and intercalibrated protocols in areas with different levels of ecosystem stress augmented by high-intensity sampling in areas at high-risk from environmental degradation.

We have drawn from several recent reports in the preparation of this document, including the United Nations' report on the status of the global marine environment (GESAMP, 1990), the IOC's report on the Global Ocean Observing System (GOOS) presented to the United Nations Conference on the Environment and Development

(UNCED) in 1992 (IOC, 1992a), the reports of several international commissions, including the Helsinki Commission (HELCOM), the Oslo-Paris Commission (OSPARCOM), the North Sea Task Force (NSTF, 1991), and the report of the International Council for the Exploration of the Sea (ICES) Working Group on Environmental Assessments and Monitoring Strategies (WGEAMS, 1992).

2. Coastal Ecosystem Component of the Global Ocean Observing System

The IOC, based on guidance from member nations, is encouraging the development of a comprehensive Global Ocean Observing System (GOOS) to provide information needed for oceanic and atmospheric forecasting for ocean management by coastal nations and for the needs of global environmental change research, and related education, training, and technical assistance programs to ensure that all countries can participate and benefit from the effort (UNESCO, 1992). The coastal ecosystem component of the GOOS is being planned to provide a basis for the assessment, monitoring, and mitigation of the present ecological conditions in the coastal areas of nations already experiencing significant economic losses of resource sustainability from degraded water quality, contaminated fisheries resources, and loss of important habitat (e.g., coral reefs, mangrove lagoons, estuaries, and embayments). Timely and effective responses to these changes in ecosystem conditions will depend in part on the quality and availability of information on the rate and magnitude of these changes at the regional ecosystem level.

The strategic design of a coastal ecosystem component for the GOOS should include pertinent existing research and monitoring investigations that measure-up to program criteria that will constitute a "core" of the program. Included in the "core" will be selected components of existing national networks of laboratories and vessels of marine resource ministries that are already engaged in coastal ecosystems monitoring, assessment, mitigation, and information transfer operations relating to marine environmental quality, living marine resources, and ecosystem health.

Mitigating actions to reduce stress on marine ecosystems are required to ensure the long-term sustainability of marine resources. The principles adopted by coastal states under the terms of the United Nations Convention for the Law of the Sea (UNCLOS) have been interpreted as supportive of the management of living marine resources and coastal habitats from an ecosystems perspective (Belsky, 1986, 1989). However, at present no single international institution has been empowered to monitor the changing ecological states of marine ecosystems and to reconcile the needs of individual nations with those of the community of nations in taking appropriate mitigation actions (Myers, 1990). In this regard, the need for a regional approach to implement research, monitoring, and stress mitigation in support of marine resources development and sustainability at less than the global level has been recognized from a strategic perspective (Taylor and Groom, 1989; Malone, 1991).

From the ecological perspective, the concept that critical processes controlling the structure and function of biological communities can best be addressed on a regional basis (Ricklefs, 1987) has been applied to ocean space in the utilization of marine ecosystems as distinct global units for marine research, monitoring, and management. The concept of monitoring and managing renewable resources from a regional ecosystem perspective has been the topic of a series of symposia and workshops initiated in 1984 and continuing through 1992, wherein the geographic extent of each region is defined on the basis of ecological criteria (Table 1). As the regional units under consideration are large, the term Large Marine Ecosystem (LME) is used to characterize them. LMEs are extensive areas of ocean space of approximately 200,000 km^2 or greater characterized by distinct bathymetry, hydrography, productivity, and trophically dependent populations (Sherman and Alexander, 1986). Several occupy semi-enclosed seas, such as the Black Sea, the Mediterranean Sea, and the Caribbean Sea. Some of these can be divided into domains, or subsystems--for example the Adriatic Sea, a subsystem of the Mediterranean Sea LME. In other LMEs geographic limits are defined by the scope of continental margins. Among these are the U. S. Northeast Continental Shelf, the East Greenland Sea, the Northwestern Australian Shelf. The seaward limit of the LMEs extends beyond the physical outer limits of the shelves, themselves, to include all or a portion of the continental slopes. Care was taken to limit the seaward boundaries to the areas affected by ocean currents, rather than relying simply on the 200-mile Exclusive Economic Zone (EEZ) or fisheries zone limits. Among the ocean current LMEs are the Humboldt Current, Canary Current, and Kuroshio Current.

It is the coastal ecosystems adjacent to the land masses that are being stressed from habitat degradation, pollution, and overexploitation of marine resources. Nearly 95% of the usable annual global biomass yield of fish and other living marine resources is produced in 49 LMEs within, and adjacent to, the boundaries of the EEZs of coastal nations located around the margins of the ocean basins, where levels of primary production are persistently higher than for the open-ocean pelagic areas of the globe (Figure 1).

Pollution at the continental margins of marine ecosystems can impact on natural productivity cycles, including eutrophication from high nitrogen and phosphorus effluent from estuaries. The presence of toxins in poorly treated sewage discharge, and loss of wetland nursery areas to coastal development are also ecosystem-level problems that need to be addressed (GESAMP, 1990). Overfishing has caused biomass flips among the dominant pelagic components of fish communities resulting in multimillion metric ton losses in potential biomass yield (Fogarty et al., 1991). The biomass flip, wherein a dominant species rapidly drops to a low level to be succeeded by another species, can generate cascading effects among other important components of the ecosystem, including marine birds (Powers and Brown, 1987), marine mammals, and zooplankton (Overholtz and Nicolas, 1979; Payne et al., 1990). Recent studies implicate climate and natural environmental changes as prime driving forces of variability in fish population levels (Kawasaki et al., 1991; Bakun, 1993; Alheit and Bernal, 1993). The growing awareness that biomass yields are being influenced by multiple driving forces in marine ecosystems around the globe has accelerated efforts to broaden research strategies to encompass food chain dynamics and the effects of environmental perturbations and pollution on living marine resources from an ecosystem perspective.

3. Monitoring Strategy

During the twenty-fifth session of the IOC Executive Council meeting in Paris, an overview of the LME Concept was presented by the National Oceanic and Atmospheric

Administration (NOAA) as a contribution to the discussion of candidate strategies for assessing and monitoring the changing states, or "health," of coastal ecosystems (IOC, 1992b). This document expands on the earlier presentation. It is focused on the LMEs around the margins of the landmasses where the pressures of overexploitation, pollution, and habitat degradation from a growing global population are stressing marine resources. Strategies are outlined in this report for monitoring the changing-states of marine ecosystems using methods that are designed to provide ecosystem-level measurements contributing to the coastal ecosystem component of the GOOS. Included in the "core" monitoring strategy is the use of the Continuous Plankton Recorder (CPR) for plankton and water quality assessment, bottom trawling for measuring changes in the fish community, and environmental/pollution assessments. These strategies can be used to measure the changing ecological states of LMEs as described in an earlier IOC report (UNESCO, 1992).

The scientific "hallmark" of the monitoring strategy recommended for the coastal ecosystem component of GOOS is a holistic approach. The areas to be monitored include river drainage basins, estuaries, bays and coastal waters out to the seaward boundary of the ecosystem. The design of the sampling strategy will be developed for the distinctive characteristics of each LME. The strategy is to assess and monitor the changing states of LMEs at all relevant scales of interest contained within their boundaries. The Program strategy should employ a hierarchical ecosystem sampling design within each LME, placing emphasis on nearshore areas under greatest stress from contaminants, eutrophication and degraded living marine resources, and relatively less emphasis on areas of low risk. This monitoring system will provide the scientific basis for remedial action at the appropriate scale in relation to environmental stress. The challenge for determining the cause and effect of natural and human induced processes of ecosystem level variability is significant. For example, within the 258,000 km^2 Northeast U.S. Continental Shelf Ecosystem, the impact of pollution from 54 million people generating about 7 million gallons of wastewater per day, and contaminants from atmospheric deposition, and 478,000 km^2 of watersheds, will need to be quantified to determine the effects of these stressors on the billion dollar/year living resource industries so as to provide a firm basis for exercising appropriate mitigation actions. At finer scales of resolution within the LME, the impacts will need to be quantified as relevant; for example, determining the water quality parameters of a specific bay or harbor, or quantifying effluent discharges from a particular watershed of interest to local officials.

Consideration should be given to the use of standard and intercalibrated protocols in areas with levels of effort focused on areas of the LME under the greatest environmental and biological stress including the watersheds, bays and estuaries, and coastal water of LMEs. Long-term historical time series data on living marine resources (some up to forty years), coupled with measured or inferred long-term pollutant loading histories, have proven useful for relating the results of intensive monitoring to the quantification of "cause and effect" mechanisms based on first principles of aquatic toxicological and ecological theory on the changing states of health and environmental stress on LMEs (Sherman et al., 1993). Maximum use of historical long-term time series data, using cutting-edge analytical techniques, supplemented with intensive monitoring, is an important component in the implementation of coastal ecosystems monitoring. Numerical models of environmental impacts need to be developed and applied in a manner that will link information on natural characteristics of coastal ecosystems and the impacts of human-induced changes to the decision-making process of resource managers. The models will be used to assist managers and scientists in designing efficient monitoring strategies. Statistical models should be utilized to evaluate the most efficient use of sampling and analytical resources.

Temporal and spatial scales influencing biological production and changing ecological states in marine ecosystems have been the topic of a number of theoretical and empirical studies. The selection of scale in any study is related to the processes under investigation. An excellent treatment of this topic can be found in Steele (1988). He indicates that in relation to general ecology of the sea, the best known work in marine population dynamics includes studies by Schaefer (1954), and Beverton and Holt (1957), following the earlier pioneering approach of Lindemann (1942). A heuristic projection was produced by Steele (1988) to illustrate scales of importance in monitoring pelagic components of the ecosystem including phytoplankton, zooplankton, fish, frontal processes, and short-term but large-area episodic effects (Figure 2). However, as noted by Steele (1988), this array of models is unsuitable for consideration of temporal or spatial variability in the ocean. The LME approach defines a spatial domain based on ecological principles and, thereby, provides a basis for focused temporal and spatial scientific research and monitoring efforts in support of management aimed at the long-term productivity and sustainability of marine habitats and resources. The theory and modelling relevant to measuring the changing states of LMEs are imbedded in contemporary studies of: (1) multistable ecosystems (Holling, 1973, 1986; Pimm, 1984; Beddington, 1986), and (2) pattern formation and spatial diffusion in ecosystems (Levin, 1978; 1990; Levin et al., 1984).

4. Perturbations and Driving Forces in LMEs

Among the marine resources at risk from global climate change and human intervention of natural productivity cycles are the fish components of coastal LMEs. Increasing attention has been focused over the past few years on synthesizing available biological and environmental information influencing the natural productivity of the fishery biomass within LMEs in an effort to identify the primary, secondary, and where important, the tertiary driving forces causing major shifts in species composition.

For nearly 75 years since the turn of the century, biological oceanographers did not achieve any great success in predicting fish yield based on food chain studies. As a result, through the mid 1970s, the predictions of the levels of biomass yields for different regions of the world ocean were open to disagreement (Ryther,1969; Alverson et al., 1970; Lasker, 1988). It is clear that "experts" have been off the mark in earlier estimates of global yield of fisheries biomass. Projections given in *The Global 2000 Report* (U. S. Council on Environmental Quality, 1980) indicated that the world annual yield was expected to rise little, if at all, by the year 2000 from the 60 million metric tons (mmt) reached in the 1970s. In contrast, estimates given in *The Resourceful Earth* (Wise, 1984) argue for an annual yield of 100-120 mmt by the year 2000. The trend is upward; the 1989 level of marine global fishery yields reached 86.5 mmt (FAO, 1992). The lack of a clear definition of actual and/or potential global yield is not unexpected, given the limited efforts presently underway to improve the global information base on living marine resource yields. A milestone in fishery science was achieved in 1975 with the convening of a symposium by the International

Council for the Exploration of the Sea that focused on changes in the fish stocks of the North Sea and their causes. The symposium, which dealt with the North Sea as an ecosystem, following the lead of Steele (1974), Cushing (1975), Andersen and Ursin (1977), and others, was prompted by a rather dramatic shift in the finfish community of the North Sea from a balance between pelagic and demersal finfish prior to 1960 to demersal domination from the mid-1960s through the mid-1970s. Although no consensus on cause and effect was reached by the participants, it was suggested by the convener (Hempel, 1978) that the previous studies of seven-and-a-half decades may have been too narrowly focused, and that future studies should take into consideration fish stocks, their competitors, predators and prey, and interactions of the fish stocks with their environments, the fisheries, habitat change, and pollution from an ecosystems perspective.

