DRIVING FORCES AFFECTING RESOURCE SUSTAINABILITY IN LARGE MARINE ECOSYSTEMS

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ABSTRACT

Located around the coastal margins of the Atlantic, Pacific and Indian Oceans are 64 Large Marine Ecosystems (LMEs). Within the boundaries of the LMEs, 95% of the world's marine fisheries biomass is produced, ocean pollution is most severe, and coastal habitats are most seriously degraded. The LMEs are also important economic areas of the world, producing goods and services valued at $10.6 trillion annually. It is in the collective interest of civil society to ensure that resources at risk are protected and sustained for present and future generations. A pragmatic approach is being applied by countries in Africa, Asia, Latin America and eastern Europe, supported by $650 million in start-up funds from the Global Environment Facility (GEF) and other donors. This LME approach uses suites of indicators to assess physical, biological, and human forcing on ecosystem productivity, fish and fisheries, pollution and ecosystem health, socioeconomics and governance. Applications of the approach for identifying and, where appropriate, mitigating the affects of principal driving forces on sustaining goods and services of four LMEs are compared and evaluated in the ecosystem context.

LME DELINEATION AND MAJOR STRESSORS

Large marine ecosystems are natural regions of ocean space encompassing coastal waters from estuaries to the seaward boundary of continental shelves and the outer margins of coastal currents. They are relatively large regions of 200,000 km^2 or greater, the natural boundaries of which are based on four ecological criteria: bathymetry, hydrography, productivity, and trophically related populations. 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 the ocean by using large marine ecosystems as the distinct units for marine resources assessment, monitoring, and management (Duda and Sherman 2002). In turn, the concept of assessment, monitoring, and management of renewable resources from an LME perspective has been the topic of a series of ongoing national and international studies, symposia case studies and workshops initiated since 1984; in each instance, the geographic extent of the LME has been defined on the basis of bathymetry, hydrography, productivity, and trophodynamics. A list of peer reviewed published volumes of LME case studies is given in Table 1.

The marine areas of the world most stressed from habitat degradation, pollution, and overexploitation of resources are the coastal ecosystems. Ninety-five percent of the usable annual global biomass yield of fish and other living marine resources is produced in 64 LMEs (Figure 1) identified within, and in some cases extending beyond, the boundaries of the EEZs of coastal states (Sherman 1994); Levels of primary production are persistently higher around the margins of the ocean basins than in the open-ocean pelagic areas (Figure 2). High population density characterizes these coastal ocean areas and contributes to the pollution that has its greatest impact on natural productivity cycles through eutrophication from high levels of nitrogen and phosphorus effluent from estuaries or air-born sources. The presence of toxins, in harmful algal blooms, and loss of wetland nursery areas to coastal development are ecosystem-level problems that also need to be addressed. Taken together, the goods and services provided to civil society from LMEs on an annual basis are estimated at $10.6 trillion (Costanza et al. 1997). It is important to ensure that resources at risk are protected and sustained for present and future generations

Efforts are underway to meet the challenges of forecasting changing biotic and abiotic conditions within the boundaries of LMEs (USEO 2004; USOAP 2004; UN General Assembly 2001). Given the multi-sectoral and multi-disciplinary demand for time-series data, consideration should be given to the use of standard and inter-calibrated protocols for measuring changing ecological states of the watersheds, bays, estuaries, and coastal water of LMEs. Long-term historical time series data on living marine resources (some up to 40-yr), 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). Steele 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). 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 and ecosystem indicators of importance in monitoring pelagic components of the ecosystem including phytoplankton, zooplankton, fish, frontal processes, and short-term but large-area episodic effects (Figure 3). Advances in technology allow for cost effective methods for measuring the changing states of LMEs using suites of indicators including those depicted in Figure 3, supplemented with other modular suites of indicators.

LME INDICATOR MODULES

A five-module indicator approach to the assessment and management of LMEs has been proven to be useful in ecosystem-based projects in the United States and elsewhere. The modules provide time-series data to support forecasting efforts. They are customized to fit the situation within the context of a transboundary diagnostic analysis (TDA) process and a strategic action plan (SAP) development process for the groups of nations or states sharing an LME. These processes are critical for integrating science into management in a practical way and establishing appropriate governance regimes. The five modules consist of 3 that are science-based indicators focused on: productivity, fish/fisheries, pollution/ecosystem health; the other two, socio-economics and governance, are focused on economic benefits to be derived from a more sustainable resource base and implementing governance mechanisms for providing stakeholders and stewardship interests with legal and administrative support for ecosystem-based management practices. The first four modules support the TDA process while the governance module is associated with periodic updating of the Strategic Action Program (SAP). Adaptive management regimes are encouraged through periodic assessment processes (TDA updates) and updating of SAPs as gaps are filled (Figure 4) (Duda and Sherman 2002; Wang 2004).

