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SUSTAINABILITY, BIOMASS YIELDS, AND HEALTH OF COASTAL ECOSYSTEMS: AN ECOLOGICAL PERSPECTIVE

by

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ABSTRACT

The sustainability, health, and biomass yields of marine resources can be enhanced by the implementation of a more holistic and ecologically based strategy for assessing, monitoring, and managing coastal ecosystems than has been generally practiced during most of this century. A major milestone was reached in advancing toward a more ecologically based management practice when the majority of coastal nations of the world endorsed the declaration made at the United Nations Conference on Environment and Development (UNCED) in 1992, to prevent, reduce, and control degradation of the marine environment, so as to maintain and improve its life-support and productive capacities; develop and increase the potential of marine living resources to meet human nutritional needs, as well as social, economic, and development goals; and promote the integrated management and sustainable development of coastal areas and the marine environment. Marine resource problems underscored by UNCED are being addressed. Post-UNCED large marine ecosystem-scale programs for advancement toward resource sustainability, ecosystem health, and economically viable biomass yields are now being implemented. The programs are being supported by international agencies as part of an effort to couple recent advances in ecological monitoring, management, and stress mitigation strategies between developed countries, and lesser developed countries around the margins of the ocean basins.

ECOSYSTEM SUSTAINABILITY

Human intervention and climate change are sources of additional 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, harmful algal blooms, emergent diseases, fallout from aerosol contaminants, and episodic losses of living marine resources from pollution effects, and overexploitation. The long-term sustainability of coastal ecosystems as sources for healthy economies appears to be diminishing. A 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, 1992). This encouragement follows from the significant milestone 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 the changing states or "health" of coastal ecosystems and the achievement of marine resource sustainability and developmental goals.

The concept of sustainability as applied to marine resources and ecosystems has been the subject of recent debate. In an article published in *Science*, Ludwig et al. (1993) argue that basic research in ecology to be conducted in support of the Sustainable Biosphere Initiative of the Ecological Society of America (Lubchenco et al., 1991) may be leading to complacency, as the most pressing issues being addressed to avoid further degradation of global renewable resources are increasing human populations and excessive use of resources, not necessarily more scientific research. They support their arguments with citations of: (1) the apparent failures in fisheries management to maintain ecologically balanced stock viability in the face of increasing fishing effort, and (2) that claims of sustainability were suspect as populations are overexploited because scientific consensus on resource status is difficult to obtain. Rosenberg et al. (1993) dispute the Ludwig et al. (1993) assertions and maintain that "fisheries management provides positive examples of sustainable resource use and lessons for future improvements." They argue that "there is a sound theoretical and empirical basis for sustainable use of marine resources, that overexploitation is not inevitable, or the result of inadequate scientific advice, and that sustainable use of renewable resources is an obtainable management objective." In the development of a sustainable harvesting management regime, Rosenberg et al. (1993) emphasize the need for taking into account environmental conditions and exploitation rates by implementing appropriate monitoring programs to identify and track the shifts in population responses. They conclude that sustainable development of marine resources is achievable if scientific advice based on biological, social, and economic considerations is an integral part of the development of policies for renewable resource use. This conclusion is in agreement with Mangel et al. (1993), who argue that "sustainable use" of renewable resources is achievable when humans use living components of ecosystems in ways that allow natural processes to replace what is used. Under these conditions, the ecosystem "will renew itself indefinitely and human use will be sustainable."