The LMEs that together produce approximately 95% of the annual global fisheries biomass yield are listed in Table 2. Although the United Nations Food and Agriculture Organization (FAO) world fishery statistics have shown an upward trend in annual biomass yields for the past three decades, it is largely the clupeoids that are increasing in abundance (FAO, 1992). A large number of stocks have been and continue to be fished at levels above long-term sustainability. The variations in abundance levels among the species constituting the annual global biomass yields are indicative of changing regional ecosystem states caused by natural environmental perturbations, overexploitation, and pollution. Although the spatial dimensions of LMEs preclude a strictly controlled experimental approach to their study, they are perfectly amenable to the comparative method of science as described by Bakun (1993). Since 1984, 29 case studies investigating the major causes of large-scale perturbations in biomass yields of LMEs have been completed (Table 1). The principal driving forces for biomass changes vary among ecosystems.

Changes in the ocean climate of the northern North Atlantic during the late 1960s and early 1970s have been considered by some marine scientists as the dominant cause of change in the food chain structure and biomass yields of at least three northern North Atlantic LMEs. Large-scale declines in the population levels of important fish stocks (e.g., capelin, cod) within the Norwegian Sea, Barents Sea, and West Greenland Sea ecosystems have been observed. In the West Greenland Sea Ecosystem, cod stocks were displaced southward since 1980, attended by a decrease in their average size and abundance. Biomass yields declined from about 300,000 metric tons (mt) per year in the mid-1960s to less than 15,000 mt in 1985. Both changes appear to have been due to short-term cooling that influenced stability of water masses, dynamics of the plankton community, and adversely affected the growth and survival of early developmental stages of cod resulting in a reduction in recruitment. Observations since the 1920s have shown that catches of cod are correlated with temperature--increasing during warm periods and declining during cool periods. The effects of fishing mortality on the decline of the cod are secondary to the major influence of climatic conditions over the North Atlantic (Hovgaard and Buch, 1990).

To the east, changes in the temperature structure of the Norwegian Sea Ecosystem also appear to be the major driving force controlling the recruitment of the commercially important cod stocks. Strong or medium production of cod biomass is related to warmer temperatures. The conditions for growth and survival of early developmental stages of cod are enhanced during warmer years when the larval cod are maintained for longer periods within coastal nursery grounds, where their most important prey organism, the copepod, *Calanus finmarchicus*, swarms in high densities under conditions of well-defined thermocline structure and consequently optimal feeding conditions of abundant phytoplankton.

The changes in biomass yields of the Barents Sea Ecosystem have been attributed primarily to changes in hydrographic conditions and secondarily to excessive fishing mortality. The average annual biomass yield (fish, crustaceans, molluscs, algae) of the ecosystem in the 1970s was about two million metric tons. However, by the 1980s annual yields declined to approximately 350,000 mt. Reduced flow of warm Atlantic water into the Barents Sea Ecosystem, coupled with excessive levels of fishing effort led to: (1) the collapse of the major fisheries of the region (cod, capelin, haddock, herring, redfish, shrimp); (2) subsequent disruption in the structure of the food chain; and (3) an increase in the abundance levels of the shrimp-like euphausiids representing a significant amount of biomass that is underutilized in relation to the potential sustained yield of this ecosystem. Given the depressed state of the fish stocks, any restoration management would need to consider significant reduction in fishing effort by fisherman of Norway and the former USSR, the coastal nations that share the resources of the Barents Sea Ecosystem (Skjoldal and Rey, 1989; Borizov, 1991).

In the North Sea Ecosystem, important species "flipped" from a dominant to a subordinate position over the decade of the 1960s. The finfish stocks of the North Sea Ecosystem have been subjected to intensive fishing mortality, resulting in a decrease in pelagic herring and mackerel yields from 5 mmt to 1.7 mmt, whereas small, fast-growing and commercially less desireable sand lance (also called sand eel), Norway pout, and sprat yields increased by 1.5 mmt along with an approximate 36% increase in gadoid yields. The causes for the biomass flips are not well understood. Several arguments suggest that the "flip" is caused by changing oceanographic conditions as the principal driving force. Other explanations support overexploitation as the major cause. However, none of the arguments can be considered more than speculative at this time, pending rigorous analysis of more recent information (Hempel, 1978; Postma and Zijlstra, 1988).

Further to the south of the North Atlantic are the Iberian Shelf and Benguela Current ecosystems, where the abundance of important fishery resources also seems to be related to climate-induced changes in the physical dynamics within each system. The alternation in abundance levels of horse mackerel and sardine within the Iberian Coastal Ecosystem is attributed to changes in natural environmental perturbation of its thermal structure rather than to any density dependent interaction among the two species (Wyatt and Perez-Gandaras, 1989).

Similarly, in the Benguela Current Ecosystem of the southwest coast of Africa, the long-term fluctuations in the abundance levels of pilchard, horse-mackerel, hakes (Figure 3), and anchovy are attributed to changes in the oceanographic regime. The Benguela LME is bounded by warm water regimes at both the equatorward and polarward extremities. Cold, nutrient-rich water upwells intensely in the central section and less intensely and seasonally in the northern and southern areas. In general, warmer environmental conditions favor the epipelagic species, and cooler conditions favor the demersal species. The environment has been a principal driving force for large-scale shifts in abundance among the fish species (Shelton et al., 1985). The effects of the fisheries on changes in species abundance are secondary. Changes in abundance of pilchard stocks have led to detectable effects in the abundance level of dependent predator species, particularly marine bird populations, and led to flips in dominant species such as anchovy replacing pilchard (Crawford et al., 1989).

In the Pacific, the greatest increases in biomass yields have been reported at the area of confluence between the Oyashio and Kuroshio Current ecosystems off Japan (Minoda, 1989; Terazaki, 1989) and in the Humboldt Current Ecosystem off Chile. In the Oyashio and Kuroshio Current ecosystems the yield of Japanese sardines increased from less than one-half million metric tons (mmt) in 1975 to just over 4 mmt in 1984. The yield of the Chilean sardine in the Humboldt Current Ecosystem also increased from about 500,000 mt in 1974 to 4.3 mmt in 1986. The increased yields have been attributed to density-independent processes involving an increase in lower food chain productivity, made possible by coastward shifts in the boundary areas of the Oyashio and Kuroshio systems and water mass shifts in the Humboldt Current Ecosystem. The effects of fishing on the sardines in both areas were of secondary importance compared to the enhanced productivity of the phytoplankton and zooplankton components of the ecosystems that provided an improved environment for growth and recruitment. Studies are underway to determine the extent of the teleconnection between the Pacific-wide El Niño events of the past decade and: (1) the multimillion metric-ton increases in yields of sardines occurring nearly simultaneously in the northern and southern hemispheres, and (2) the dramatic decline in the biomass yields of anchovy in the northern areas of the Humboldt Current Ecosystem in the early 1970s from about 12 mmt in 1970 to less than 2 mmt by 1976 (Canon, 1986; Figure 4).

Although less dramatic, the long-term shifts in abundance levels of both sardines and anchovies within the California Current Ecosystem (Figure 5) are considered the result primarily of natural environmental change and secondarily of intensive fishing, rather than of any density-dependent competition between the two species (MacCall, 1986).

To the north and west of Australia lies the relatively pristine Banda Sea Ecosystem, where no large-scale fisheries are presently conducted. The ecosystem is under the influence of monsoon-induced seasonal periods of large-scale upwelling and downwelling. Biological feedback to these environmental signals is reflected in the changes in phytoplankton, mesozooplankton, micronekton, and fish. During upwelling events, productivity of the ecosystem is enhanced by a factor of 2 to 3. The biomass of pelagic fish resources is also higher during the upwelling period. The fish biomass of the ecosystem is estimated at between 600,000 mt to 900,000 mt in the peak upwelling season (August), and 150,000 mt to 250,000 mt in the downwelling period (February). The estimated sustained annual biomass yield of the ecosystem is approximately 30,000 mt of pelagic fish (Zijlstra and Baars, 1990).

Changes in biomass yields of two other Pacific rim LMEs have been the result of overexploitation. The introduction of highly efficient modern trawlers to the Gulf of Thailand Ecosystem in an effort to increase fishing efficiencies, led to excessive fishing mortality and a marked reduction in annual yields of biomass of fish for human consumption between 1977 and 1982 (Piyakarnchana, 1989; Figure 6).

Intensive fishery effort resulted in the depletion of the demersal fish stocks and dramatic reductions in the biomass yields of the Yellow Sea Ecosystem. Between 1958 and

1968 fisheries yields declined from 180,000 mt to less than 10,000 mt. The fishery then shifted to harvesting pelagic stocks reaching a level of 200,000 mt in 1972, followed by a reduction to less than 20,000 mt in 1981. The fisheries of the Yellow Sea in 1982 shifted principally to anchovy and sardine with a total annual yield of all species 40% lower than the 1958 level. The demersal fishery remains in a depleted state (Tang, 1989; Figure 7).

The importance of a natural predator driving an ecosystem is evidenced in the large-scale changes in the community structure of the Great Barrier Reef Ecosystem that extends over 230,000 km^2 of the Queensland continental shelf. The predation by the crown-of-thorns starfish in the 1960s and 1970s, resulted in a shift in the biomass of corals, community structure of the benthos, and a decoupling of energy transfer to several fish stocks (Bradbury and Mundy, 1989).

In the enclosed and semi-enclosed marine ecosystems, the effects of pollution in the form of coastal eutrophication attibuted to high levels of nitrate and phosphate inputs from population centers have resulted in unusual phytoplankton blooms, oxygen depletion, biotoxin generated mortalities, and changes in ecosystem trophodynamics (Smayda, 1991). Among the impacted ecosystems are the Black Sea (Zaitsev, 1992; Caddy, 1993), Baltic Sea (Kullenberg, 1986), and Adriatic Sea (Bombace, 1993).

5. Management Considerations

Empirical and theoretical aspects of yield models for large marine ecosystems have been reviewed by several ecologists. According to Beddington (1986), Daan (1986), Levin (1990), and Mangel (1991), published dynamic models of marine ecosystems offer little guidance on the detailed behavior of communities. However, these authors concur on the need for covering the common ground between observation and theory by implementing monitoring efforts on the large spatial and long temporal scales (decadal) of "key" components of the LMEs. The sequence for improving the understanding of the possible mechanisms underlying observed patterns in LMEs is described by Levin (1990) as examination of: (1) statistical analyses of observed distributional patterns of physical and biological variables; (2) construction of competing models of variability and patchiness based on statistical analyses and natural scales of variability of critical processes; (3) evaluation of competing models through experimental and theoretical studies of component systems; and (4) integration of validated component models to provide predictive models for population dynamics and redistribution. The approach suggested by Levin (1990) is consistent with the recent observation by Mangel (1991) that empirical support for the currently used models of LMEs is relatively weak, and that a new generation of models is needed that serves to enhance the linkage between theory and empirical results.

There is a growing awareness among marine scientists, geographers, economists, government representatives, and lawyers, of the utility of a more holistic ecosystem approach to resource management (Byrne, 1986; Christy, 1986; Alexander, 1989; Belsky, 1989; Crawford et al., 1989; Morgan, 1989; Prescott, 1989). On a global scale the loss of sustained biomass yields from LMEs from mismanagement and overexploitation has not been fully investigated but is likely very large (Gulland, 1984).

Effective management strategies for LMEs will be contingent on the identification of the major driving forces causing large-scale changes in biomass yields. Management of species responding to strong environmental signals will be enhanced by improving the understanding of the physical factors forcing biological changes; whereas in other LMEs, where the prime driving force is predation, options can be explored for implementing adaptive management strategies. Remedial actions are required to ensure that the "pollution" of the coastal zone of LMEs is reduced and does not become a principal driving force in any LME. For at least one LME, the Antarctic, a management regime has evolved based on an ecosystem perspective in the adoption and implementation of the Convention for the Conservation of Antarctic Marine Living Resources (Sherman and Ryan, 1988). Efforts are also underway to implement ecosystem management within the LMEs of the U.S. EEZ, for example, in the northern California Current Ecosystem (Bottom et al. 1989). Concerns remain regarding the socioeconomic and political difficulties in management across national boundaries as in the case of the Sea of Japan Ecosystem where the fishery resources are shared by five countries (Morgan, 1988), or the North Sea Ecosystem, or the Caribbean Sea Ecosystem where 38 nations share the resources.