Productivity Module Indicators

- Primary productivity can be related to the carrying capacity of an ecosystem for supporting fish resources (Pauly and Christensen 1995). Measurements of ecosystem productivity can be useful indicators of the growing problem of coastal eutrophication. In several LMEs, excessive nutrient loadings of coastal waters have been related to algal blooms implicated in mass mortalities of living resources, emergence of pathogens (e.g., cholera, vibrios, red tides, and paralytic shellfish toxins), and explosive growth of nonindigenous species (Epstein 1993, 1996).
- The ecosystem parameters measured and used as indicators of changing conditions in the productivity module are hydrography, nutrients, primary production, zooplankton biomass and species composition (Edwards et al. 2000a, 2000b). Plankton inhabiting LMEs have been measured over decadal time scales by deploying continuous plankton recorder systems monthly across ecosystems from commercial vessels of opportunity as well as from fixed stations. Advanced plankton recorders can be fitted with sensors for temperature, salinity, chlorophyll, nitrate/nitrite, petroleum, hydrocarbons, light, bioluminescence, and primary productivity, providing the means for *in situ* monitoring and for calibrating satellite-derived oceanographic data. Properly calibrated satellite data can provide information on such ecosystem aspects as physical state (i.e. surface temperature), nutrient characteristics, primary productivity and chlorophyll concentration (Berman and Sherman 2001; Aiken *et al.* 1999).

Fish and Fisheries Module Indicators

- Changes in biodiversity and species dominance within fish communities of LMEs have resulted from excessive exploitation, naturally occurring environmental shifts due to climate change and coastal pollution. Changes in biodiversity and species dominance in a fish community can rise up the food web to apex predators and cascade down the food web to plankton components of the ecosystem (Frank *et al.* 2005; Choi *et al*. 2004; Pauly and Christensen 1995).
- The Fish and Fisheries Module includes both fisheries-independent bottom-trawl surveys and pelagic-species acoustic surveys to obtain time-series information on changes in fish biodiversity, population dynamics, and abundance levels. Standardized sampling procedures, when employed from small calibrated trawlers, can provide important information on changes in fish populations (NOAA 1993; NEFSC 1999, 2002) Sherman et al. 2002, 2003). Commercial fish catch provides biological samples for stock identification, stomach content analyses, age-growth relationships, fecundity, as well as data for preparing stock assessments and for clarifying and quantifying multispecies trophic relationships and pathological conditions. The survey vessels can also be used as platforms for obtaining water,

sediment, and benthic samples for monitoring harmful algal blooms, diseases, anoxia, and changes in benthic communities.

Pollution and Ecosystem Health Module Indicators

- In several LMEs, pollution and eutrophication have been important driving forces of change in biomass yields. Assessing the changing status of pollution and health of an entire LME is scientifically challenging. Ecosystem health is a concept of wide interest for which a single precise scientific definition is difficult. The health paradigm is based on multiple-state comparisons of ecosystem resilience and stability, and is an evolving concept that has been the subject of a number of meetings (NOAA 1993). To be healthy and sustainable, an ecosystem must maintain its metabolic activity level and its internal structure and organization, and must resist external stress over time and space scales relevant to the ecosystem (Costanza 1992).
- The Pollution and Ecosystem Health Module measures pollution effects on the ecosystem through the bivalve monitoring strategy of the U.S. Environmental Protection Agency's (EPA's) Mussel-Watch Program, through the pathobiological examination of fish; through the estuarine and nearshore monitoring of contaminants and contaminant effects in the water column, the substrate, and in selected groups of organisms, through similar efforts. Where possible, bioaccumulation and trophic transfer of contaminants are assessed, and critical life history stages and selected food web organisms are examined for indicators of exposure to, and effects from, contaminants. Effects of impaired reproductive capacity, organ disease, and impaired growth from contaminants are measured. Assessments are made of contaminant impacts at both species and population levels. Implementation of protocols to assess the frequency and effect of harmful algal blooms, emergent diseases, and multiple marine ecological disturbances (Sherman 2000) are included in the pollution module. In the United States, the EPA has developed a suite of 5 coastal condition indicators: water quality index, sediment quality index, benthic index, coastal habitat index, and fish tissue contaminants index. The 2004 report, "National Coastal Condition Report II," includes results from EPA's analyses of coastal condition indicators and NOAA's fish stock assessments by LMEs aligned with EPA's National Coastal Assessment (NCA) regions (USEPA 2001, 2004).