An ecosystems approach for ecologists interested in contributing toward a scientifically based strategy for resource sustainability is given by Holling (1993). He emphasizes the need to recognize that there is an emerging science that is multidisciplinary and 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 more traditional, but nonetheless important, disciplinary oriented ecological studies can contribute more to resource sustainability when they are conducted within a framework of science at the level of organization that is multidisciplinary and focused on issues affecting populations within an ecosystems perspective. The international GLOBEC regional programs (Skjoldal et al., 1993), the International Geosphere-Biosphere Program on the Land-Oceans Interaction in the Coastal Zone Program (IGBP, 1994) and Joint Global Ocean Flux Study (IGBP, 1994) are examples of the newly emerging large-scale multidisciplinary marine ecosystem science. Linkages between these process-oriented studies and the more applied studies that are focused on supporting the sustainability of marine resources are being encouraged by national and international funding agencies concerned with the sustainability of natural resources. In this regard, the definition of sustainability used by Holling and carried forward in this perspective 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 would be important to establish institutional arrangements for ensuring that appropriate socioeconomic considerations are exercised 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 (North Sea Task Force, 1991). 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). An effort to develop a management system for the Barents Sea Ecosystem that provides stronger links between science and socioeconomic considerations from an ecosystems perspective is under consideration (Eikeland, 1992).

Large Marine Ecosystems (LME) Concept

An essential component of an ecosystem management regime is the inclusion of a scientifically based strategy that monitors and assesses 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, and therefore, would include a range of activities needed to provide management information about ecosystem conditions, contaminants, and resources at risk. Based on experiences in North America, Europe, and elsewhere, the core component of a comprehensive coastal ecosystem assessment and 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 (NRC, 1990). The principal characteristic of a comprehensive ecosystem assessment and 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.

This 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. Several recent reports that address these issues have been consulted in the preparation of this perspective, 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 UNCED in 1992 (IOC, 1992), 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).

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 (IUCN, 1990; 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 & Groom, 1989; Malone, 1991; Hey, 1992). Achievement of UNCED goals will require the implementation of a new paradigm aimed at greater integration of the highly sectorized approach to solving problems of coastal habitat degradation, marine pollution, and the overexploitation of fisheries than has been practiced in ocean monitoring and management by coastal nations during most of this century. It will also require a working partnership between the developed and developing nations of the world. Such an approach; if aided by external funding sources and based on principles of ecology and sustainable development would represent a significant advance to efforts of limited scope and application presently aimed in this direction in developing countries.

An ecological framework that may be useful in achieving the UNCED objectives is the large marine ecosystem concept (LME). LMEs are areas which are being subjected to increasing 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. The LMEs 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. They are relatively large ocean regions 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).

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 an LME perspective has been the topic of a series of national and international symposia and workshops initiated in 1984, wherein the geographic extent of each region is defined on the basis of ecological criteria (Table 1). The spawning and feeding migrations of fish communities within the LMEs have evolved in response to the distinct bathymetry, hydrography, productivity, and trophodynamics of the system. As the spatial dimension of biological and physical processes directly influencing the success of population renewals within the regions under consideration are large, the term large marine ecosystem is used to characterize them. 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 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 some cases extending beyond, the boundaries of the EEZs of coastal nations located around the margins of the ocean basins (Figure 1).

Levels of primary production are persistently higher around the margins of the ocean basins than for the open-ocean pelagic areas of the globe. It is within these coastal ocean areas that pollution has its greatest impact on natural productivity cycles, including eutrophication from high nitrogen and phosphorus effluent from estuaries. The presence of toxins in poorly treated sewage discharge, harmful algal blooms, and loss of wetland nursery areas to coastal development are also ecosystem-level problems that need to be addressed (GESAMP, 1990). Within several of the coastal LMEs, 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 & Brown, 1987), marine mammals, and zooplankton (Overholtz & 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 & 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 monitoring strategies to encompass food chain dynamics and the effects of environmental perturbations and pollution on living marine resources from an ecosystem perspective.

PERTURBATIONS AND DRIVING FORCES IN LMEs

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 (1960 through 1990), 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).