A systems approach to the management of LMEs is depicted in Table 3. The LMEs represent the link between local events (e.g., fishing, pollution, environment) occurring on the daily-to-seasonal temporal scale and their effects on living marine resources and the more ubiquitous global effects of climate changes on the multidecadal timescale. The regional and temporal focus of season to decade is consistent with the evolved spawning and feeding migrations of the fishes. These migrations are seasonal and occur over hundreds to thousands of kilometers within the unique physical and biological characteristics of the regional LME to which they have adapted. As the fisheries represent most of the usable biomass yield of the LMEs and fish populations consist of several age classes, it follows that measures of variability in growth, recruitment, and mortality should be conducted over multiyear timescales. Consideration of the naturally occurring environmental events and the human-induced perturbations affecting demography of the populations within the ecosystem is necessary. Based on scientific inferences of the principal causes of variability in abundance and with due consideration to socioeconomic needs, management options from an ecosystems perspective can be considered for implementation. The final element in the system, with regard to the concept of resource maintenance and sustained yield, is the feedback loop that allows for evaluation of the effects of management actions at the fisheries level (single species, multispecies) and the ecosystem level.

It will be necessary to conduct supportive research on the processes controlling sustained productivity of LMEs. Within several of the LMEs, including the Northeast Shelf, Gulf of Mexico, California Current, and Eastern Bering Sea, important hypotheses concerned with the growing impacts of pollution, overexploitation, and environmental changes on sustained biomass yields are under investigation (Table 4). By comparing the results of research among the different systems, it should be possible to accelerate an understanding of how the systems respond and recover from stress. The comparisons should allow for narrowing the context of unresolved problems and capitalizing on research efforts underway in the various ecosystems. Recent reports describing the effects of biological and physical perturbations on the fisheries biomass yields of 29 large marine ecosystems (Table 1) address questions similar to those posed a few years ago by Beddington (1984):

"There are a number of scientific questions which are central to the rational management of marine communities, but all revolve around the question of sustainability.

"What levels of mortality imposed by a fishery will permit a sustainable yield? Are there levels below which a fish population will not recover? Can judicious manipulation of the catch composition of the fishery alter the potential of the community to produce yields of a particular type, e.g., high value species? Can a community be depleted to a level where its potential for producing a harvestable resource is reduced?

"With the exception of the first question, these questions and others like them are rarely explicitly addressed in the scientific bodies of the various fisheries' organizations. Instead, such bodies concentrate on the estimation of stock abundance and the calculation of allowable catch levels, although often implicit in the advice given by these bodies to management are a set of beliefs about the answers to such questions."

Given the increasing number of responsibilities of government agencies for: (1) managing fisheries, (2) mitigating pollution, (3) reducing environmental stress, and (4) restoring lost habitat, it is not surprising that interest is growing to pursue resource management problems from an ecosystem perspective.

6. Ecosystem Assessment and Monitoring

In the USA, greater emphasis has been focused over the past decade within the National Marine Fisheries Service of the NOAA, on approaching fisheries research from a regional ecosystem perspective in LMEs within and adjacent to the EEZ of the United States--The Northeast Continental Shelf, the Southeast Continental Shelf, the Gulf of Mexico, the California Current, the Gulf of Alaska, the Eastern Bering Sea, and the Insular Pacific including the Hawaiian Islands. These ecosystems, in 1991, yielded 4.3 million metric tons of fisheries biomass valued at approximately $16.5 billion to the economy of the United States.

The sampling programs providing the biomass assessments within the U. S. EEZ have been described in Folio Map 7 produced by the Office of Oceanography and Marine Assessment of NOAA's National Ocean Service. The map depicts the seven ecosystems under investigation (Figure 8). Sampling programs supporting biomass estimates in LMEs within and adjacent to the EEZ of the United States are designed to: (1) provide detailed statistical analyses of fish and invertebrate populations constituting the principal yield species of biomass, (2) estimate future trends in biomass yields, and (3) monitor changes in the principal populations. The information obtained by these programs provides managers with a more complete understanding of the dynamics of marine ecosystems and how these dynamics affect harvestable stocks. Additionally, by tracking components of the ecosystems, these programs can detect changes, natural or human-induced, and warn of events with possible economic repercussions. Although sampling schemes and efforts vary among programs (depending on habitats, species present, and specific regional concerns), they generally involve systematic collection and analysis of catch-statistics; the use of NOAA vessels for fisheries-independent bottom and midwater trawl surveys for adults and juveniles; ichthyoplankton surveys for larvae and eggs; measurements of zooplankton standing stock, primary productivity, nutrient concentrations, and important physical parameters (e.g., water temperature, salinity, density, current velocity and direction, air temperature, cloud cover, light conditions); and, in some habitats, measurements of contaminants and their effects. At the shoreward margin of the LMEs, monitoring efforts include the use of mussels and other biological indicator species to measure pollution effects as part of NOAA's Status and Trends Program. The pilot Environmental Monitoring Assessment Program (EMAP) of the Environmental Protection Agency that focused on the estuarine and nearshore monitoring of contaminants in the water column, substrate, and selected groups of organisms, will be extended to more open waters of LMEs in cooperation with NOAA during 1993 and 1994.

A monitoring strategy for measuring the changing states of LMEs was recommended by a panel of international experts that met at Cornell University in July 1991 (Table 5) (Sherman and Laughlin, 1992). The two monitoring methods recommended are: (1) regular trawling using a stratified random sampling design, and (2) plankton surveys. The large-scale changes in the fisheries of the North Sea and the Northeast Continental Shelf of the United States have been successfully detected using trawling techniques for several decades (Azarovitz and Grosslein, 1987). The surveys have been conducted by relatively large research vessels. However, standardized sampling procedures, when deployed from small calibrated trawlers, can provide important information on fish stocks. The fish catch provides biological samples for stomach analyses, age and growth, fecundity, and size comparisons (ICES, 1991), and data for clarifying and quantifying multispecies trophic relationships. Samples of trawl-caught fish can also be used to monitor gross pathological conditions that may be associated with coastal pollution. The need for both biological and environmental monitoring in the North Sea Ecosystem has been emphasized following the Symposium on Long-Term Changes in the Fish Stocks of the North Sea Ecosystem (Hempel, 1978). In this regard, physical measurements can be made from small trawlers or ships-of-opportunity, using readily available and relatively inexpensive systems for measuring temperature and salinity of the water column. Standard logs for weather observations, important in detecting global change, are an important component of the data-collecting effort. The monitoring of changes in fish stocks is ongoing in LMEs across the North Atlantic basin, including the Northeast U. S. Shelf, the Canadian Scotian Shelf, Newfoundland Shelf; and on the Greenland Shelf, Icelandic Shelf, Norwegian Shelf, Barents Sea Shelf, and the North Sea. The plankton of LMEs can be measured at a relatively low cost by deploying CPR systems from commercial vessels of opportunity (Glover, 1967). The advanced plankton recorders can be fitted with sensors for temperature, salinity, chlorophyll, nitrate/nitrite, light, bioluminescence, zooplankton, and ichthyoplankton (Aiken, 1981; UNESCO, 1992), providing the means to monitor changes in phytoplankton, zooplankton, primary productivity, species composition and dominance, and long-term changes in the physical and nutrient characteristics of the LME, as well as longer term changes relating to the biofeedback of the plankton to the stress of climate change (Colebrook, 1986; Dickson et al., 1988; Jossi and Smith, 1990; Sherman et al., 1990b). Plankton monitoring using the CPR system is at present expanding in the North Atlantic.

A critical feature of the LME monitoring strategy is the development of a consistent long-term data base for understanding interannual changes and multi-year trends in biomass yields for each of the LMEs. For example, during the late 1960s and early 1970s, when there was intense foreign fishing within the Northeast U. S. Continental Shelf Ecosystem, marked alterations in fish abundances were recorded. Significant shifts among species abundances were observed. The finfish biomass of important species (e.g., cod, haddock, flounders, herring, and mackerel) declined by approximately 50% (Figure 9). This was followed by increases in the biomass of sand lance (Figure 10) and elasmobranchs (dogfish and skates) (Figure 11) and led to the conclusion that the overall carrying capacity of the ecosystem for finfish did not change. The excessive fishing effort on highly valued species allowed for low-valued species to increase in abundance. Analyses of catch-per-unit-effort and fishery-independent bottom trawling survey data were critical sources of information used to implicate overfishing as the cause of the shifts in relative abundance among the species of the fish community within the shelf ecosystem. It is important to note, however, that the lower-end of the food chain in the offshore waters of the ecosystem remained unchanged, largely as described by Bigelow (1926) and Riley et al. (1949), suggesting that ecosystem productivity remained high during a period of species dominance shifts among the fish community caused by human interventions through fishing (Sherman et al., 1983). The natural "resilience" of the ecosystem in relation to recovery from stress can be documented in the recovery of mackerel to former (pre-1960) levels of abundance and the apparent recovery of herring to 1960's level of abundance on Georges Bank (Murawski, 1991; Smith and Morse, 1990). The gyre systems of the Gulf of Maine and Georges Bank subsystems and the nutrient enrichment of the estuaries in the southern half of the Northeast Shelf Ecosystem contribute to the maintenance on the shelf of relatively high levels of phytoplankton and zooplankton prey fields for planktivores including fish larvae, menhaden, herring, mackerel, sand lance, butterfish, and marine birds and mammals.

7. Changing Ecosystem States and "Health" Indices

The topic of change and persistence in marine communities and the need for multispecies and ecosystem perspectives in fishery management relate to the reports of changing states of marine ecosystems (Sugihara et al., 1984). Collapses of the Pacific sardine in the California Current Ecosystem, the pilchard in the Benguela Current Ecosystem, and the anchovy in the Humboldt Current Ecosystem, are but a few examples of cascading effects on other ecosystem components including marine birds (MacCall, 1986; Croxall, 1987; Burger, 1988; Crawford et al., 1989). Ecosystem "health" is a concept of wide interest for which a single precise scientific definition is problematical. Ecosystem health is used herein, to describe the resilience, stability, and productivity of the ecosystem in relation to the changing states of ecosystems. In present practice, assessing the health of LMEs relies on a series of indicators and indices (Costanza, 1992; Rapport, 1992; Norton and Ulanowicz, 1992; Karr, 1992). The overriding objective is to monitor changes in health from an ecosystem perspective as a measure of the overall performance of a complex system (Costanza, 1992). The health paradigm is based on the multiple-state comparisons of ecosystem resilience and stability (Pimm, 1984; Holling, 1986; Costanza, 1992) and is an evolving concept. Definitions of several variables important to the changing states and health of marine ecosystems are given in Table 6. Following the definition of Costanza (1992), to be healthy and sustainable, an ecosystem must maintain its metabolic activity level, its internal structure and organization, and must be resistent to external stress over time and space frames relative to the ecosystem (Table 7). These concepts were discussed at a workshop convened by NOAA/NMFS at the Northeast Fisheries Science Center's Narragansett Laboratory in April 1992. Among the indices discussed by the participants were five that are being considered as experimental measures of changing ecosystem states and health--(1) diversity; (2) stability; (3) yields; (4) production; and (5) resilience (Sherman, 1993).

The data from which to derive the experimental indices are obtained from time-series monitoring of key ecosystem parameters. A prototype effort to validate the utility of the indices is under development by NOAA at the Northeast Fisheries Science Center. The ecosystem sampling strategy is focused on parameters relating to the resources at risk from overexploitation, species protected by legislative authority (marine mammals), and other key biological and physical components at the lower end of the food chain (plankton, nutrients, hydrography) (Sherman and Laughlin, 1992). The parameters of interest depicted in Figure 12 include zooplankton composition, zooplankton biomass, water column structure, photosynthetically active radiation (PAR), transparency, chlorophyll-*a*, NO_2, NO_3, primary production, pollution, marine mammal biomass, marine mammal composition, runoff, wind stress, seabird community structure, seabird counts, finfish composition, finfish biomass, domoic acid, saxitoxin, and paralytic shellfish poisoning (PSP). The experimental parameters selected incorporate the behavior of individuals, the resultant responses of populations and communities, as well as their interactions with the physical and chemical environment. The selected parameters, if measured in all LMEs, will permit comparison of relative changing states and health status among ecosystems. The interrelations between the datasets and the selected parameters are indicated by the arrows leading from column 1 to column 2 in the figure. The measured ecosystem components are depicted in relation to ecosystem structure in a diagrammatic conceptualization of patterns and activities within the LME at different levels of complexity (Figure 13).

Initial efforts to examine changing ecosystem states and relative health within a single ecosystem are underway for four subareas of the U.S. Northeast Continental Shelf Ecosystem--Gulf of Maine, Georges Bank, Southern New England, Mid-Atlantic Bight. Initial studies of the structure, function, and productivity of the system have been reported (Sherman et al., 1988). It appears that the principal driving force in relation to sustainable ecosystem yield is fishing mortality expressed as predation on the fish stocks of the system, and that long-term sustainability of high economic yield species will be dependent on the application of adaptive management strategies (Sissenwine and Cohen, 1991; Murawski, 1991).

