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MODULAR STRATEGIES FOR ASSESSING THE CHANGING STATES OF LARGE MARINE ECOSYSTEMS

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ABSTRACT

Indices are being developed by NOAA in collaboration with the Woods Hole Oceanographic Institute to be used as measures of changing ecosystem states. The data from which to derive the indices are obtained from time-series assessments of key ecosystem parameters measured over several decades within the northeastern U. S. Shelf Ecosystem. The indices are generated by synthesizing the results of assessments made using five linked modules to evaluate ecosystem sustainability: (1) productivity, (2) fish and fisheries, (3) pollution and ecosystem health, (4) socioeconomic conditions, and (5) governance.

1. INTRODUCTION

The sustainability, biomass yields, and health of marine resources can be enhanced by the implementation of a more holistic and ecologically based strategy for assessing and managing coastal ecosystems than has been generally practiced during most of this century. In recognition of the need to provide financial support to developing nations for building national and regional capacities, for a more ecologically oriented approach to marine resources management practices, the World Bank and the Global Environmental Facility have encouraged the development and implementation of multinational projects focused on improving the sustainability of marine resources within the extent of whole ecosystems. An estimated 2 billion dollars has been pledged by donor nations to the Global Environmental Facility to support efforts to improve assessments and management of global natural resources. This action is in direct response to the declarations agreed to by the family of nations during the United Nations Conference on Environment and Development (UNCED) convened in Brazil in 1992. Post-UNCED activities now being supported around the world to mitigate global environmental stressors have been highlighted in a series of international environmental conventions, declarations, and protocols that have come into force since 1992 (Cicin-Sain, 1996).

Post-UNCED concern has been expressed over the deteriorating condition of the worlds coastal ecosystems that produce most of the worlds living marine resources. Within the nearshore 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, harmful algal blooms, emergent diseases, fallout from aerosol contaminants, and episodic losses of living marine resources from pollution effects, and overexploitation. Coastal pollution, changes in biodiversity, the degraded states of fish stocks, and the loss of coastal habitat generally are limiting achievement of the full economic potential of coastal ecosystems. Present efforts to address these problems by local, regional national, and international institutions responsible for resource stewardship has been less than successful. Informed decisions for ensuring the long-term development and sustainability of coastal marine resources can best be made when based on sound scientifically derived options. For most coastal ecosystems, existing data useful for studies of perturbations to habitats and populations at the species, community, and ecosystem level is difficult to synthesize because of spatially and temporally fragmented character, lack of comparability, and inaccessibility. To overcome these shortcomings there is a need for a more coherent and integrative assessment of the changing states of the ecosystem that is directly linked to institutions responsible for the governance of the ecosystem.

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, 1992). This encouragement follows from the significant milestone achieved in June 1992 with the adoption by a majority of coastal countries of follow-on actions to the UNCED declarations on the ocean. They 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 importance of providing developing nations the "capacity" to carry toward projects in support of the sustainability of marine resources.

2. ECOSYSTEM SUSTAINABILITY

An ecosystems approach for scientists, economists, and resource managers interested in contributing toward a scientifically based strategy for resource sustainability is given by Holling (1993) who emphasizes the need to recognize the emerging multidisciplinary science that is focused on populations and ecosystems on large spatial scales that include socioeconomic considerations in planning and implementation appropriate to the issue of resource sustainability. The definition of sustainability used by Holling and carried forward in this paper focuses on ecosystem studies in support of "the social and economic development of a region with the goals to invest in the maintenance and restoration of critical ecosystem functions, to synthesize and make accessible knowledge and understanding for economies, and to develop and communicate the understanding that provides a foundation of trust for citizens" (Holling, 1993). In practice, therefore, it is important to establish institutional arrangements for ensuring that appropriate socioeconomic considerations are taken into account in the application of science in support of regimes aimed at the sustainability of renewable resources. Regional examples of this approach to ecosystem sustainability can be found in the objectives of the Convention for the Conservation of Antarctic Living Marine Resources (Scully, 1993), and the ministerial declarations for the protection of the Black Sea (Hey & Mee, 1993), and the North Sea (NSTF, 1991; NSQSR, 1993). The Black Sea Declaration refers specifically to the objectives of UNCED Agenda 21, Chapter 17; that calls for integrated management and sustainable development of coastal areas, marine environmental protection, sustainable use and conservation of living resources under national jurisdiction, and the need for addressing critical uncertainties for the management of the marine environment and strengthening of international and regional cooperation and coordination (Hey & Mee, 1993).