An effort was initiated in 1984 to convene a series of symposia and conferences to provide an international forum for bringing forward the results of multidisciplinary syntheses of available information on the principal driving forces of change in biomass yields for selected LMEs. Since 1984, case studies investigating the major causes of large-scale perturbations in biomass yields of 29 LMEs have been completed (Table 1). The principal driving forces for biomass changes vary among ecosystems. Results of the case studies, including generalizations on principal, secondary, and tertiary driving forces, are given in five volumes published in cooperation with the American Association for the Advancement of Science. A list of the principal investigators and contributors to the volumes is given in Table 1. In some systems, natural environmental perturbation is the principal driver of change in fisheries biomass production (e.g., Oyashio, Kuroshio, Benguela, and Humboldt Current Ecosystems). In several shelf ecosystems, overexploitation is the principal source of changes in the structure of the fish community and biomass yields (e.g., Gulf of Thailand, Northeast Shelf of the U.S., Yellow Sea Ecosystems). And in other ecosystems, the principal cause for structural change in the fish community is the effect of coastal eutrophication (e.g., Black Sea, northwest Adriatic Sea Ecosystems). For several other systems, the evidence for causes of observed changes in biomass yield are inconclusive (e.g., Gulf of Mexico, East Bering Sea, North Sea Ecosystems).

CORE ASSESSMENT AND MONITORING MODULES FOR LMEs

Consideration should be given to the use of standard and intercalibrated protocols for measuring changing ecological states of the watersheds, bays, estuaries, coastal waters and biomass yields of LMEs. Long-term historical time series data on living marine resources (some up to 40 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 affecting the changing ecological states of LMEs. 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 & Holt (1957), following the earlier pioneering approach of Lindemann (1942). However, as noted by Steele (1988), this array of models is unsuitable for consideration of temporal or spatial variability in the ocean. 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). 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.

A monitoring strategy for measuring the changing states of LMEs suitable for implementation on the coasts of developing countries was recommended by a panel of international experts that met at Cornell University in July 1991 (Sherman & Laughlin, 1992). The strategy included: (1) regular trawling using a stratified random sampling design to measure changes in the fish community; (2) plankton surveys to measure biofeedback to perturbations at the planktonic trophic level; and (3) measurements on the effects of pollution.

Trawling Module

Changes in the biodiversity, abundance, and distribution of the fish populations of the North Sea and the Northeast Continental Shelf of the United States have been assessed using trawling techniques for several decades (Azarovitz & 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 diverse changes in fish species. The fish catch provides biological samples for population demographics and trophic interactions involving studies of age and growth, fecundity, and predator-prey dynamics (ICES, 1991), data and the collection of samples to monitor coastal pollution. Samples of trawl-caught fish can be used in studies of contaminant burdens and 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.

Plankton Module

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 the stress of climate 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 is at present expanding in the North Atlantic (Colebrook et al., 1991).

Pollution and Ecosystem Health Effects Module

The implementation of the protocols for International Mussel Watch, Status and Trends of Contaminant Loading in Fish Tissues and Sediments (White and Robertson, in press), and methods for monitoring the frequency and extent of harmful algal blooms (Smayda, 1991; IOC, 1993a) and emergent vectors of disease (Epstein, 1993) provides the ecosystem health module of the balanced LME "core" monitoring effort.

SOCIOECONOMIC COMPONENTS

A distinguishing feature of the LME approach is 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 information is to be closely integrated with the enclosed science throughout, and is designed to respond adaptively to enhanced scientific information. This component of the LME approach to marine resources management, was developed by James Broadus, 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 is a well-known example that has 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 coastal/marine systems.

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, environmental disturbance) 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. Similarly, changes in populations of marine mammals and marine bird species will require multiple-year time-series observations. Consideration of the naturally occurring environmental events and the human-induced perturbations, including coastal pollution, 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 that consider both fisheries and ecosystem health.

PRESENT AND FUTURE ECOSYSTEM SUSTAINABILITY EFFORTS

The "core" assessment and monitoring 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 in the United States and the International GLOBEC Program. Developing LME monitoring strategies are compatible with the proposed Global Ocean Observing System (GOOS) of the IOC and those modules to be focused on living marine resources and ecosystem health (IOC, 1993b).

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 assessment and monitoring studies aimed at enhancing the long-term sustainability of marine resources. 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 socio-economic 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; (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) the effort of the IOC to encourage the implementation of a GOOS; and (5) renewed national interests in improving the health of degraded coastal ecosystems. 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).