Socioeconomic Module Indicators

- This module emphasizes the practical application of scientific findings to managing LMEs and the explicit integration of social and economic indicators and analyses with all other scientific assessments to assure that prospective management measures are cost-effective. Economists and policy analysts work closely with ecologists and other scientists to identify and evaluate management options that are both scientifically credible and economically practical with regard to the use of ecosystem goods and services.
- In order to respond adaptively to enhanced scientific information, socioeconomic considerations must be closely integrated with science. This component of the LME approach to marine resources management has recently been described as the human dimensions of LMEs. A framework has been developed by the Department of Natural Resource Economics at the University of Rhode Island for monitoring and assessment of the human dimensions of LMEs and for incorporating socioeconomic considerations into an adaptive management approach for LMEs (Sutinen *et al.* 2000). One of the more critical considerations, a method for economic valuations of LME goods and services, has been developed using framework matrices for ecological states and economic consequences of change (Hoagland *et al.* 2005).

Governance Module Indicators

- The Governance Module is evolving, based on demonstration projects now underway in several ecosystems, such that ecosystems will be managed more holistically than in the past. In LME assessment and management projects supported by the Global Environment Facility for the Yellow Sea, the Guinea Current , and the Benguela Current LMEs, agreements have been reached among the environmental ministers of the countries bordering these LMEs to enter into joint resource assessment and management activities as part of building institutions. One of the major goals of the Benguela Current LME (BCLME) Programme is to establish a Benguela Current Commission which will enable Angola, Namibia and South Africa to engage constructively and peacefully in resolving the transboundary fisheries and environmental issues that threaten the integrity of the BCLME.

- A preliminary study has found that the establishment of a Benguela Current Commission (BCC) can be justified on several grounds. These include the need for an appropriate institution to implement an ecosystem-based management approach in the BCLME and the need to fulfill the international obligations and undertakings of the three countries of the Benguela. Other motives for the establishment of a regional commission include the need to develop a better understanding of the BCLME, to improve the management of human impacts on the BCLME, to facilitate regional capacity building and to increase the benefits derived from transboundary management and harvesting of fish stocks.
- A phased approach towards establishing a Benguela Current Commission has been recommended. The first priority would be to draft the necessary agreement between the three countries of the Benguela region. Thereafter, working groups and joint management committees could be brought into operation to address the most pressing transboundary concerns.
- An Interim Benguela Current Commission (IBCC) is seen as a preliminary step towards a permanent Commission. It would provide the three countries with an opportunity to test and strengthen the institutional structures that will be required for a permanent Commission. It is envisaged that the BCLME Programme's existing structures would support the IBCC until new structures are made operational.
- Elsewhere, the Great Barrier Reef LME and the Antarctic LME are also being managed from an ecosystem perspective, the latter under the Commission for the Conservation of Antarctic Marine Living Resources. Governance profiles of LMEs are being explored to determine their utility in promoting long-term sustainability of ecosystem resources (Juda and Hennessey 2001). In each of the LMEs, governance jurisdiction can be scaled to ensure conformance with existing legislated mandates and authorities.
- Agreement was reached recently by UNEP to engage GEF-supported LME projects as the assessment and management components of the UNEP Regional Seas Programme (IOC 2005)

APPLICATION OF ECOSYSTEM INDICATORS TO LME ASSESSMENT AND MANAGEMENT

For this report we examined the forces driving changes in biomass yields of four LMEs based on the studies currently in progress for the Yellow Sea in Asia, the Benguela Current in Africa, and the U.S. Northeast Shelf and the Canadian Scotian Shelf LMEs in North America. In each case, the stewardship agencies responsible for the long term sustainability of the fishery resources at risk, applied information consistent with two or more of the 5 LME modules and their indicators to assess the changing states of the ecosystems under investigation. In each case, the identification of root causes for the biomass yield changes were identified by the principal investigators and reported in the literature. Legally mandated management actions were implemented following deliberations on the broader ecosystem considerations made possible from the indicator assessments of LME productivity, fish and fisheries, pollution and ecosystem health, socioeconomics and governance.

THE YELLOW SEA LME

Productivity (YSLME)

The Yellow Sea LME is an important shared resource supporting substantial populations of marine fish, invertebrates, mammals, and seabirds. It is rated as a Class I, highly productive (> $300 gC/m^2y$) LME, based on Sea WiFS global primary productivity estimates (Watson et al. 2003). The LME is bordered by China, South Korea and North Korea.