3. LME MODULES AND CHANGING ECOSYSTEM STATES OF HEALTH

An essential component of an ecosystem management regime is the inclusion of a scientifically based strategy to monitor and assess the changing states and health of the ecosystem by tracking key biological and environmental parameters. From this perspective, marine ecosystem assessment and 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. It would include, therefore, a range of activities needed to provide management information about ecosystem conditions, contaminants, and resources at risk.

An ecological framework that can serve as a basis for achieving the UNCED objectives is the large marine ecosystem (LME) concept. LMEs are increasingly being subjected to stress from growing exploitation of fish and other renewable resources, coastal zone damage, habitat losses, river basin runoff, dumping of urban wastes, and fallout from aerosol contaminants. These are regions of ocean space encompassing coastal areas from river basins and estuaries on out to the seaward boundary of continental shelves and the seaward margins of coastal current systems; LMEs 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 ecosystems with multiple steady states, and on the pattern formation and spatial diffusion within ecosystems (Holling, 1973, 1986, 1993; Pimm, 1984; AAAS, 1986, 1989, 1990, 1991, 1993; Beddington, 1986; Mangel, 1991; Levin, 1993, Sherman, 1994).

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 assessing and managing renewable resources from an LME perspective has been the topic of a series of national and international symposia and workshops initiated in 1984 and continuing through to the present, wherein the geographic extent of each region is defined on the basis of ecological criteria (Table 1). By comparing conditions in similar LMEs it is possible to gain global-scale insights to the economic losses likely to result from increasing degradation of LMEs caused by eutrophication, pollution, overexploitation, or climate change (Bakun 1995).

Several LMEs are semi-enclosed, including the Black Sea, the Baltic Sea, the Mediterranean Sea, and the Caribbean Sea. Within the extent of LMEs, domains or subsystems can be characterized. For example the Adriatic Sea is a subsystem of the Mediterranean Sea LME. In other LMEs, geographic limits are defined by the scope of continental shelves. Among these are the U.S. Northeast Continental Shelf and its four subsystems--the Gulf of Maine, Georges Bank, Southern New England, and the Mid-Atlantic Bight (Sherman et al., 1988)--the Icelandic Shelf, the Yellow Sea, the North Sea, and the Northwestern Australian Shelf. For LMEs with narrow shelf areas and well-defined currents, the seaward boundaries are limited to the areas affected by coastal currents, rather than relying on the 200-mile Exclusive Economic Zone (EEZ) limits. Among the coastal current LMEs are the Humboldt Current, California Current, Canary Current, Kuroshio Current, and Benguela 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 identified within, and in many cases extending beyond, the boundaries of the EEZs of single coastal nations located around the margins of the ocean basins (Figure 1).

Five indices are being developed by NOAA incollaboration with the Marine Policy Center of the Woods Hole Oceanographic Laboratory to be used as measures of changing ecosystem states --(1) biodiversity; (2) stability; (3) yields; (4) productivity; and (5) resilience, (Sherman and Solow, 1992). The data from which to derive the indices are obtained from time-series assessments of key ecosystem parameters. that are obtained by synthesizing the results of assessments made using five linked modules to assess ecosystem sustainability: (1) productivity, (2) fish and fisheries, (3) pollution and ecosystem state, (4) socioeconomic conditions and (5) governance.

3.1 Productivity Module

Productivity can be related to the carrying capacity of the ecosystem for supporting fish resources (Pauly and Christensen, 1995). Recently it has been reported that the maximum global level of primary productivity for supporting the average annual world catch of fisheries has been reached, and further large-scale "unmanaged" increases in fisheries yields from marine ecosystems is likely to be at trophic levels below fish in the marine food chain (Beddington, 1995). Evidence of this effect appears to be corroborated by the recent changes in the species composition of the catches of fisheries from the East China Sea LME (Chen and Shen, 1995). Measurement of ecosystem productivity can also serve as a useful indication of the growing problem of coastal eutrophication (NSQSR, 1993). In several LMEs, excessive nutrient loadings of coastal waters have been related to algal blooms that have been implicated in mass mortalities of living resources, emergence of pathogens (eg. cholera, vibrios, red tides, paralytic shellfish toxins) and explosive growth of non-indigenous species (Epstein, 1993).