A more holistic approach to coastal ecosystems assessment and monitoring as a means for fostering international cooperation in achieving sustainability objectives for marine resources between the more developed and less developed countries is presently underway. The 49 large marine ecosystems that have been identified for comparative sustainability studies 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, particularly in the stressed coastal ecosystems adjacent to centers of population densities in developing countries. 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 of the more developed countries (e.g., Belgium, Canada, Denmark, France, Germany, The Netherlands, Norway, and the United Kingdom). are prepared to assist developing nations in implementing coastal ecosystem assessment, monitoring, and mitigation, programs aimed at providing a scientific basis for improving the prospects for the long-term sustainable development of marine resources (Sherman et al., 1992). Two of these programs are in the advanced planning stage, one for the Gulf of Guinea Ecosystem that brings together into a single program effort five countries of the region--Ivory Coast, Ghana, Nigeria, Benin, and Cameroon. The other program is being developed jointly by marine specialists from China and Korea for the Yellow Sea large marine ecosystem (Wu & Qiu, 1993). The first of these projects is scheduled to be implemented in the Gulf of Guinea LME in summer, 1994.

A comprehensive regional project to assess, monitor, and mitigate stresses on the Black Sea Ecosystem is being supported by the GEF (Mee, 1992). It appears that marine resource managers and scientists are being responsive to implementing mitigation actions for marine resources at risk from overexploitation and habitat degradation and that initiatives in support of a more comprehensive systems approach for ensuring the long-term sustainability of marine resources are likely to be underway in marine ecosystems of Africa, and Asia.

The growing partnership among funding agencies, marine ecologists, and socioeconomic interests marks an important step toward realization of the UNCED declaration aimed at reversing the declining condition of coastal ecosystems, and enhancing the long-term sustainability of marine resources.

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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	W. J. Richards and M. F. McGowan
	4	B. E. Brown et al.
California Current	1	A. MacCall
	4	M. Mullin
	5	D. Bottom
Eastern Bering Shelf	1	L. Incze and J. D. Schumacher
West Greenland Shelf	3	H. Hovgaard and E. Buch
Norwegian Sea	3	B. Ellertsen et al.
Barents Sea	2	H. R. Skjoldal and F. Rey
	4	V. Borisov
North Sea	1	N. Daan
Baltic Sea	1	G. Kullenberg
Iberian Coastal	2	T. Wyatt and G. Perez-Gandaras
Mediterranean-Adriatic Sea	5	G. Bombace
Canary Current	5	C. Bas
Gulf of Guinea	5	D. Binet and E. Marchal
Benguela Current	2	R.J.M. Crawford et al.
Patagonian Shelf	5	A. Bakun
Caribbean Sea	3	W. J. Richards and J. A. 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	J. Alheit and P. Bernal
Indonesia Seas-Banda Sea	3	J. J. Zijlstra and M. A. Baars
Bay of Bengal	5	S. N. Dwivedi
Antarctic Marine	1&5	R. T. Scully et al.
Weddell Sea	3	G. Hempel
Kuroshio Current	2	M. Terazaki
Oyashio Current	2	T. Minoda
Great Barrier Reef	2	R. H. Bradbury and C. N. Mundy
	5	G. Kelleher
South China Sea	5	D. Pauly and V. Christensen

*Vol. 1, Variability and Management of Large Marine Ecosystems, AAAS Selected Symposium 99, Westview Press, Boulder, 1986. 319 pp.
Vol. 2, Biomass Yields and Geography of Large Marine Ecosystems, AAAS Selected Symposium 111, Westview Press, Boulder, CO, 1989. 493 pp.
Vol. 3, Large Marine Ecosystems: Patterns, Processes, and Yields, AAAS Symposium, AAAS Press, Washington, DC, 1990. 242 pp.
Vol. 4, Food Chains, Yields, Models, and Management of Large Marine Ecosystems, AAAS Symposium, Westview Press, Boulder, CO. 1991. 320 pp.
Vol. 5, Stress, Mitigation, and Sustainability of Large Marine Ecosystems, AAAS Press, Washington, DC, 1993. 376 pp.