Several alternative management strategies for the fish stocks of the U.S. Northeast Continental Shelf Ecosystem are under consideration by the New England Fisheries Management Council and the Atlantic States Marine Fisheries Commission. In addition to fisheries management issues and significant biomass flips among dominant species, the Northeast Continental Shelf Ecosystem is also under stress from the increasing frequency of unusual plankton blooms, and eutrophication within the nearshore coastal zone resulting from high levels of phosphate and nitrate discharges into drainage basins. Whether the increases in the frequency and extent of nearshore plankton blooms are responsible for the rise in incidence of biotoxin related shellfish closures and marine mammal mortalities, remains an important open question that is the subject of considerable concern to state and federal management agencies (Sherman et al., 1992a; Smayda, 1991).

8. Present and Future Efforts

The topics of change and persistence in marine communities, and the need for multispecies and ecosystem perspectives in fisheries management were reviewed at the Dahlem Conference on Exploitation of Marine Communities in 1984 (May, 1984). The designation and management of LMEs is, at present, an evolving scientific and geopolitical process (Morgan, 1988; Alexander, 1989). Sufficient progress has been made to allow for useful comparisons among different processes influencing large-scale changes in the biomass yields of LMEs (Bax and Laevastu, 1990).

Among the ecosystems being managed from a more holistic perspective are: the Yellow Sea Ecosystem, where the principal effort is underway by the Peoples Republic of China (Tang, 1989); the multispecies fisheries of the Benguela Current Ecosystem under the management of the government of South Africa (Crawford et al., 1989); the Great Barrier Reef Ecosystem (Bradbury and Mundy, 1989) and the Northwest Australian Continental Shelf Ecosystem (Sainsbury, 1988) under management by the state and federal governments of Australia; the Antarctic marine ecosystem under the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) and its 21-nation membership (Scully et al., 1986; Sherman and Ryan, 1988). Within the EEZ of the United States, the state governments of Washington and Oregon have developed a comprehensive plan for the management of marine resources within the Northern California Current Ecosystem (Bottom et al., 1989).

The broad-spectrum approach to LME research and monitoring provides a conceptual framework for collaboration in process-oriented studies conducted by the National Science Foundation (NSF)-NOAA sponsored GLOBal ocean ECosystems dynamics (GLOBEC) program on the Northeast Continental Shelf (GLOBEC, 1991) and proposed for other LMEs (e.g., California Current, Antarctic marine ecosystem) and the proposed Indian Ocean-Somalia Current Ecosystem study planned as part of the Joint Global Ocean Flux Studies (JGOFS).

With a minimum of expense and effort, ongoing FAO fisheries programs can be strengthened by refocusing them around the natural boundaries of regional LMEs. The United Nations Environment Program (UNEP) Regional Seas programs can be enhanced by taking a more holistic ecosystems approach to pollution issues as part of an overall effort to improve the health of the oceans. The LME research and monitoring strategies are compatible with the proposed GOOS, and will, in fact, strengthen GOOS by adding an ecosystem module to the existing physical and meteorological modules (IOC, 1992a). The LME approach will complement the GLOBEC studies and provide useful data inputs to JGOFS. The concept has been discussed at meetings of ICES, International Council for the Scientific Exploration of the Mediterranean Sea (ICSEM), FAO, IOC, International Union for Conservation of Nature and Natural Resources (IUCN), and United Nations Environment Program (UNEP) with generally favorable responses for developing the concept more fully and implementing it more widely within the United Nations framework of ongoing programs. The concept is wholly compatible with the FAO interest in studying "catchment basins" and quantifying their impact on enclosed and semi-enclosed seas (e.g., LMEs). The observations presently underway under the IOC/OSLR (Ocean Studies Related to Living Resources) program now operating within the California Current, Humboldt Current, and Iberian Coastal ecosystems provide an important framework for expanded LME studies of these systems in relation to not only fisheries issues, but also problems of pollution and coastal zone management.

Future effort directed at an improved definition of ecosystem health that will consider both natural environmental perturbation as well as the effects of human intervention on the changing states of ecosystems will focus on:

(1) The development of ecosystem change and health indices and indicators for LMEs.

(2) The development of component models of LMEs incorporating measurements of changing states and health indicators rather than single, large models that generally have limited prediction capability.

(3) The development and evaluation of models using health indicators that are directly applicable to management decisions. They should be simple in construction, allow for interaction with resource managers, and provide sufficient flexibility for testing hypotheses for a range of scenarios.

Efforts are underway to link scientific and societal needs to support long-term, broad-area coastal ocean assessment and monitoring studies. If the proposition for time-series monitoring of changing ecosystem states is to be realized in this period of shrinking budgets, it would be in the best interests of science and society to be tightly linked in the endeavor. The basis for the linkage can be found in a series of recent developments revolving around: (1) recent interest in global climate change; (2) legal precedent for international cooperation implicit in the Law of the Sea; (3) a growing interest in marine ecosystems as regional units for marine research, monitoring, and management; (4) and the effort of the IOC to encourage the implementation of a GOOS. Global climate change has become a factor in the sustainability of biomass production in LMEs. The rather large-scale fluctuations in marine biomass yields of LMEs over the past several decades when considered in the light of the growing concerns over coastal pollution and habitat loss, are serving to accelerate movement toward the development and implementation of a coastal component for GOOS. The core monitoring strategy for large marine ecosystems proposed for the coastal GOOS is designed to provide biological, physical, and chemical data pertinent to the development of indices to monitor changing states of LMEs. The indices are the basis for improving the dialogue between scientists and resource managers, for implementing mitigation strategies where appropriate, and for reinforcing the need for the long-term (multidecadal) ecosystem-wide monitoring programs.

The more holistic, ecosystem-wide approach to broad-area coastal and ocean marine resource assessment through monitoring studies is a means for fostering international cooperation and support in regions where the resources of the ecosystem are shared by several countries. The 49 large marine ecosystems that have been identified are located around the margins of the ocean basins and extend over the coastlines of several countries. They are in regions of the world ocean most affected by overexploitation, pollution, and habitat degradation, and collectively represent target areas for mitigation effort. The Global Environment Facility (GEF) of the World Bank, in collaboration with NOAA, IOC, UNEP, FAO, Natural Environment Research Council (NERC), the Sir Alister Hardy Foundation for Ocean Science, and scientists from national marine resource agencies of several countries (e.g., Belgium, Cameroon, China, Denmark, Estonia, Germany, Ivory Coast, Japan, Kenya, Korea, The Netherlands, Nigeria, Norway, Philippines, Poland, Thailand) are prepared to support LME assessment, mitigation, and coastal monitoring activities of the kind proposed recently in a commentary by Duarte et al. (1992). These efforts will include a comparative approach to long-term monitoring of the environment which allows for examination of data sets from various areas, and is supported by "robust international management and funding systems." It appears that resource managers and scientists are being responsive in reversing the cancellation of monitoring programs described by Duarte et al. (1992), and that monitoring initiatives related to the long-term sustainability of marine resources are underway in Europe and elsewhere (Sherman et al., 1992b).

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Table 1. List of 29 Large Marine Ecosystems and sub-systems for which syntheses relating to principal, secondary, or tertiary driving forces controlling variability in biomass yields have been completed by February 1993.

Large Marine Ecosystem	Volume No.*	Authors
U.S. Northeast Continental Shelf	1	M. Sissenwine
	4	P. Falkowski
U.S. Southeast Continental Shelf	4	J. Yoder
Gulf of Mexico	2	Richards and McGowan
	4	Brown et al.
California Current	1	A. MacCall
	4	M. Mullin
	5	D. Bottom
Eastern Bering Shelf	1	Incze and Schumacher
West Greenland Shelf	3	Hovgaard and Buch
Norwegian Sea	3	Ellertsen et al.
Barents Sea	2	Skjoldal and Rey
	4	V. Borisov
North Sea	1	N. Daan
Baltic Sea	1	G. Kullenberg
Iberian Coastal	2	Wyatt and Perez-Gandaras
Mediterranean-Adriatic Sea	5	G. Bombace
Canary Current	5	C. Bas
Gulf of Guinea	5	Binet and Marchal
Benguela Current	2	Crawford et al.
Patagonian Shelf	5	A. Bakun
Caribbean Sea	3	Richards & Bohnsack
South China Sea-Gulf of Thailand	2	T. Piyakarnchana
Yellow Sea	2	Q. Tang
Sea of Okhotsk	5	V. V. Kusnetsov
Humboldt Current	5	Alheit and Bernal
Indonesia Seas-Banda Sea	3	Zijlstra and Baars
Bay of Bengal	5	S. N. Dwivedi
Antarctic Marine	1&5	Scully et al.
Weddell Sea	3	G. Hempel
Kuroshio Current	2	M. Terazaki
Oyashio Current	2	T. Minoda
Great Barrier Reef	2	Bradbury and Mundy
	5	Kelleher
South China Sea	5	Pauly and Christensen

*Vol. 1, Variability and Management of Large Marine Ecosystems, Edited by K. Sherman and L. M. Alexander, AAAS Selected Symposium 99, Westview Press, Boulder, CO, 1986.

Vol. 2, Biomass Yields and Geography of Large Marine Ecosystems, Edited by K. Sherman and L. M. Alexander, AAAS Selected Symposium 111, Westview Press, Boulder, CO, 1989.

Vol. 3, Large Marine Ecosystems: Patterns, Processes, and Yields, Edited by K. Sherman, L. M. Alexander, and B. D. Gold. AAAS Symposium, AAAS Publishers, Washington, DC, 1990.

Vol. 4, Food Chains, Yields, Models, and Management of Large Marine Ecosystems, Edited by K. Sherman, L. M. Alexander, and B. D. Gold, AAAS Symposium, Westview Press, Boulder, CO. 1991.

Vol. 5, Stress, Mitigation, and Sustainability of Large Marine Ecosystems, Edited by K. Sherman, L. M. Alexander, and B. D. Gold, AAAS Publishers, Washington, DC [1993].

Table 2. Contributions by country, and large marine ecosystem (LME) representing 95 percent of the annual global catch in 1990.

Country	Percentage of[1] world marine nominal catch	LMEs producing annual biomass yield	Cumulative percentages
Japan	12.25	Oyashio Current, Kuroshio Current; Sea of Okhotsk, Sea of Japan, Yellow Sea, East China Sea, W. Bering Sea, E. Bering Sea, and Scotia Sea	
USSR	11.37	Sea of Okhotsk, Barents Sea, Norwegian Shelf, W. Bering Sea, E. Bering Sea, and Scotia Sea	
China	8.28	W. Bering Sea, Yellow Sea, E. China Sea, and S. China Sea	
Peru	8.27	Humboldt Current	
USA	6.76	Northeast US Shelf, Southeast US Shelf, Gulf of Mexico, California Current, Gulf of Alaska, and E. Bering Sea	
Chile	5.98	Humboldt Current	52.91
Korea Republic	3.28F*	Yellow Sea, Sea of Japan, E. China Sea, and Kuroshio Current	
Thailand	2.96F	South China Sea, and Indonesian Seas	
India	2.78	Bay of Bengal and Arabian Sea	
Indonesia	2.76	Indonesian Seas	
Norway	2.11	Norwegian Shelf and Barents Sea	
Korea D. P. Rep.	1.98F	Sea of Japan and Yellow Sea	
Philippines	1.96	S. China Sea, Sulu-Celebes Sea	
Canada	1.90	Scotian Shelf, Northeast U.S. Shelf, Newfoundland Shelf	

[1]Percentages based on fish catch statistics from FAO 1990 Yearbook, vol. 70, FAO, 1992.

*F = Percentage calculated using FAO estimate from available sources of information.

Table 2 continued.

Country	Percentage of[1] world marine nominal catch	LMEs producing annual biomass yield	Cumulative percentages
Iceland	1.82	Icelandic Shelf	
Denmark	2.07	Baltic Sea and North Sea	76.25
Spain	1.73	Iberian Coastal Current and Canary Current	
Mexico	1.46	Gulf of California, Gulf of Mexico, and California Current	
France	1.03F	North Sea, Biscay-Celtic Shelf, Mediterranean Sea	80.47
Viet Nam	0.74	South China Sea	
Myanmar	0.72	Bay of Bengal, Andaman Sea	
Brazil	0.71F	Patagonian Shelf and Brazil Current	
Malaysia	0.71F	Gulf of Thailand, Andaman Sea, Indonesian Seas, and S. China Sea	
UK-Scotland	0.70	North Sea	
New Zealand	0.68	New Zealand Shelf Ecosystem	
Morocco	0.68	Canary Current	
Argentina	0.66	Patagonian Shelf	
Italy	0.57	Mediterranean Sea	
Netherlands	0.52	North Sea	
Poland	0.52	Baltic Sea	
Ecuador	0.47	Humboldt Current	
Pakistan	0.44	Bay of Bengal	

[1]Percentages based on fish catch statistics from FAO 1990 Yearbook, vol. 70, FAO, 1992.