The ecosystem parameters measured in the productivity module are primary productivity and chlorophyll biomass, zooplankton biodiversity and biomass, water column structure, photosynthetically active radiation (PAR), transparency, and, NO_2, and NO_3. The plankton of LMEs can be measured by deploying Continuous Plankton Recorder (CPR) systems from commercial vessels of opportunity (Glover, 1967). The advanced plankton recorders can be fitted with sensors for temperature, salinity, chlorophyll, nitrate/nitrite, petroleum hydrocarbons, light, bioluminescence, and primary productivity (Aiken, 1981; Aiken & Bellan, 1990; Williams & Aiken, 1990; UNESCO, 1992; Williams, 1993), 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 environmental change (Colebrook, 1986; Dickson et al., 1988; Jossi & Smith, 1990; Hayes et al., 1993; Jossi & Goulet, 1993; Williams, 1993). Plankton monitoring using the CPR system has been expanding in the North Atlantic (Colebrook et al., 1991).

3.2 The Fish and Fisheries Module

Changes in biodiversity among the dominant species within the fish communities of LMEs have resulted from excessive exploitation (Sissenwine and Cohen, 1991), naturally occurring environmental shifts in the climate regime (Bakun, 1993) or coastal pollution (Mee, 1992; Bombace, 1993). Changes in the biodiversity of the fish community can generate cascading effects up the food chain to apex predators and down the food chain to plankton components of the ecosystem (Overholtz and Nicolas, 1979; Payne et al, 1990). These three sources of variability in fisheries yield are operable in most LMEs. However, they can be described as primary, secondary, and tertiary driving forces in fisheries yields, contingent on the ecosystem under investigation. For example, in the Humboldt Current, Benguela Current and California Current LMEs, the primary driving force influencing variability in fisheries yield is the influence of changes in upwelling strength (MacCall, 1986; Crawford et al, 1989; Alheit and Bernal, 1993; Bakun, 1993, 1995); fishing and pollution effects are secondary and tertiary effects on fisheries yields. In Continental Shelf LMEs including the Yellow Sea and Northeast U. S. Shelf, excessive fisheries effort has been the cause of large-scale declines in catch and changes in the biodiversity and dominance in the fish community (Tang, 1993; Sissenwine, 1986). In these ecosystems, pollution and environmental perturbation are of secondary and tertiary influence. In contrast, significant coastal pollution and eutrophication have been the principal factors driving the changes in fisheries yields of the Northwest Adriatic (Bombace, 1993), the Black Sea (Mee, 1992) and the near coastal areas of the Baltic Sea (Kullenberg, 1986). Overexploitation and natural environmental changes are of secondary and tertiary importance. Consideration of the driving forces of change in biomass yield is important when developing options for management of living marine resources for long-term sustainability.

The Fish and Fisheries module includes fisheries-independent bottom trawl surveys and acoustic surveys for pelagic species to obtain time-series information on changes in biodiversity of the fish community. Standardized sampling procedures, when deployed from small calibrated trawlers, can provide important information on diverse changes in fish species. The fish catch provides biological samples for stomach analyses, age and growth, fecundity, and size comparisons (ICES, 1991), data for clarifying and quantifying multispecies trophic relationships, and the collection of samples to monitor coastal pollution. Samples of trawl-caught fish can be used to monitor pathological conditions that may be associated with coastal pollution. The trawlers can also be used as platforms for obtaining water, sediment, and benthic samples for monitoring harmful algal blooms, virus vectors of disease, eutrophication, anoxia, and changes in benthic community studies.

3.3 Pollution and Ecosystem Health Module

In several LMEs, pollution has been a principal driving force in changes of biomass yields. Assessing the changing status of pollution and health of the entire LME is challenging. 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, productivity, biodiversity, and yield of the ecosystem in relation to the changing states of ecosystems. Methods to assess the health of LMEs are being developed from modifications to a series of indicators and indices described by several investigators (e.g. Costanza 1992, Rapport 1992, Norton & 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.

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 resistant to external stress over time and space frames relevant to the ecosystem. These concepts were discussed by panels of experts at 2 workshops convened in 1992 by NOAA (Sherman 1993). It was decided at the workshops to refine initial strategies for measuring the changing states of selected marine ecosystems to an approach based on five ecosystem indices--productivity biodiversity resilience stability, and yield. It is relatively easy to propose qualitative characteristics that in some sense reflect the state of an ecosystem. For example, in the case of large marine ecosystems, the proposed five characteristics, fall into three groups: productivity and yield, stability and resilience, and diversity. With the exceptions of productivity and yield, it is somewhat more challenging to translate these qualitative characteristics into quantitative characteristics that can be measured and monitored on a routine basis. An effort to validate the utility of the indices is under development by the Marine Policy Center, Woods Hole Oceanographic Institution in collaboration with NOAA's Northeast Fisheries Science Center. In broad terms, diversity refers to some property of the relative abundances of species or other groups within a biological community. Diversity measures seek to collapse the vector of relative abundances into a scalar quantity that can be monitored over time. One technical problem with traditional diversity measures is that they are invariant to permutations of the elements of the vector of relative abundances. As a result, they are insensitive to ecological changes in which one species or group of species replaces another. A second problem is that, even if a change in diversity is detected, the measure provides no information about which species are involved in the change.