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. Some fraction of the catch made by fishing operations of long-distance trawlers may be actually caught in other LMEs.

*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. Some fraction of the catch made by fishing operations of long-distance trawlers may be actually caught in other LMEs.

*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. Some fraction of the catch made by fishing operations of long-distance trawlers may be actually caught in other LMEs.
*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. Some fraction of the catch made by fishing operations of long-distance trawlers may be actually caught in other LMEs.
*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.

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, Toxic Effects, Aerosol Contaminants, Eutrophication Effects, Pollution Effects, Viral Disease Vectors)

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

   3.1 Bioenvironmental and Socioeconomic Models

   3.2 Management to Optimize Sustainable Fisheries Yields

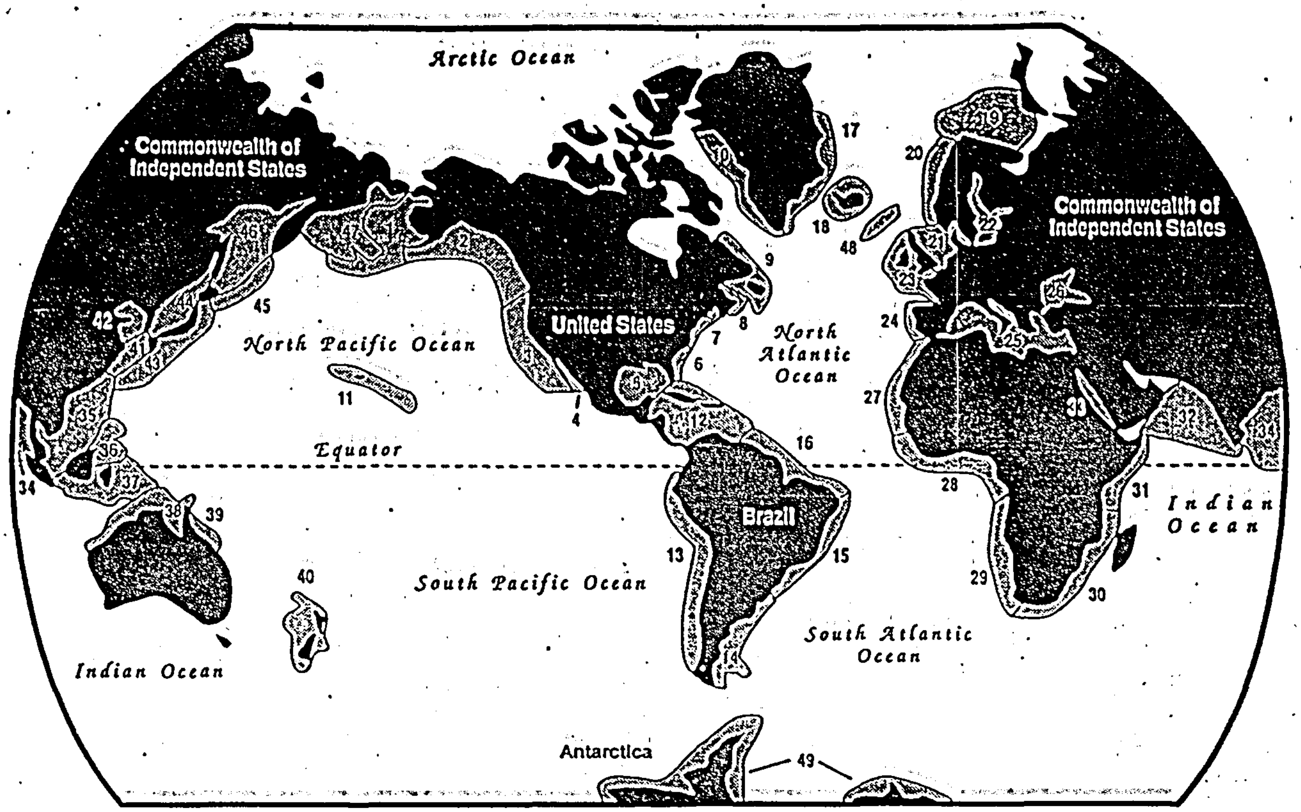
   3.3. Mitigation of Pollution Stress; Improvement of Ecosystem "Health"

4. Feedback Loop

   4.1 Evaluation of Ecosystem "Health"

   4.2 Evaluation of Fisheries Status

   4.3 Evaluation of Management Practices



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.