Fish and Fisheries (YSLME)

In the case of the Yellow Sea LME fish and fisheries, a 40-year time series of catch data and fish species biomass data from the late 1950s to the late 1990s, revealed a significant shift in the dominance of the fisheries, from a demersal dominated yield of croaker and hairtail in the 1950s, to anchovy and other small pelagics in the 1990s (Figure 5). Coincident to the decline in demersal stocks was: (1) a reduction in the mean size of fishery catches to a mean length of 20 cm and a mean weight of 20 grams, (2) a decline in the abundance of zooplankton (Figure 6), and (3) reduction in the average trophic level of dominant species in the fisheries catch from 4.1 in 1959 to 3.4 in 1999 (Tang 2003, 2005). These changes were attributed to excessive fishing effort as the root cause; no evidence of significant environmental perturbation or coastal pollution has been implicated in the changes reported in dominant species biomass yields over the 40-year period (Tang 2003)

Whether the decline in zooplankton from over a 27-year period (1959-1986) is related to the increasing abundance of small fast-growing anchovy and other pelagic species is not clear from the available data, and needs to be clarified. However, the biomass of the Yellow Sea benthos was observed to be relatively stable, at a long term mean of 23 mg/m2 from 1959 through 1992 (Tang 1993, 2003). Following a critical review of the "indicators" of changing ecosystem states and socioeconomics and governance, fishing effort by Chinese fishermen was significantly reduced in the Yellow Sea by the Chinese government. Since 1995, no fishing by Chinese vessels has been allowed during the summer months in an effort to initiate recovery of the depleted demersal species (Tang 2003).

Pollution and Ecosystem Health (YSLME)

She, 1999, analysed the sources and concentrations of pollutants entering the LME (river inputs, heavily polluted bays) and reported on the disappearance of species, the increased occurrence of red tides, and the concentration of pollutants in organisms. Outbreaks of harmful algal blooms have increased along the Yellow Sea coast, particularly in the presence of islands, and in areas where large dams have been built that restrict water circulation. The HABs have caused significant economic losses to the aquaculture industry. China and the two Koreas have very large human populations living in the Yellow Sea drainage basin. Many environmental problems are of a transboundary nature including industrial wastewater containing major pollutants from port cities; non-point source contaminants of agricultural origin (pesticides); oil discharged from vessels and ports; and oil production. The GEF Strategic Action Plan for the Yellow Sea LME, China and Korea will support pollution assessment and control activities in coastal waters around the margins of the LME.

Socio-economic conditions (YSLME)

More than 600 million people, or 10% of the world's population, inhabit the areas that drain into the Yellow Sea Large Marine Ecosystem. The coastal areas are heavily dependent on the Yellow Sea LME for economic development, recreation, tourism and food. Aquaculture and mariculture are a major use of the coastal waters (Duda and Sherman 2002). Mariculture is a growing industrial activity in this LME (Lee and Sutinen 1999. The sea is extremely important as a highway for international shipping. Trade is growing among the three countries that border the LME. China has major ports, as have South Korea (Inchon) and North Korea (Nampo). Offshore oil exploration is taking placein China and North Korea. Information on petroleum and shipping is given in Lee and Sutinen (1999). Several sites of picturesque beauty along the coastline are being promoted as tourist attractions (granite mountains of China, swimming beaches of South Korea). The Yellow Sea LME Project focuses on socioeconomic benefits as they relate to resource sustainability options.

Governance (YSLME)

Notable progress is being made in the GEF-sponsored International Waters LME Project which involves China and South Korea. It is supported by $25 million in GEF grants and in-kind contributions by the participating countries and other donor countries. The two countries surrounding the LME share some aspects of historical and cultural background, but differ in political systems, political and economic alignment, and levels of economic development. For more information on the problems and constraints of fisheries management, see Lee and Sutinen (1999). The transboundary issues that need to be addressed are the management of marine resources, industrial pollution and ecosystem health. The GEF-LME project is supporting Chinese and Korean collaboration and cooperation in monitoring and assessment activities within the LME.

THE BENGUELA CURRENT LME

This LME is a western boundary LME characterized by strong wind-driven coastal upwelling, bordered by Angola, Namibia, and South Africa.. It is a highly variable LME where responses to short-term climate perturbations affect the biomass yields. The principal upwelling center is situated off southern Namibia. The upwelling system is bounded at both northern and southern ends by warm water systems, the tropical/equatorial eastern Atlantic and the Indian Ocean's Agulhas Current (Figure 7). Sharp horizontal gradients (fronts) exist at these boundaries, but these display substantial variability in time and space—at times pulsating in phase and at others not. Interaction between the LME and the adjacent ocean systems occurs over thousands of kilometers (Benguela Current Large Marine Ecosystem Transboundary Diagnostic Analysis 1999). There are also teleconnections between the Benguela and processes in the North Atlantic and Indo-Pacific Oceans (e.g. El Niño). Shannon and O'Toole (2003) describe the oceanography and environmental variability of the Benguela Current.