To overcome these problems, Solow (1994) developed a method for extracting a smooth trend from a time series of relative abundances. The method is similar to principal component analysis. Unlike traditional diversity measures, this approach, which is illustrated in Sherman, et al. (1996), is sensitive to regime shifts. Moreover, if a significant trend is identified, the method also provides information about which species contribute to it.

The stability of a community of interacting populations already has a specific meaning in ecology. If Y_t is a vector of abundances in period t and Y_t follows the model:

$$Y_t = F(Y_{t-1})$$

then, provided an equilibrium exists, the community is stable if the eigenvalues of the Jacobian of F evaluated at equilibrium are all less than 1 in modulus (May, 1974). If the system is stable, then the spectral radius (i.e., the maximum modulus of these eigenvalues) measures the rate at which the system returns to equilibrium and is, therefore, a reasonable measure of resilience.

Although there is a large theoretical literature on the stability of nonlinear dynamical systems, to our knowledge, no formal statistical test of stability has been proposed. We are currently developing a test of stability in a collection of populations by extending Bulmer's test for density dependence in a single population (Bulmer, 1985). Although Bulmer was interested in testing for density dependence, under the single-species model that he considered, density dependence and stability are equivalent. This single-species model is easily extended to the multi-species case. Let X_t be the vector of log abundances in period t. Under the extension of Bulmer's model:

$$X_t - \mu = A\ (X_{t-1} - \mu) + \varepsilon_t$$

where μ is a vector of mean levels of log abundance, A is a matrix of coefficients, and ε_t is a sequence of independent, multivariate normal errors or innovations. In statistical terminology, this model is called a first-order vector autoregressive (VAR(1)) process. The model is stable if the spectral radius of A is less than 1. A convenient test statistic is the spectral radius of the ordinary least squares estimate of A. The distribution of this test statistic under the null hypothesis that it is equal to 1 can be estimated by simulating from the VAR(1) model with unit spectral radius that is closest in a particular sense to the fitted model.

The data from which to define the experimental indices are obtained from time series monitoring of key ecosystem parameters. The ecosystem monitoring 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). The parameters of interest depicted in Fig. 2 include zooplankton composition, zooplankton biomass, water column structure, photosynthetically active radiation (PAR), transparency, chlorophyll-*a*, NO2, NO3, primary production, pollution, marine mammal biomass, marine mammal composition, runoff, wind stress, seabird community structure, seabird counts, finfish composition, finish 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 selection of key parameters should permit comparison of relative changing stages and health status among ecosystems. The interrelations between the data sets and the selected parameters are indicated by the arrows leading from column 1 to column 2 in the figure. The measured ecosystem components are shown in relation to ecosystem structure in a diagrammatic conceptualization of patterns and activities within the LME at different levels of complexity as depicted by Likens (1992) (Fig. 3).

Fish, benthic invertebrates and other biological indicator species are used in the pollution and ecosystem health module to measure pollution effects on the ecosystem including the bivalve monitoring strategy of "Mussel-Watch", the pathobiological examination of fish (Goldberg, 1976; Farrington et al., 1983; ICES, 1988; O'Connor & Ehler, 1991) and the estuarine and nearshore monitoring of contaminants in the water column, substrate, and selected groups of organisms. An important component of the associated research to support the assessment is the definition of routes of exposure to toxic contaminants of selected finfish and shellfish and the assessment exposure to toxic chemicals by several life history stages. The routes of bioaccumulation and trophic transfer of contaminants is assessed and critical life history stages and selected food-chain organisms are examined for a variety of parameters that indicate exposure to, and effects of, contaminants. Contaminant-related effects measured include diseases, impaired reproductive capacity, and impaired growth. Many of these effects can be caused by direct exposure to contaminants, or by indirect effects, such as those resulting from alterations in prey organisms. The assessment of chemical contaminant exposure and effects on fishing resources and food-chain organisms consists of a suite of parameters, including biochemical responses that are clearly linked to contaminant exposure coupled with measurements of organ disease and reproductive status that have been used in previous studies to establish links between exposure and effects. The specific suite of parameters measured will cover the same general responses and thus allow for comparable assessment of the physiological status of each species sampled as it relates to chemical contaminant exposure and effects at the individual species and population level. The implementation of protocols for assessing the frequency and effect of harmful algal blooms (Smayda, 1991) and emergent diseases (Epstein, 1993) would be included in the pollution module.