*F = Percentage calculated using FAO estimate from available sources of information.

Table 2 continued.

Country	Percentage of[1] world marine nominal catch	LMEs producing annual biomass yield	Cumulative percentages
Turkey	0.41	Black Sea, Mediterranean Sea	
Germany (F.R. and N.L.)	0.41	Baltic Sea and Scotia Sea	
Ghana	0.40	Gulf of Guinea	
Portugal	0.39	Iberian Shelf and Canary Current	90.20
Venezuela	0.38	Caribbean Sea	
Namibia	0.35	Benguela Current	
Faeroe Islands	0.34	Faeroe Plateau	
Senegal	0.34	Gulf of Guinea and Canary Current	
Sweden	0.31	Baltic Sea	
Bangladesh	0.31	Bay of Bengal	
Ireland	0.28	Biscay-Celtic Shelf	
Hong Kong	0.28	S. China Sea	
Nigeria	0.26	Gulf of Guinea	
Australia	0.25	N. Australian Shelf and Great Barrier Reef	
Iran, I.R.	0.24F	Arabian Sea	
UK Eng., Wales	0.21	North Sea	
Cuba	0.20	Caribbean Sea	
Panama	0.19	California Current and Caribbean Sea	
Greenland	0.17	East Greenland Shelf, West Greenland Shelf	

[1]Percentages based on fish catch statistics from FAO 1990 Yearbook, vol. 70, FAO, 1992.

*F = Percentage calculated using FAO estimate from available sources of information.

Table 2 continued.

Country	Percentage of[1] world marine nominal catch	LMEs producing annual biomass yield	Cumulative percentages
Sri Lanka	0.19	Bay of Bengal	
Greece	0.16	Mediterranean Sea	
Oman	0.15	Arabian Sea	
Angola	0.12	Guinea Current, Angola Basin	
United Arab Em.	0.11	Arabian Sea	95.01

[1]Percentages based on fish catch statistics from FAO 1990 Yearbook, vol. 70 FAO, 1992.

*F = Percentage calculated using FAO estimate from available sources of information.

Table 3. Key spatial and temporal scales and principal elements of a systems approach to the research and management of large marine ecosystems. (From Sherman, 1991.)

1. Spatial-Temporal Scales

	Spatial	Temporal	Unit
1.1	**Global** (World Ocean)	Millennia-Decadal	Pelagic Biogeographic
1.2	**Regional** (Exclusive Economic Zones)	Decadal-Seasonal	Large Marine Ecosystems
1.3	**Local**	Seasonal-Daily	Subsystems

2. Research Elements

   2.1 Spawning Strategies

   2.2 Feeding Strategies

   2.3 Productivity, Trophodynamics

   2.4 Stock Fluctuations/Recruitment/Mortality

   2.5 Natural Variability
   (Hydrography, Currents, Water Masses, Weather)

   2.6 Human Perturbations
   (Fishing, Waste Disposal, Petrogenic Hydrocarbon Impacts, Aerosol Contaminants, Eutrophication Effects)

3. Management Elements--Options and Advice--International, National, Local

   3.1 Bioenvironmental and Socioeconomic Models

   3.2 Management to Optimize Fisheries Yields

4. Feedback Loop

   4.1 Evaluation of Ecosystem Status

   4.2 Evaluation of Fisheries Status

   4.3 Evaluation of Management Practices

Table 4. Selected Hypotheses Concerning Variability in Biomass Yields of Large Marine Ecosystems. Note that references can be found in Table 1. (From Sherman, 1991.)

Ecosystem	Predominant Variables	Hypothesis
Oyashio Current Kuroshio Current California Current Humboldt Current Benguela Current Iberian Coastal	Density-independent natural environmental perturbations	Clupeoid Population Increases: Predominant variables influencing changes in biomass of clupeoids are major increases in water-column productivity resulting from shifts in the direction and flow velocities of the currents and changes in upwelling within the ecosystem.
Yellow Sea U. S. Northeast Continental Shelf Gulf of Thailand	Density-dependent predation	Declines in Fish Stocks: Precipitous decline in biomass of fish stocks is the result of excessive fishing mortality, reducing the probability of reproductive success. Losses in biomass are attributed to excesses of human predation expressed as overfishing.
Great Barrier Reef	Density-dependent predation	Change in Ecosystem Structure: The extreme predation pressure of crown-of-thorns starfish has disrupted normal food chain linkage between benthic primary production and the fish component of the reef ecosystem.
East Greenland Sea Barents Sea Norwegian Sea	Density-independent natural environmental perturbations	Shifts in Abundance of Fish Stock Biomass: Major shifts in the levels of fish stock biomass within the ecosystems are attributed to large-scale environmental changes in water movements and temperature structure.

Table 4 continued.

Ecosystem	Predominant Variables	Hypothesis
Baltic Sea	Density-independent pollution	Changes in Ecosystem Productivity Levels: The apparent increases in productivity levels are attributed to the effects of nitrate enrichment resulting from elevated levels of agricultural contaminant inputs from the bordering land masses.
Antarctic Marine	Density-dependent perturbations	Status of Krill Stocks: Annual natural production cycle of krill is in balance with food requirements of dependent predator populations. Surplus production is available to support economically significant yields, but sustainable level of fishing effort is unknown.
	Density-independent natural environmental perturbations	Shifts in Abundance in Krill Biomass: Major shifts in abundance levels of krill biomass within the ecosystem are attributed to large-scale changes in water movements and productivity.

Table 5. Core marine ecosystem monitoring program. The Core Program is based on transects sampled by UOR or instrumented CPR, supplemented by satellite oceanography and systematic trawl and acoustic surveys. (From Sherman and Laughlin, 1992.)

Candidate parameters for the Core Program include:

•Chlorophyll Fluorescence	•Salinity structure	•Temperature structure
•+Primary Production	•Nutrients	
•Diatom/Flagellate Ratio	NO_2	•Stratification index
Zooplankton composition and Biomass	NO_3	•Transparency
•Copepod Diversity	Pollution index (e.g., hydrocarbons, sewage)	•PAR
Fisheries Survey		Rainfall or Runoff, Wind strength and direction

Assessment

Changes in Abundance and Distribution

Biology

Length

Age and Growth

Predator-Prey

Pathology

Acoustics for Pelagics

Nets for Demersals

Physical Measurements

Temperature

Salinity

Chemical Measurements

Water samples (nutrients, productivity, pollutants)

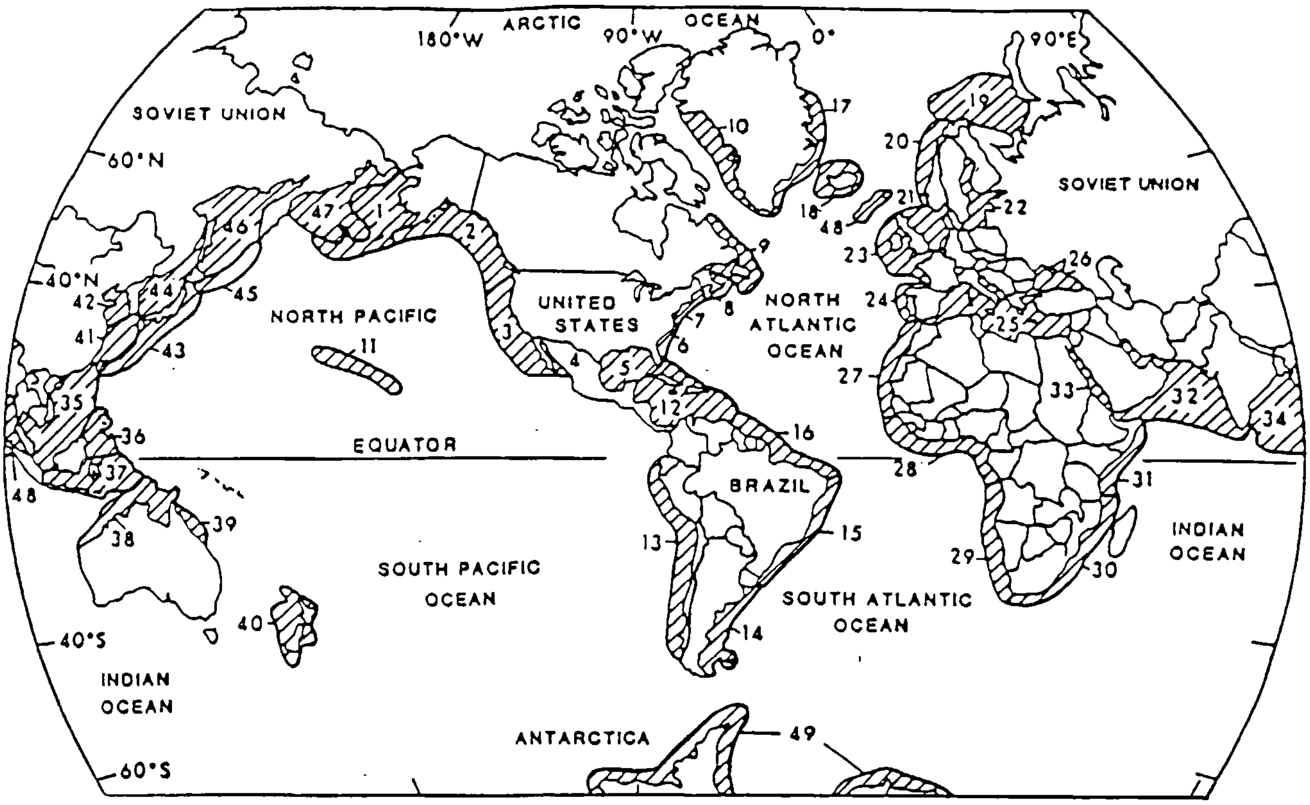
•Measurements derived from instrumented CPR/UOR sensors.
•+Based on inclusion of double-flash pump and probe system.

Table 6. Definitions of some important variables (adapted and expanded from Costanza, 1992.)

Variable	Definition	Units
Stability		
Homeostasis	Maintenance of a steady state in living organisms by the use of feedback control processes.	
Stable	A system is stable if, and only if, the variables all return to the initial equilibrium following their being perturbed from it. A system is locally stable if this return applies to small perturbations, and globally stable if it applies to all possible perturbations.	Binary
Sustainable	A system that can maintain its structure and function indefinitely. All non-successional (i.e., climax) ecosystems are sustainable, but they may not be stable (see resilience below). Sustainability is a policy goal for economic systems.	Binary
Resilience	1. How fast the variables return towards their equilibrium following a perturbation. Not defined for unstable systems (Pimm, 1984). 2. The ability of a system to maintain its structure and patterns of behavior in the face of disturbance (Holling, 1986).	Time
Resistance	The degree to which a variable is changed, following a perturbation.	Nondimensional and continuous
Variability	The variance of population densities over time, or allied measures such as the standard deviation or coefficient of variation (sd/mean).	
Complexity		
Species richness	The number of species in a system.	Integer
Connectance	The number of actual interspecific interactions divided by the possible interspecific interactions.	Dimensionless
Interaction strength	The mean magnitude of interspecific interaction: the size of the effect of one species' density on the growth rate of another species.	
Evenness	The variance of the species abundance districution.	
Diversity indices	Measures that combine evenness and richness with a particular weighting for each. One important member of this family is the information theoretic index, H.	Bits
Ascendency	An information theoretic measure that combines the average mutual information (a measure of connectedness) and the total throughput of the system as a scaling factor (see Ulanowicz, 1992).	
Other Variables		
Perturbation	A change to a system's inputs or environment beyond the normal range of variation.	Varies
Stress	A perturbation with a negative effect on a system.	
Subsidy	A perturbation with a positive effect on a system.	

Table 7. Indices of vigor, organization, and resilience in various fields. (From Costanza, 1992.)