Productivity (BCLME)

The LME is an important center of marine biodiversity and is one of the most productive ocean areas in the world (Figure 8). It is considered a Class I, highly productive (>300 gC/m^2yr), ecosystem based on SeaWiFS global primary productivity estimates. It supports a large biomass of fish, crustaceans, sea birds and marine mammals. It presents favorable conditions for a rich production of small pelagics, herrings, sardines and anchovies. Information on the long-term variability of chlorophyll, primary productivity, and zooplankton biomass and biodiversity is limited to aperiodic observations. From the early 70s, through the late 80s, it has been suggested that chlorophyll levels decreased from $3.5 mg/m^3$ to $2.0 mg/m^3$(Brown et al. 1991). With regard to zooplankton, from 1951 through 1996, there appears to have been a 10-fold increase in near-coastal zooplankton abundance in an embayment in the southern Benguela in all taxonomic groups according to Verheye and Richardson (1998) (Figure 9). The causes of this increasing zooplankton trend are not understood. Changes in temperature forcing of the LME that have been measured as SST anomalies (Figure 10) are also not well understood. Additional information is needed on physical forcing and trophic linkages on the variability observed in the shifts in abundance of the principal fish species, marine mammals, and marine birds including penguins of the

Benguela Current LME. A GEF grant and in-kind support of $38 million to the three countries, Angola, Namibia and South Africa participating in the Benguela Current LME assessment and management project, will allow for significant additional support for initiating time-series measurement of selected indicators of the ecosystem's productivity, fish and fisheries, pollution and ecosystem health, socioeconomics, gains to be achieved and governance practices to be implemented. The LME's considerable natural climatic environmental variability can severely impact the ecosystem and lead to a marked decline in fish abundance and availability. There is still a limited understanding of this highly variable and complex system of physical, chemical and biological interactions and processes.

Fish and Fisheries (BCLME)

The FAO 10-year trend shows decreasing catches of hake, herring, sardine, anchovy and miscellaneous pelagic fish (FAO 1999). Cod, hake, and haddock represent about 21% of the catch. Herring, sardine, and anchovy represent about 38% of the catch. Miscellaneous pelagic fish represent about 32% of the catch. The total catch decreased from 1.3 million tons in 1990 to 900,000 in 1996 and then rose to 1.2 million tons in 1999 (Garibaldi and Limongelli 2003). Anchovies and sardines are key trophic links in the ecosystem (Shannon et al. 1988). For more information on sardines, anchovies, sardinellas, hakes and rock lobster, and for transboundary considerations, see Shannon and O'Toole 2003. This LME is extremely rich in fishery resources. The confluence of warm and cooler waters provides a protected spawning area for the northern sardine and anchovy populations (Shelton and Hutchings 1990). But the status and yield of the ecosystem as a whole is difficult to predict. There have been major changes in the abundance, composition, distribution and availability of marine species. During those periods 1971-1977; 1980-1989, 1990-1995; significant differences in the trophic level of the fisheries of the northern Benguela LME were detected. During the initial period of examination, 1976-1977, the trophic level of the fishery was at 2.85 when smaller pelagics were more dominant in the catches than during the second period, wherein higher trophic level horse mackerel, hake, and mesopelagics dominated, increasing the trophic level to 3.25. During the ore recent period of examination, 1990-1995, the trophic level was again reduced to 3.1 as a result of lower overall biomass yield, and a predominance of sardine, horse mackerel and mesopelagics in the catches (Heymans et al. 2004).

The Transboundary Diagnostic Analysis (TDA) identifies overharvesting and wastage through the dumping of by-catch and undersize fish (www.bclme.org) as causes of biomass variability. It also identifies a loss of biotic integrity including changes in fish community composition, species and diversity. Mariculture is underdeveloped. The role of non-harvested species in the ecosystem is unknown. There was a period from the 1960s through the 1980s of heavy exploitation of resources by foreign fleets, resulting in severe declines in the abundance of several fish stocks (Figures 11 and 12). Superimposed on this fishing pressure is the impact of the inherent natural environmental ecosystem variability and change (Shannon and O'Toole 2003) Global climate change could intensify coastal winds and disrupt the balance of upwelling, sheltered areas and mixing that is so favorable to the anchovy and sardine fisheries (Bakun 1993). This poses difficulties in determining sustainable use and management of the LME living resources. The governments of Angola, Namibia and South Africa have agreed to try to improve predictability of the ecosystem, harmonize the management of shared stocks, assess non-exploited species and develop a regional mariculture policy. They have agreed to conduct joint surveys and assessments of shared fish stocks over a 5-year period that began in 2002. They have committed to a compliance with the FAO Code of Conduct for responsible fisheries. Three new programs and initiatives (ENVIFISH—Environmental conditions and fluctuations in distribution of small pelagic fish stocks, VIBES, a program focusing on the variability of pelagic fisheries resource in the Benguela Current, and BENEFIT, Benguela environment fisheries interaction training program) focus on fish resource dynamics. The University of British Columbia Fisheries Center has detailed fish catch statistics for this LME (http://fisheries.ubc.ca).