3.4 The Socioeconomic Module

This module is characterized by its emphasis on practical applications of its scientific findings in managing the LME and on the explicit integration of economic analysis with the scientific research to assure that prospective management measures are cost-effective. Economists and policy analysts will need to work closely with ecologists and other scientists to identify and evaluate management options that are both scientifically credible and economically practical.

The economic and management research will be closely integrated with the science throughout, and is designed intentionally to respond adaptively to enhanced scientific information. This component of the LME approach to marine resources management, was developed by the late James Broadus, former Director of the Marine Policy Center, Woods Hole Oceanographic Institution. It consists of six interrelated elements:

(1) *Human forcing functions*--The natural starting point is a generalized characterization of the ways in which human activities affect the natural marine system and the expected *sensitivity* of these forcing functions to various types and levels of human activity. Population dynamics, coastal development, and land-use practices in the system's drainage basin are clear examples. Work integrating the efforts of natural and social scientists should concentrate further on resolving apparent effects (such as eutrophication-associated red tide events or changing fish population structures) that are confounded by cycles or complex dynamics in the natural system itself. Progress is possible, too, in achieving better characterizations of the way in which human forcing is mediated by alternate management options. Emphasis should be on isolating and quantifying those forcing activities (sewage discharge, agricultural runoff, fishing effort) likely to be expressed most

prominently in effects on the natural system.

(2) *Assessing Impacts*--Another natural element in the systemic approach is to estimate and even predict the economic impacts of unmanaged degradation in the natural system and, obversely, the expected benefits of management measures. Such assessment is a form of standard benefit-cost analysis, but it requires scientific information to describe the effects of human forcing so they may be quantified in economic terms. Initial analysis should focus on the social and economic sectors likely to experience the largest impacts: fishing, aquaculture, public health, recreation, and tourism.

(3) *Feedbacks*--Collaborative effort should also be devoted to identifying and estimating the feedbacks of economic impacts into the human forcing function. Extensive coastal eutrophication, for example, associated with coastal development and runoff, might reduce the suitability of coastal areas for aquaculture production and increase its exposure to red tide damage, thereby putting a premium on capture fishery and increasing pressure on wild stocks. Similar feedbacks, both negative and positive, should be addressed and expressed in economic terms for all the major sectors.

(4) *Ecosystem Service/The Value of Biodiversity*--Special consideration should be given to improved knowledge of how the natural system generates economic values. Many valuable services provided by natural systems are not traded in markets or included in planning evaluations, so extra care must be made to assure that they are not sacrificed through ignorance. The services provided by coastal wetlands as nurseries for fisheries, natural pollution filters, and storm buffers are well-known examples that have particular relevance to coastal reclamation activities. Other examples are more subtle, including the importance of predator-prey relationships and the possibility of losing unrecognized "keystone" species in a valuable ecosystem. Experience suggests that growing economic values on aesthetic and recreational/tourism amenities may be expected in the LME setting as well. A variety of sources of economic value arising from the natural diversity of the LME should be identified and assessed in regard to existing uses and potential management innovations.

(5) *Environmental Economics*--Many of the elements described in this section comprise topics in Environmental Economics. Specialists in that field attempt to estimate the economic values (both use and non-use) associated with environmental resources and to identify the conditions associated with their optimal management (to derive the greatest net benefits for society). An important element is the collaboration between scholars from developing nations and those from the developed countries to transfer and adapt to the needs and techniques of Environmental Economics.

(6) *Integrated Assessment*--The ultimate objective is the integration of all the results achieved above, with scientific characterizations of the LME, into a comprehensive analytic framework (decision support environment) that will permit integrated assessment of human practices, effects, and

management options in the region. Such work is at the forefront of recent research on the human dimensions of global environmental change as well as research on human interactions with natural marine systems.

3.5 Governance Module

The Governance module is evolving based on case studies now underway among several ecosystems that have been targeted to be managed from a more holistic perspective; the Yellow Sea Ecosystem, where an effort aimed at more ecosystem oriented resource management is underway by the Peoples Republic of China (Tang, 1989); the multispecies fisheries of the southern Benguela Current Ecosystem under the management of the government of South Africa (Crawford et al., 1989); the Great Barrier Reef Ecosystem (Bradbury & Mundy, 1989; Kelleher, 1993) and the Northwest Australian Continental Shelf Ecosystem (Sainsbury, 1988) under management by the state and federal governments of Australia; and 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 & Ryan, 1988). Movement toward ecosystems management is emerging for the North Sea (NSTF, 1991; NSQSR, 1993), the Barents Sea (Eikeland, 1992), and the Black Sea (Hey & Mee, 1993). Within the EEZ of the United States, the state governments of Washington and Oregon have been developing a comprehensive plan for the management of marine resources within the Northern California Current Ecosystem (Bottom et al., 1989).