Component of health	Related concepts	Existing related measures	Fields of origin	Probable method of solution
Vigor	Function Productivity System Throughput	GPP, NPP, GEP---> GNP-------------------> Metabolism----------->	Ecology Economics Biology	Measurement
Organization	Structure Biodiversity	Diversity index Average Mutual Information Predictability--------->	Ecology	Network analysis
Resilience		Scope for growth--->	Ecology	Simulation modelling
Combinations		Ascendancy----------->	Ecology	



WORLD MAP OF LARGE MARINE ECOSYSTEMS

1. Eastern Bering Sea
2. Gulf of Alaska
3. California Current
4. Gulf of California
5. Gulf of Mexico
6. Southeast U.S. Continental Shelf
7. Northeast U.S. Continental Shelf
8. Scotian Shelf
9. Newfoundland Shelf
10. West Greenland Shelf
11. Insular Pacific–Hawaiian
12. Caribbean Sea
13. Humboldt Current
14. Patagonian Shelf
15. Brazil Current
16. Northeast Brazil Shelf
17. East Greenland Shelf
18. Iceland Shelf
19. Barents Sea
20. Norwegian Shelf
21. North Sea
22. Baltic Sea
23. Celtic-Biscay Shelf
24. Iberian Coastal
25. Mediterranean Sea
26. Black Sea
27. Canary Current
28. Guinea Current
29. Benguela Current
30. Agulhas Current
31. Somali Coastal Current
32. Arabian Sea
33. Red Sea
34. Bay of Bengal
35. South China Sea
36. Sulu-Celebes Seas
37. Indonesian Seas
38. Northern Australian Shelf
39. Great Barrier Reef
40. New Zealand Shelf
41. East China Sea
42. Yellow Sea
43. Kuroshio Current
44. Sea of Japan
45. Oyashio Current
46. Sea of Okhotsk
47. West Bering Sea
48. Faroe Plateau
49. Antarctic

Figure 1. Boundaries of 49 large marine ecosystems.

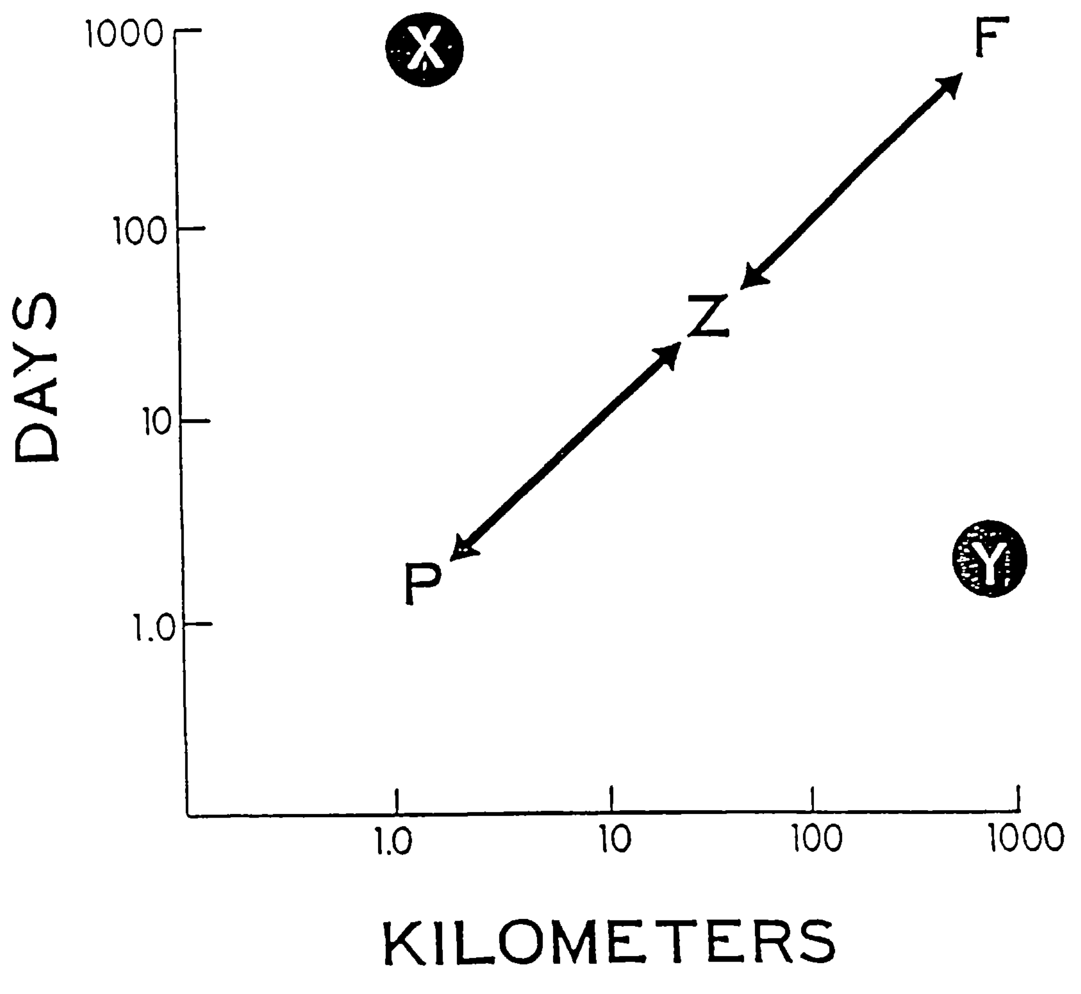


Figure 2. A simple set of scale relations for the food web P (phytoplankton), Z (zooplankton) and F (pelagic fish), Two physical processes are indicated by X, predictable fronts with small cross-front dimensions and (Y) unpredictable weather events occurring on relatively large scales. (Steele, 1988.)

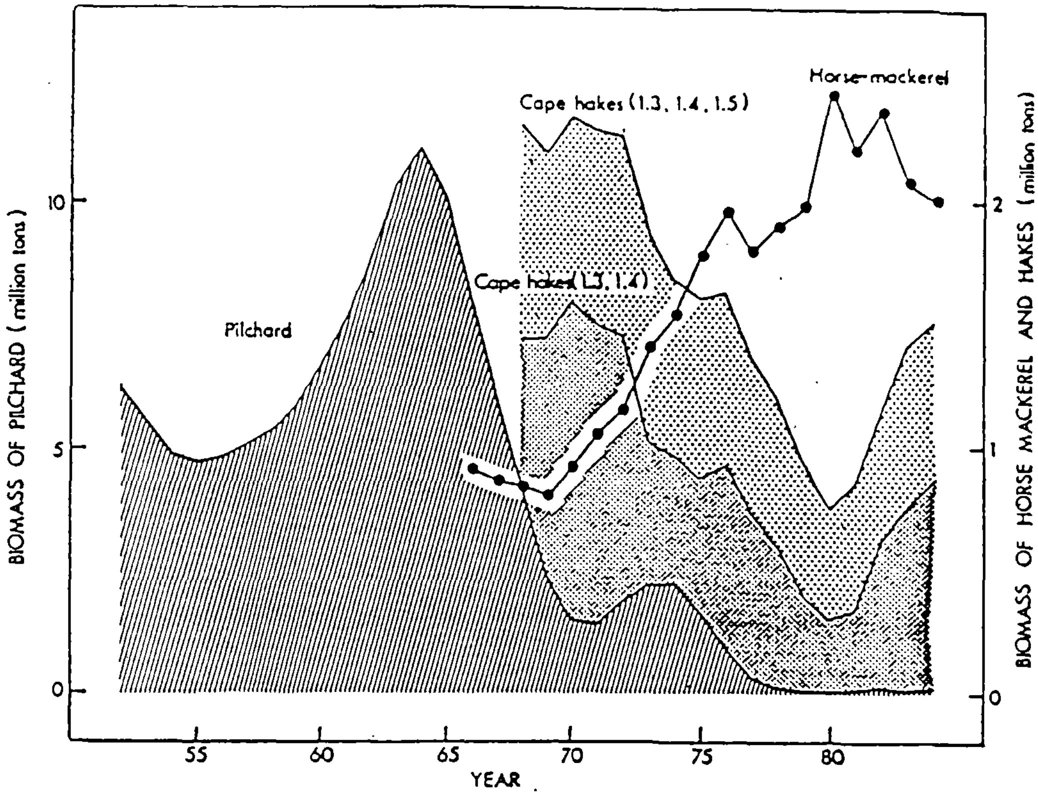


Figure 3. Estimates of the biomass of pilchard (*Sardinops ocellatus*), Cape horse-mackerel (*Trachurus capensis*), and Cape hakes (*Merluccius capensis* and *M. paradoxus*) of the Benguela Current ecosystem showing expansion of the horse-mackerel resource following collapse of the pilchard resource and the opposite trends in biomasses of horse-mackerel and Cape hakes during the 1950s through the 1980s. (From Crawford et al., 1989.)

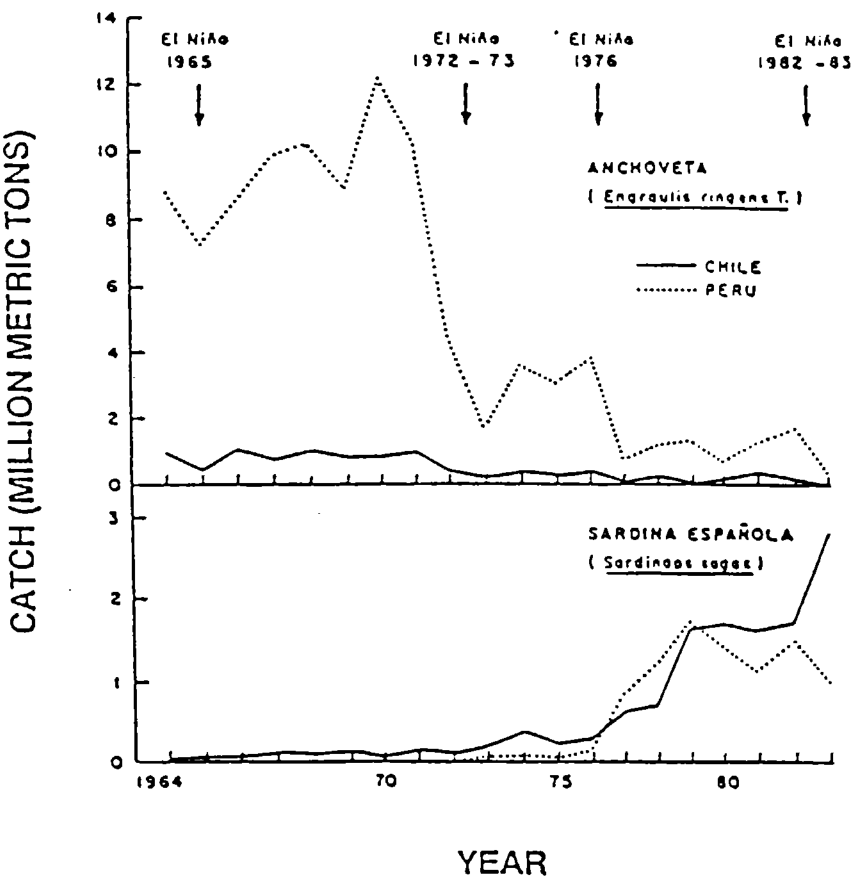


Figure 4. Fluctuations in the catch of anchovies and sardines from the waters of the Humboldt Current ecosystem off the coasts of Chile and Peru. (From Canon, 1986.)

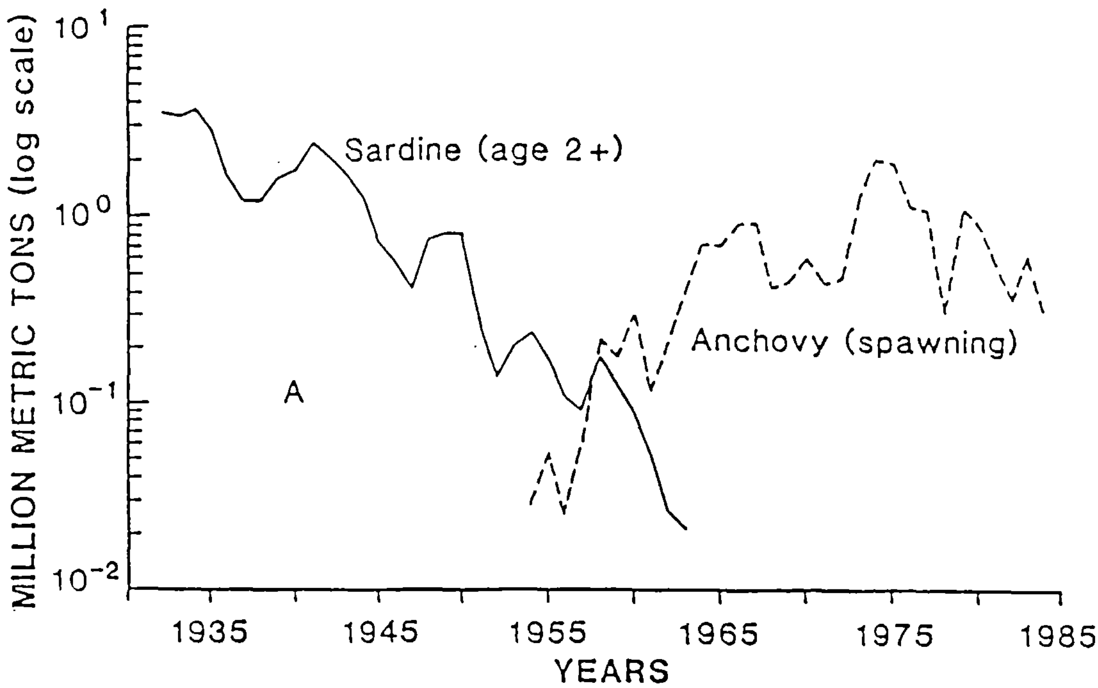


Figure 5. Time series of sardine (age 2+) and anchovy spawning biomass (log scale) of the California Current ecosystem. "A" denotes approximate anchovy spawning biomass in 1940-1941. (From MacCall, 1986.)