Pollution and Ecosystem Health (BCLME)

Health concerns focus on endangered and vulnerable species, altered food webs (changes in community composition, species and diversity), and the disruption of fish, bird and mammal migrations due to El Niño–type short term climate driver events. Top predators such as marine mammals and coastal birds (e.g. African penguins) are now threatened or endangered. Alien species such as the Mediterranean blue mussel have been introduced through ballast water, bilge water and mariculture operations. There is habitat destruction and modification (wetlands, mangroves, lagoons), and loss or modification of ecotones. The Transboundary Diagnostic Analysis (TDA) identifies chronic and catastrophic deterioration in water quality. Harmful algal blooms (HABs) occur of the coasts of all three countries. There is high pollution risk associated with ongoing seabed mining and petroleum exploration and production. A substantial volume of oil is transported through this LME. Pollution from industries and poorly planned and managed coastal developments and near shore activities is resulting in a rapid degradation of vulnerable coastal habitats. The rapid expansion of coastal cities has created pollution "hot spots" in all three countries, with resultant deterioration in water quality. The problem is aggravated by an increase in marine litter from land and shipping activities. The increased nutrient loading of coastal waters is caused by sewage discharge from aging water treatment infrastructure, and by industry. Other issues are the disposal of illegal hazardous waste, and lack of public awareness.

Socioeconomic conditions (BCLME)

Near shore and offshore sediments hold rich deposits of minerals (diamonds, phosphorite, diatomite), as well as oil and gas reserves. Extensive diamond mining is being conducted by dredging along the coasts and continental shelves of Namibia and South Africa. Capped abandoned wellheads hamper fishing, while drill cuttings and hydrocarbon spills impact on the environment. Due to the natural beauty of the coastal regions, their biodiversity and their culture, significant tourism has developed in some areas. Marine life that is not harvested, such as whales, dolphins and seabirds, is increasingly recognized as a valuable resource for nature-based tourism. However, pollution in some coastal environments will lead to a loss of tourism and employment. Fur seals were harvested in the early 17th century. This was followed by extensive whaling operations in the 18th and 19th centuries. Commercial trawling started around 1900. Commercial guano production from penguins, gannets and cormorants began in the early 20th century (Cooper et al. 1982). Commercial purse seine fishing for sardine was initiated in the 1950s (www.bclme.org). Unpredictable fisheries yields have sometimes resulted in the closure of fish canning factories. Artisanal fishermen experience loss of income and unemployment and many of the coastal communities are poor. The civil war in Angola led to the migration of part of the affected populations to the coastal areas. The Transboundary Diagnostic Analysis (TDA) examines the socioeconomic consequences of non-optimal harvesting of living resources, mining and drilling impacts, a hampered mariculture industry, harmful algal blooms, and the variability of the LME. The 3 countries bordering the LME are making efforts to develop a viable mariculture policy, and to solve conflicts between fisheries and coastal and offshore diamond, gold, oil and gas production. They are cooperatively analyzing the socioeconomic consequences of harvesting methods, in order to improve the sustainable use of the living resources, in compliance with the FAO Code of Conduct for Responsible Fishing. They are phasing out subsidies that encourage the continuation of non-environmentally friendly technologies. Reports have been prepared on the socio-economics of some key maritime industries, off-shore oil and gas exploration and production, and diamond mining. An Overview of the socio-economics of some key maritime industries in the Benguela Current region is available at the BCLME website (www.bclme.org).

Governance (BCLME)
The three countries have agreed to ensure an integrated and sustainable approach to the assessment and management of their marine resources (O'Toole et al. 2001). They are establishing an Interim Benguela Current Commission (IBCC) to strengthen regional cooperation and address the gaps in current knowledge. The priorities addressed are increased fishing pressure, toxic algal blooms and pollution from ongoing seabed mining and petroleum production. For information on the successes of BENEFIT (The Benguela-Environment-Fisheries-Interaction & Training), launched in 1997. Information on the interim Benguela Commission is given at www.bclme.org under "Reports" and "Institutional Arrangements."