4. IMPLEMENTATION OF THE LME APPROACH

Efforts are underway to place greater focus on the linkage between scientific and societal needs and the utility of long-term, broad-area coastal ocean assessments aimed at enhancing the long-term sustainability of marine resources. If the proposition for time-series assessments of changing ecosystem states is to be realized in this period of shrinking budgets, it would be in the best interests of science and socioeconomic interests to be tightly linked in the endeavor. The basis for the linkage was emphasized not only in the UNCED declarations on the oceans, but also in a series of recent developments revolving around: (1) global climate change, ozone depletion and biodiversity issues; (2) the 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; and (4) renewed national interests in improving the health of degraded coastal ecosystems and promoting the recovery of depressed fish populations from overexploitation. In the United States, this interest has resulted in the enactment of recent legislation mandating the establishment of a national coastal monitoring program for assessing the changing states of "coastal ecosystem health" and reporting the findings to the U.S. Congress as a recurring biannual responsibility of NOAA and EPA (NCMA, 1992).

Based on examination of the bathymetry, hydrography productivity and trophic linkages of marine populations of the eastern half of the United States, the spatial extent of three LMEs has been determined - the Northeast U.S. Shelf large marine ecosystem, the

Southeast U.S. Shelf large marine ecosystem and the Gulf of Mexico large marine ecosystems. Scientific reports on the characteristics of these and other LMEs have been published (Table 1). Efforts are now underway within these ecosystems to consolidate existing resource and sustainability activities into the framework of the five LME modules in support of the U.S. National Coastal Monitoring Program. An implementation effort is underway in the Gulf of Guinea LME supported by the World Bank, the Global Environmental Facility, the United Nations Development Program, and the United Nations Industrial Development Organization. Participating countries include Ghana, Ivory Coast, Nigeria, Benin and, Cameroon. The project is being conducted in collaboration with NOAA with technical assistance from marine specialists of the United Kingdom, FAO, IOC, and IUCN. Other LME projects are being planned for the Yellow Sea by scientists and resource managers from China and Korea; for the Baltic Sea with marine specialists from Poland, Russia, Estonia, Latvia, and Lithuania in collaboration with marine experts from Finland, Germany, Sweden and Denmark; for the Benguela Current ecosystem with experts from Angola, Namibia, South Africa;, and the Somalia Current ecosystem with marine specialists from Kenya and Tanzania, with some technical assistance from marine specialists of Denmark, Germany, Norway, France, the United States, and the United Kingdom. The ongoing and proposed projects are based on assessments of the changing states of LMEs described in five peer reviewed published volumes. A list of the LMEs for which analyses have been published and the principal authors of the reports are summarized in Table 1. The results of more recent LME syntheses are given in reports recently published by IUCN on the LMEs of the Indian Ocean, and the LMEs of the Pacific Rim (Okemwa et al. 1995; Tang and Sherman 1995).