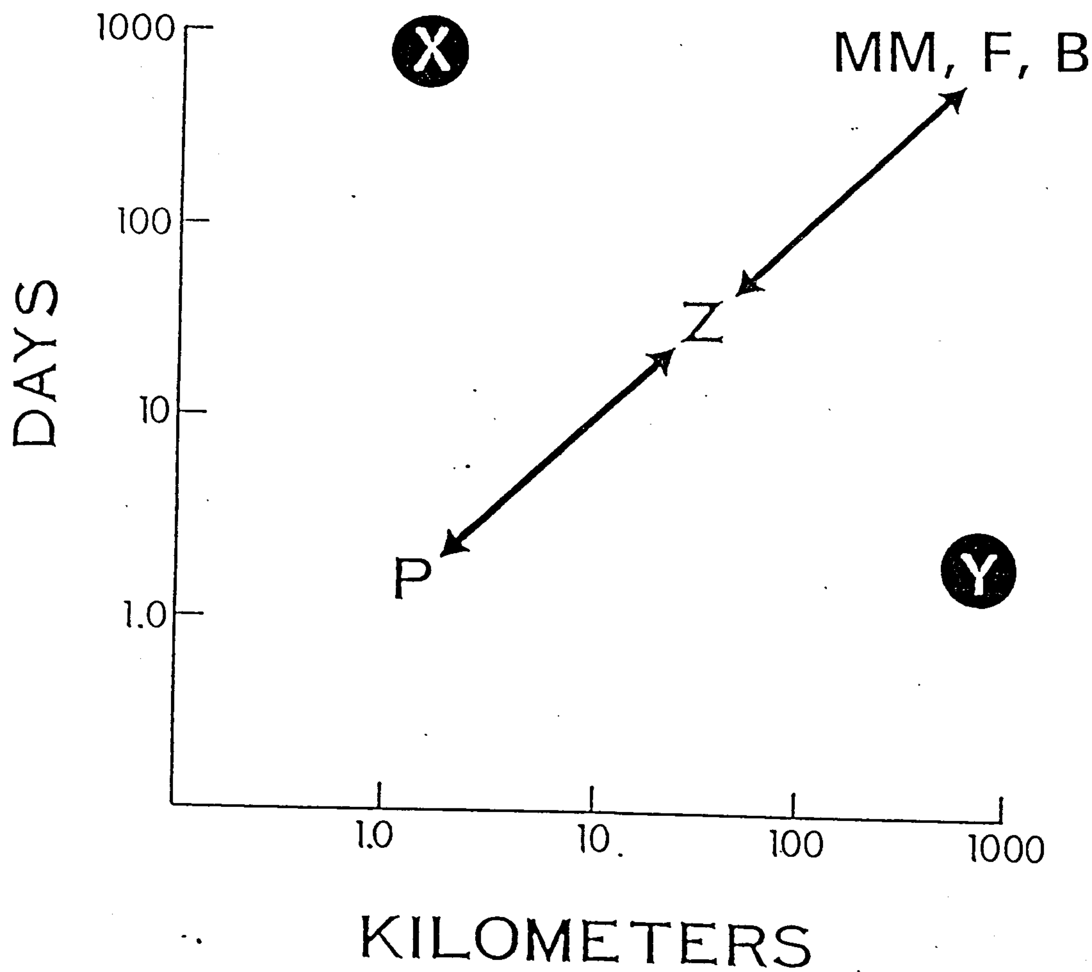


Figure 2. A simple set of scale relations for the food web P (phytoplankton), Z (zooplankton), F (fish), MM (marine mammals), and B (birds). Two physical processes are indicated by X, predictable fronts with small cross-front dimensions and (Y) weather events occurring over relatively large scales. (Adapted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