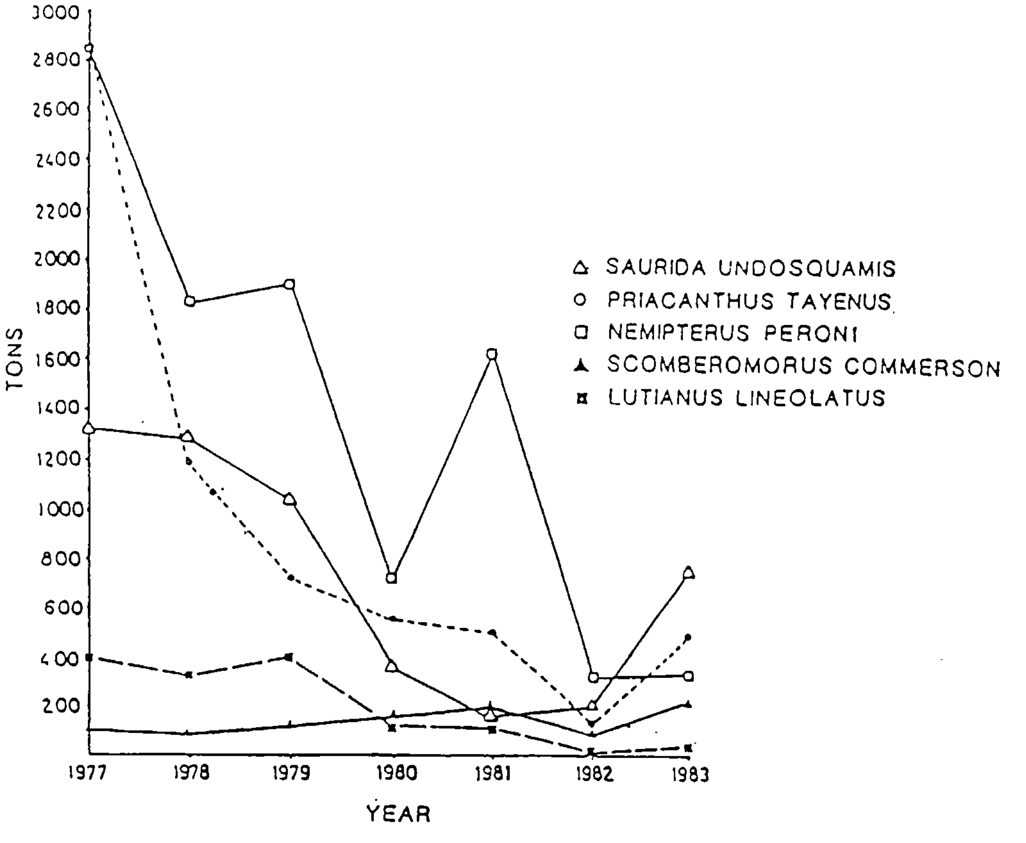


Figure 6. Decline in the total catch of carnivorous feeding species of fish from the Gulf of Thailand ecosystem. (From Piyakarnchana, 1989.)

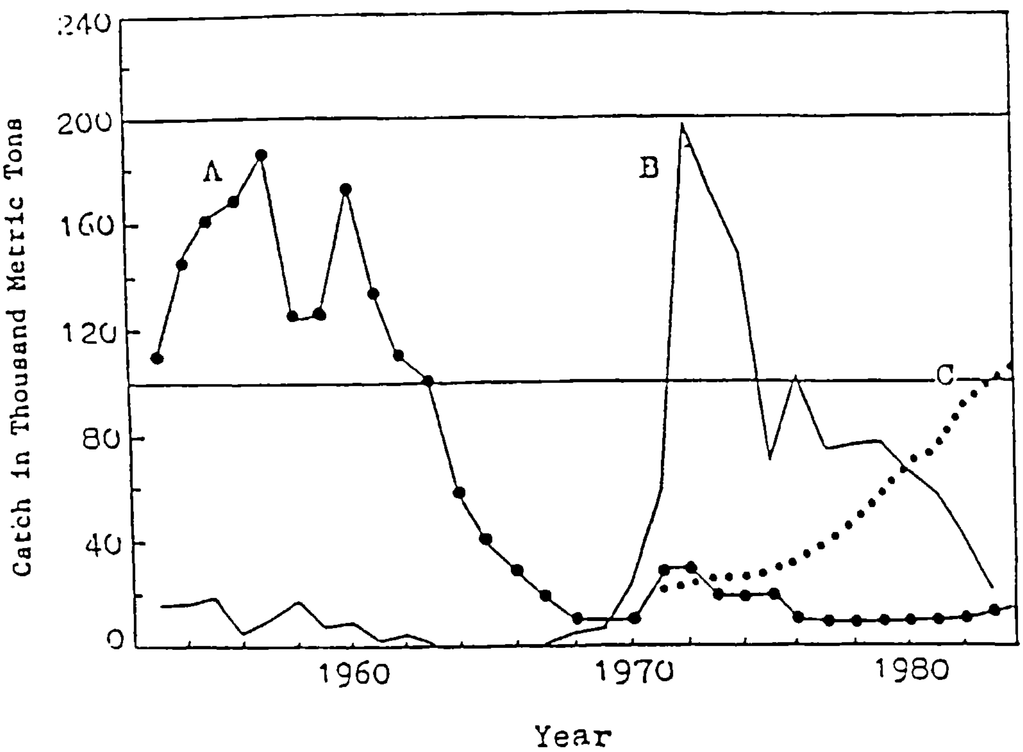


Figure 7. Annual catch of dominant species: (A) small yellow croaker and hairtail; (B) Pacific herring and Japanese mackerel; (C) *Setipinna taty*, anchovy and scaled sardine of the Yellow Sea ecosystem, 1953 through 1984. (From Tang, 1989.)

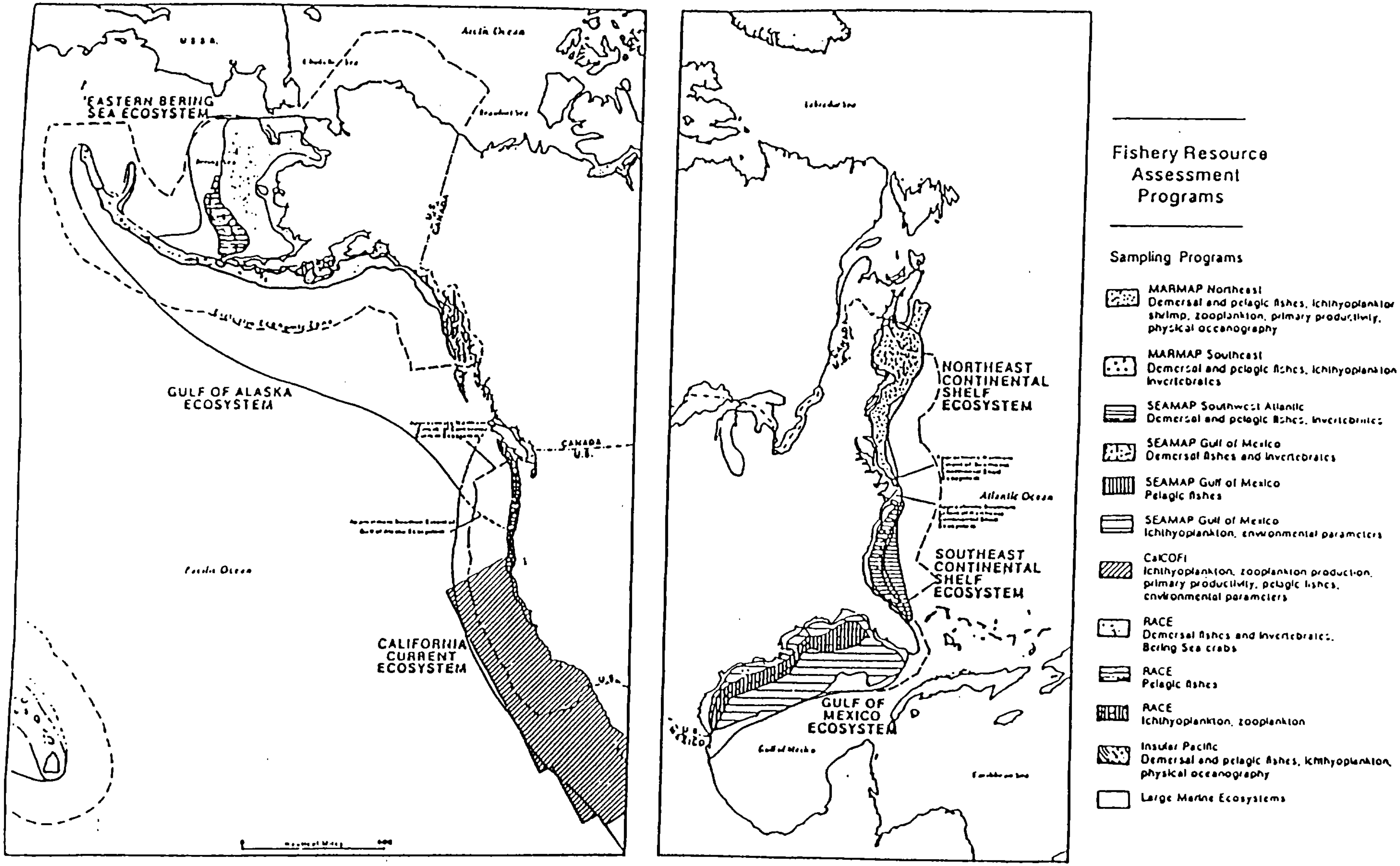


Figure 8. Large marine ecosystems of the United States. [This figure is a modified version of Folio Map No. 7, "A National Atlas: Health and Use of Coastal Waters, United States of America." U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Ocean Service, Office of Oceanography and Marine Assessment, Washington, D.C., 1988].

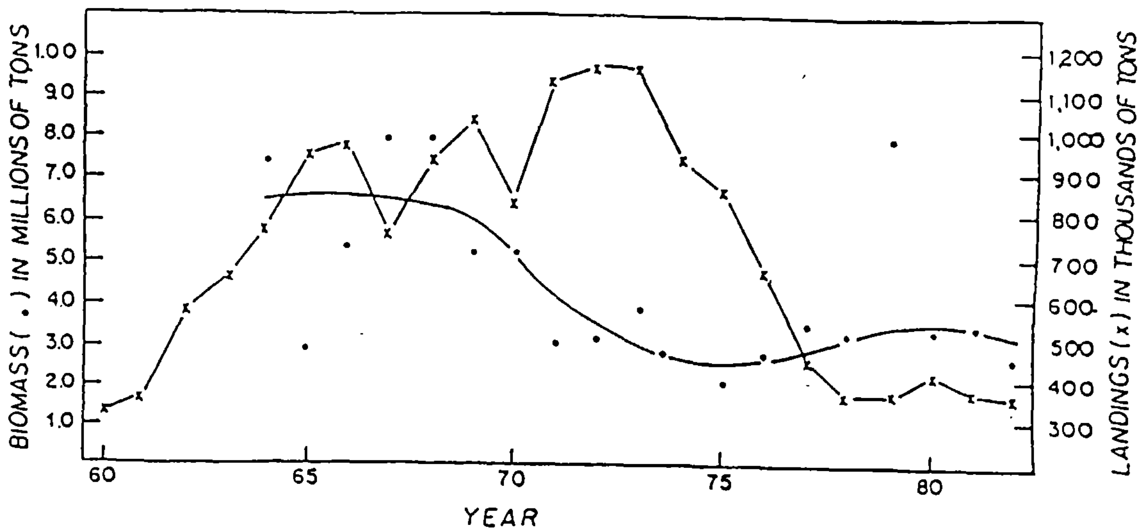


Figure 9. Annual catch trends, excluding menhaden and large pelagic species, e.g., large sharks and tuna, and estimated biomass of "exploitable" fish and squid of the Northeastern Continental Shelf ecosystem, 1960 to 1982. (From Sissenwine, 1986.)