Table 1. List of 29 large marine ecosystems and subsystems 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	Source	Authors
U.S. Northeast Continental Shelf	AAAS (1986)	M. Sissenwine
	AAAS (1991)	P. Falkowski
U.S. Southeast Continental Shelf	AAAS (1991)	J. Yoder
Gulf of Mexico	AAAS (1989)	W. J. Richards & M. F. McGowan
	AAAS (1991)	B. E. Brown et al.
California Current	AAAS (1986)	A. MacCall
	AAAS (1991)	M. Mullin
	AAAS (1993)	D. Bottom
Eastern Bering Shelf	AAAS (1986)	L. Incze & J. D. Schumacher
West Greenland Shelf	AAAS (1990)	H. Hovgaard & E. Buch
Norwegian Sea	AAAS (1990)	B. Ellertsen et al.
Barents Sea	AAAS (1989)	H. R. Skjoldal & F. Rey
	AAAS (1991)	V. Borisov
North Sea	AAAS (1986)	N. Daan
Baltic Sea	AAAS (1986)	G. Kullenberg
Iberian Coastal	AAAS (1989)	T. Wyatt & G. Perez-Gandaras
Mediterranean — Adriatic Sea	AAAS (1993)	G. Bombace
Canary Current	AAAS (1993)	C. Bas
Gulf of Guinea	AAAS (1993)	D. Binet & E. Marchal
Benguela Current	AAAS (1989)	R. J. M. Crawford et al.
Patagonian Shelf	AAAS (1993)	A. Bakun
Caribbean Sea	AAAS (1990)	W. J. Richards & J. A. Bohnsack
South China Sea — Gulf of Thailand	AAAS (1989)	T. Piyakarnchana
Yellow Sea	AAAS (1989)	Q. Tang
Sea of Okhotsk	AAAS (1993)	V. V. Kusnetsov
Humboldt Current	AAAS (1993)	J. Alheit & P. Bernal
Indonesia Seas — Banda Sea	AAAS (1990)	J. J. Zijlstra & M. A. Baars
Bay of Bengal	AAAS (1993)	S. N. Dwivedi
Antarctic Marine	AAAS (1986, 1993)	R. T. Scully et al.
Weddell Sea	AAAS (1990)	G. Hempel
Kuroshio Current	AAAS (1989)	M. Terazaki
Oyashio Current	AAAS (1989)	T. Minoda
Great Barrier Reef	AAAS (1989)	R. H. Bradbury & C. N. Mundy
	AAAS (1993)	G. Kelleher
South China Sea	AAAS (1993)	D. Pauly & V. Christensen