NORTHEAST U.S. CONTINENTAL SHELF

The Northeast U.S. Continental Shelf Large Marine Ecosystem is characterized by its temperate climate. It extends from the Gulf of Maine to Cape Hatteras along the Atlantic Ocean. Intensive fishing is the primary driving force in the LME, with climate as the secondary driving force. Important hypotheses concerned with the growing impacts of pollution, overexploitation, and environmental changes on sustained biomass yields are under investigation. Efforts to examine changing ecosystem states and the relative health of this LME are underway in four major subareas: the Gulf of Maine, Georges Bank, Southern New England and the estuarine-dominated waters of the Mid-Atlantic Bight. This LME is structurally very complex, with marked temperature and climate changes, winds, river runoff, estuarine exchanges, tides and complex circulation regimes. It is historically a very productive LME of the Northern Hemisphere. LME book chapters, articles, and a volume are available pertaining to this LME and they include Falkowski 1991, Sissenwine and Cohen 1991, Sherman, Jaworski and Smayda 1996; Murawski 1996, 2000; Sherman et al. 2002, and Sherman et al. 2003.

Productivity (NESLME)
This LME is bounded on the east or seaward side by the Gulf Stream. Its complex circulation with meanders and rings greatly influence the LME. The gyre systems of the Gulf of Maine and Georges Bank, and the nutrient enrichment of estuaries in the southern half of the LME 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. For a map of surface circulation, see Sherman et al 2003, p.96. For an overview of the physical oceanography of the Shelf, see Brooks 1996. The Northeast U.S. Continental Shelf is considered a Category I (>300 gC/m^2yr), highly productive, ecosystem according to SeaWiFS global primary productivity estimates. Since 1977, the NOAA Northeast Fisheries Science Center has monitored this LME for estimates of primary productivity and chlorophyll-*a*. Productivity varies in the 4 major sub-areas, and from season to season. A map of estimated annual primary production is

given in Figure 13. Zooplankton is used as an indicator of major changes in stability of the lower levels of the food web and of biofeedback responses to oceanographic changes (Durbin and Durbin1996). The zooplankton biomass over the past two decades has been stable with regard to biomass and the abundance of dominant species (Figure 14 and Figure 15). There appears to be sufficient residual sustainability in biodiversity and abundance of zooplankton within the ecosystem to support the recovery of herring and mackerel from their low levels in the mid 1970s and the initiation of recovery of demersal fish stocks beginning in the mid-1990s.

Fish and Fisheries (NESLME)

Much has been published on the status of living marine resources in the Northeast Shelf LME, including population assessments in Sherman, Jaworski and Smayda (1996), the status of living marine resources in Our Living Oceans (NOAA 1995 and 1999), in NEFSC Status of Stocks reports, for example. The catch composition of this LME is quite diverse. In the late 1960s and early 1970s there was intense foreign fishing within the LME. The precipitous decline in biomass of fish stocks during this period was the result of excessive fishing mortality (Murawski et al. 1999). The catch of demersal fish stocks declined from 750,000mt in 1965 to less than 100,000 mt in 1995 (Figure 16).

Significant biomass flips have occurred among dominant species. Dogfish and skates increased in abundance in the 1970s, as groundfish and flounders declined. But a decrease of dogfish and skates has been observed since 1990 (NOAA 1999). Landings and an abundance index of principal groundfish and flounders from 1960 to 2000 are reported in Sherman et al. (2003)(Figure 16). The status of Northeast demersal fisheries resources, and for pelagic fisheries (Atlantic mackerel, Atlantic herring, bluefish and butterfish) can be found in the Our Living Oceans report (NOAA 1999). The long-term potential yield is set at 1,589,158 tons for this LME (NOAA 1999). The long-term sustainability of high economic yield species depends on the rebuilding of fish stocks through the application of adaptive management strategies (Murawski 1996). The recovery trend of George’s Bank yellowtail and haddock observed in the late 1990s is linked to reductions in the exploitation rate (Figure17). Information on fishery management plans for this LME is available in appendix 2 of Our Living Oceans. After 1994, there was an emergency closure of portions of Georges Bank, and severe restrictions were placed on the fishing of haddock. The New England Fishery Management Council (NEFMC) imposed strict restrictions on the fishing of groundfish, and there are efforts to reduce the currently high fishing mortality on lobsters. The Council took measures to reduce fishing effort through reductions of days at sea, a moratorium on new vessel entrants, area closures and an increase in the ring diameter of scallop dredges (NOAA 1999). The closure of half of the U.S. portion of Georges Bank to scallop harvesting to protect groundfish stocks appears to have contributed to an increase in sea scallop stock biomass. The virtual elimination of foreign fishing on Atlantic herring and mackerel stocks has resulted in the recovery of both species to former abundance levels, as neither species is a high priority table fish for the U.S. consumer (Figure 18). Other agencies involved in fisheries management are the Atlantic States Marine Fisheries Commission and the Mid Atlantic Fishery Management Council. The Northeast Fisheries Science Center compiles available information on the distribution, abundance, and habitat requirements for each of the 38 commercially valuable species managed by the New England and Mid-Atlantic Fishery Management Councils (NOAA 1999).