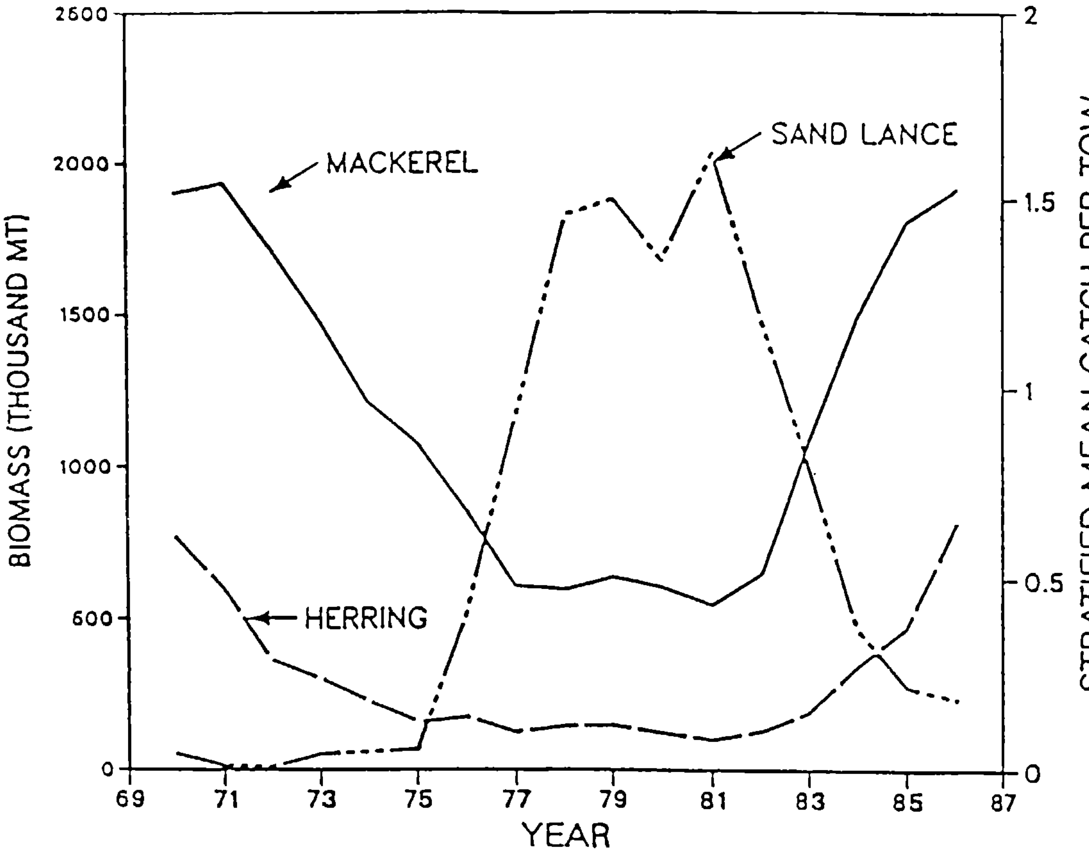


Figure 10. Trends in biomass of mackerel (age 1+_ and herring (age 3+) derived from virtual population analysis and trends in relative abundance (stratified mean catch per tow (kg)) of sand lance (age 2+) based on research vessel surveys. (From Fogarty et al., 1991.)

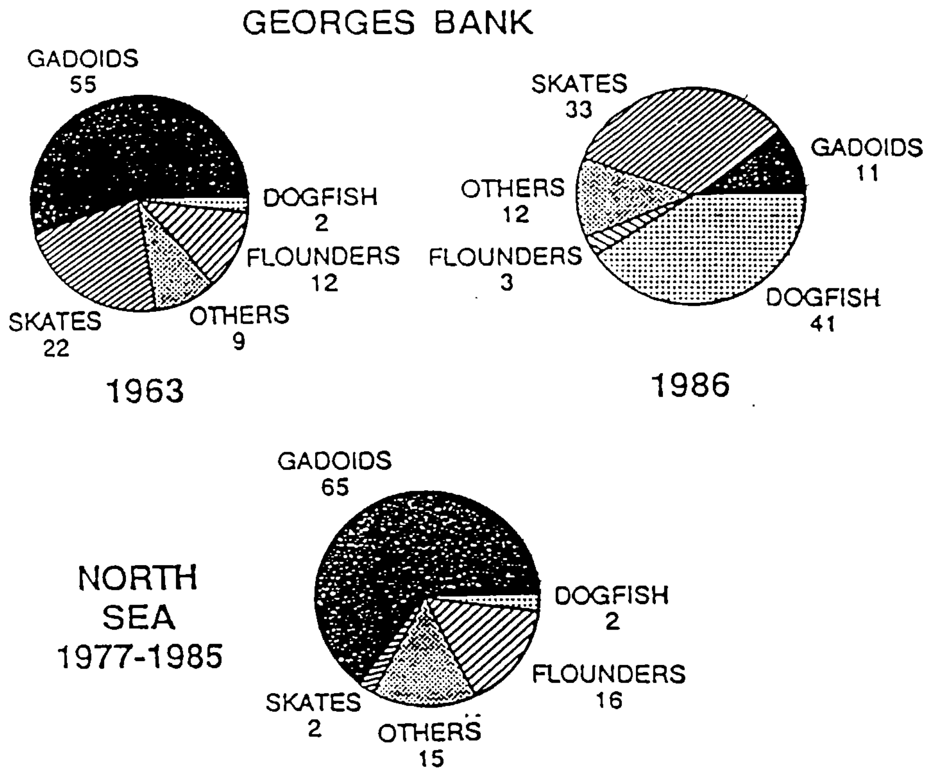


Figure 11. Species shift and abundance of small elasmobranchs (dogfish and skates) on Georges Bank within the Northeast Continental Shelf ecosystem of the United States compared with the North Sea ecosystem. (From Sherman et al., 1990b.)

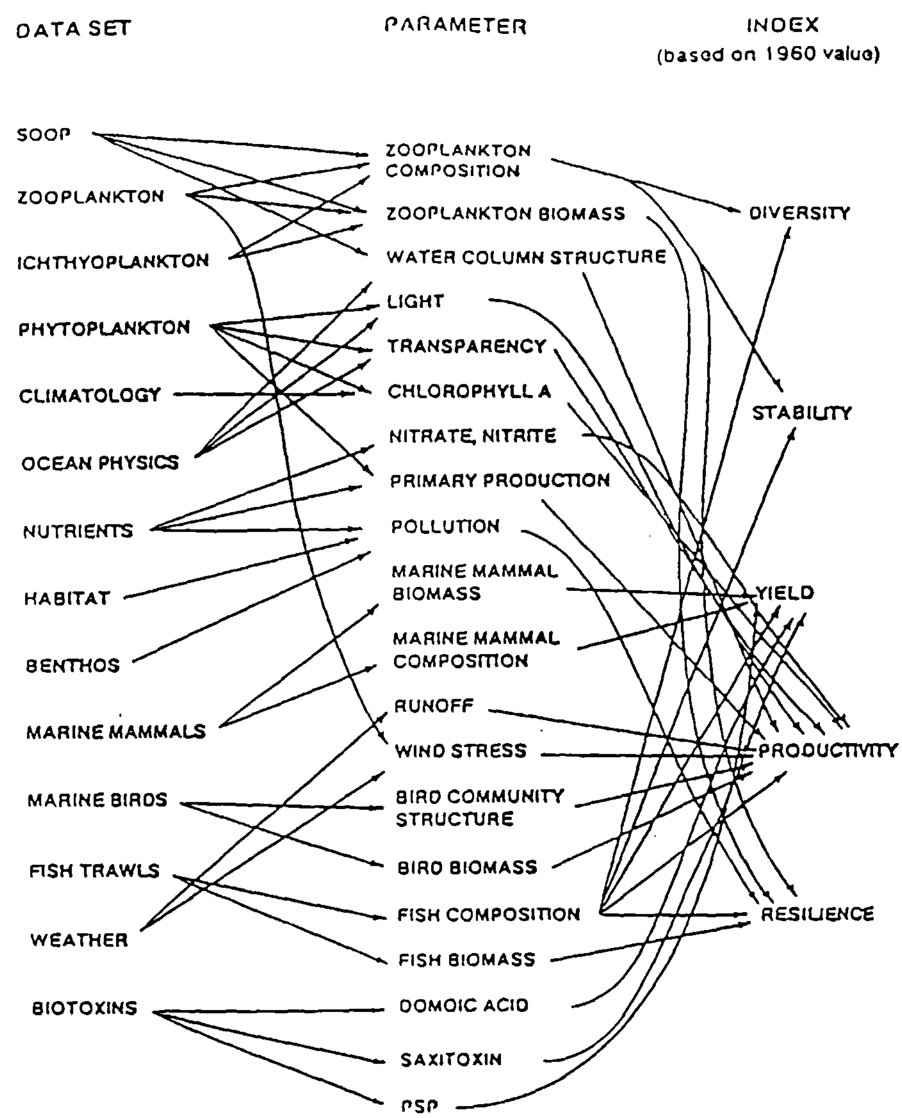


Figure 12. A schematic representation of the data bases and experimental parameters for indexing the changing states of large marine ecosystems. The data base represents time-series measurements of key ecosystem components from the U.S. Northeast Continental Shelf ecosystem. Indices will be based on changes compared with the ecosystem state in 1960.

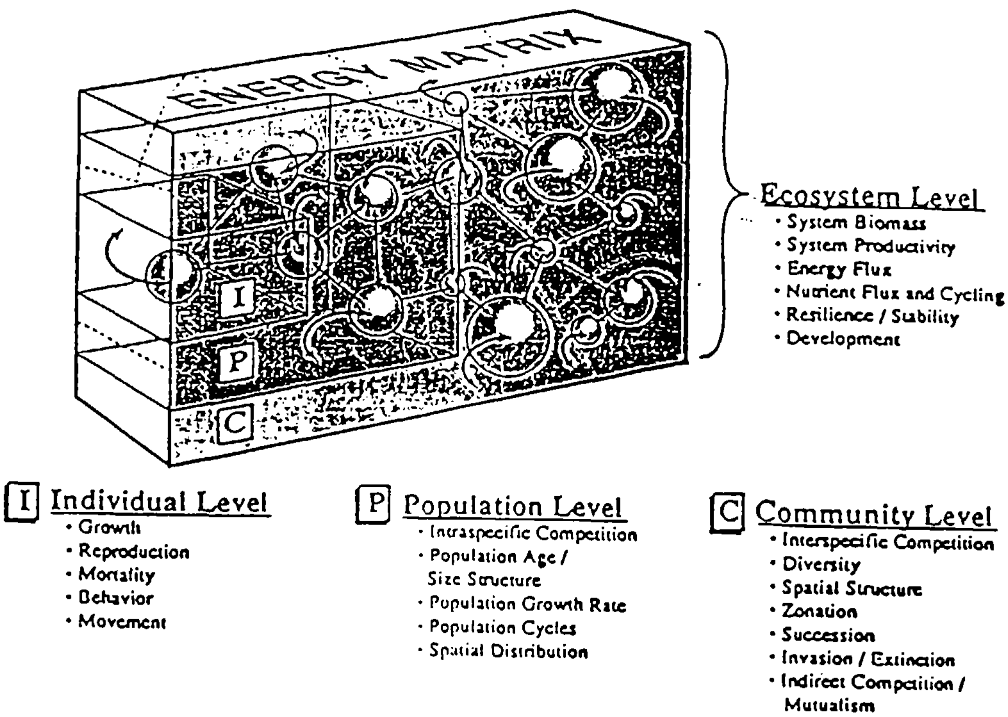


Figure 13. Diagrammatic conceptualization of patterns and activities at different levels of complexity. Each sphere represents an individual abiotic or biotic entity. Abiotic is defined as nonliving matter. Broad, double-headed arrows indicate feedback between entities and the energy matrix for the system. The thin arrows represent direct interactions between individual entities. Much of ecology is devoted to studying interactions between biotic and abiotic entities with a focus on the effects of such interactions on individuals (I), populations (P), or communities (C) of organisms. Ecosystem ecology studies these interactions from the viewpoint of their effect on both the biotic and abiotic entities and within the context of the system. The boundaries of the system must be established to conduct quantitative studies of flux. Figure 1 depicts the boundaries of LMEs, located around the margins of the ocean basins, where the influence of overexploitation, pollution, and habitat degradation and climate change are affecting the structure and function of the ecosystems. (From Likens, 1992.)