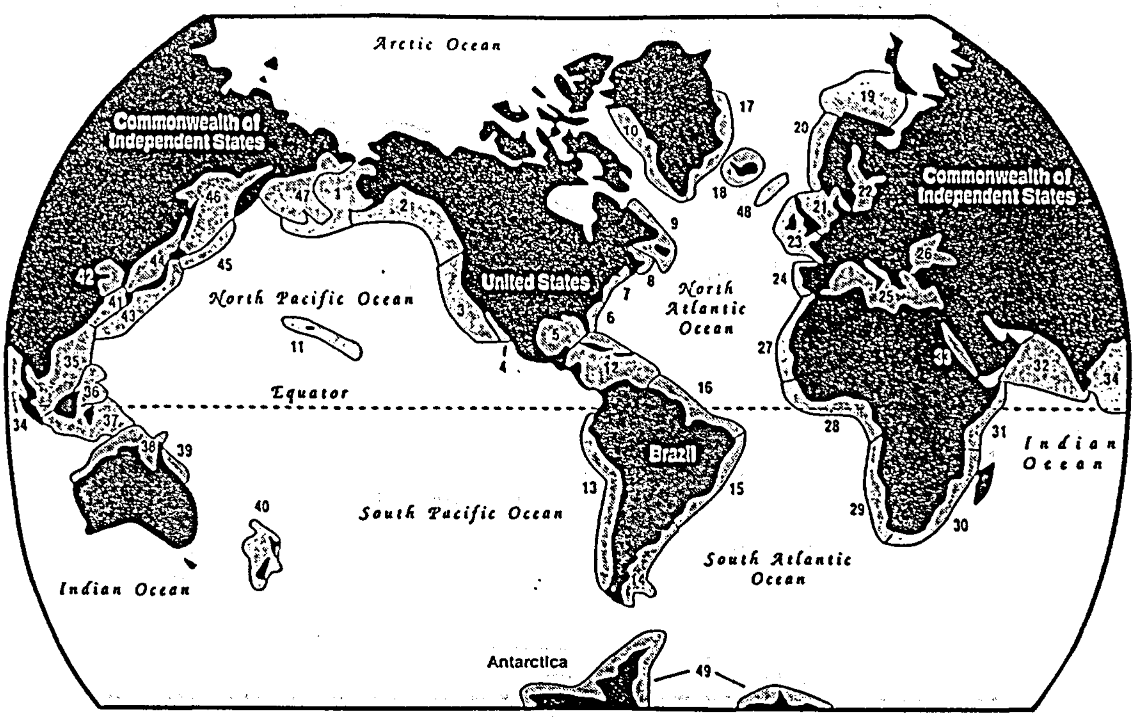

Fig. 1. Boundaries of 49 large marine ecosystems

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

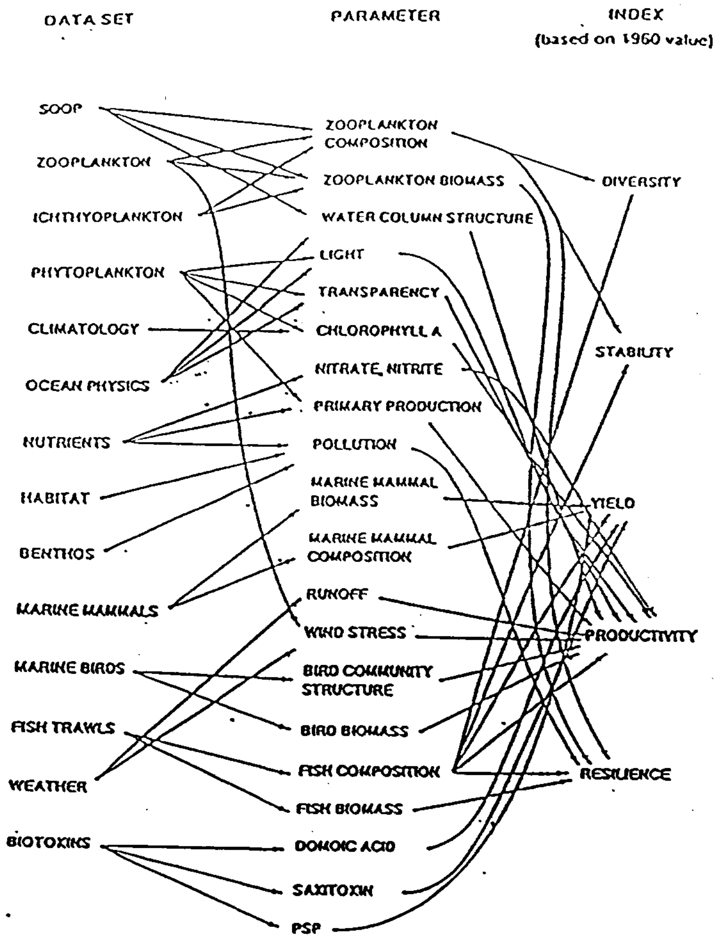

Fig. 2 A schematic representation of the data bases and experimental parameters for indexing the changing states of large marine ecosystems. The data base represents time-series measurements of key ecosystem components from the U.S. Northeast Continental Shelf ecosystem. Indices are based on changes compared with the ecosystem state in 1960

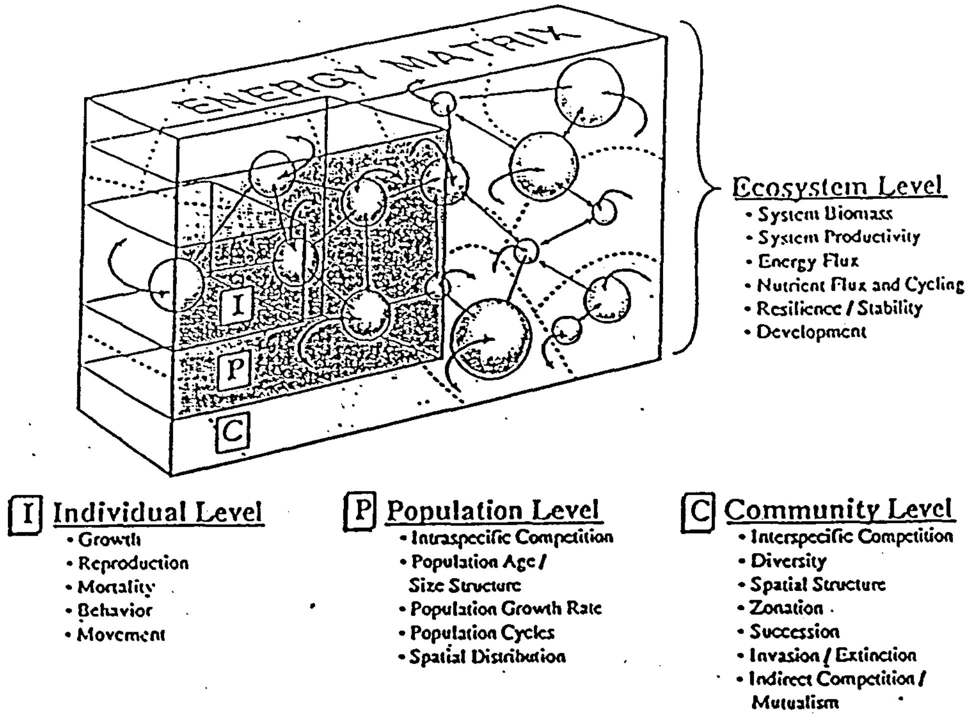

Fig. 3. Diagrammatic conceptualization of patterns and activities at different levels of complexity. Each sphere represents an individual abiotic or biotic entity. Abiotic is defined as nonliving matter. Broad, double-headed arrows indicate feedback between entities and the energy matrix for the system. 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. Fig. 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)

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