Pollution and Ecosystem Health (NESLME)

The US Northeast Shelf LME is under considerable stress from growing near-coastal eutrophication resulting from high levels of phosphate and nitrate discharges into drainage basins (Jaworski and Howarth 1996). Whether the increases in the frequency and extent of nearshore plankton blooms are responsible for the rise in incidence of biotoxin-related shellfish closures (White and Robertson 1996) and marine mammals mortalities, remains an important open question. It is of considerable concern to state and federal management agencies. For this LME as a whole, water clarity is good, dissolved oxygen and coastal wetlands are fair, eutrophic condition, sediment, benthos and fish tissue are poor.(EPA 2001). Indicators monitoring and assessments reveal that 60% of estuarine areas have a high potential of increasing eutrophication or existing high concentrations of chlorophyll *a.* Over 25% of sediments are enriched or exceed the ERL/ERM guidance. Nearly 40% of wetlands along the coast were eliminated between 1780 and 1980. About 10% of fish have elevated levels of contaminants in their edible tissues (EPA 2001, 2004). Benthic community degradation, fish tissue contamination and eutrophication are increasing. Coastal contaminaton is especially high along the urbanized and densely populated areas and in poorly flushed waters. Flux levels of zinc, cadmium, copper, lead and nickel are highest in the southern New England region, reflecting the level of urbanization and industrializaton. Heavy metal concentrations in demersal fish, crustaceans and bivalve mollusks continue to be monitored as biological indicators (Schwartz et al. 1996).

Socioeconomic conditions (NESLME)

The population of the coastal counties of the Northeast coast increased 52% between 1970 and 1990 (U.S. Bureau of the Census 1996). Major rivers systems (Hudson, Delaware, Chesapeake) contribute nitrates to estuaries and coastal systems from agriculture fertilization, atmospheric deposition and sewage. During the late 1960s and early 1970s, when there was the intense foreign fishing mentioned earlier, marked declines in fish abundances were attributed to overfishing (Sherman and Busch 1995). 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 abundance. Northeast fishermen were adversely affected by the collapse of the groundfish fishery in the late 1980s. Effort reductions led to curtailed revenues for fishermen (NOAA 1999; Sutinen and Hennessey 2005). A vessel buyout program (1995-1998) provided economic assistance to fishermen adversely affected. This resulted in an approximate 20% reduction in fishing effort (NOAA 1999). But local fishermen, especially in the New England area, are at odds with the imposition of fishery management rules which they say jeopardize their ability to earn a living. Pollution reduced the use by humans of the marine and coastal resources, but there have been improvements in sewage treatment facilities and the treatment of storm water.

Governance (NESLME)

Governance in this LME is complex, with evidence of progress since 1994. In the 1970s, excessive fishing mortality imposed on the LME's resources by European factory ships precipitated the passage of U.S. legislation. The 1976 Magnuson Fishing Management Act established a 200-mile Exclusive Economic Zone for the United States that extended jurisdiction over marine fish and fisheries and led to the recovery of Atlantic mackerel and herring stock inhabiting the LME. But the Act's single species focus neglected predator-prey relationships and other interactions. This focus has often resulted in conflicting goals and by-catch mortality (Murawski 1996). A joint MAFMC-ASMFC Fishery Management Plan initially approved in 1988, has resulted in increased biomass. Regulatory measures since 1994 aimed at a managed recovery of depleted fish stocks through reductions in days at sea, increased minimum mesh sizes, expanded closed areas, and trip limits, have led to the initiation of good recruitment and recovery of the spawning biomass of haddock and of yellowtail flounder stocks (Figure 19). In terms of pollution and ecosystem health, major programs are being implemented to address the existing problems. For example, the Chesapeake Bay Program's partnership with the bordering states has specific targets for improving the water quality of the Bay (EPA 2001). Wetlands protection regulations have reduced the loss of wetlands. Coordinated programs with participation from states, academic institutions, the private sector and federal government are underway to improve monitoring strategies aimed at mitigating the detrimental effects of habitat loss, coastal pollution, eutrophication and overexploitation.

SCOTIAN SHELF

The Scotian Shelf Large Marine Ecosystem is bordered on the landward side by the Canadian province of Nova Scotia and extends offshore to the shelf break, more than 200 nautical miles (nm) from the coast at some points. To the north it is separated from the Newfoundland Labrador Shelf LME by the Laurentian Channel. To the South, it extends to the Fundian Channel (Northeast Channel). The Scotian Shelf LME has a complex topography consisting of numerous offshore shallow banks and deep mid-shelf basins. It tends to be divided into eastern and western systems. The eastern Scotian Shelf includes Emerald Bank. The Nova Scotia Current hugs the coastline in a southwestward direction and enters the Gulf of Maine through the Northeast channel (Zwanenburg et al. 2002; Zwanenburg 2003).

Productivity (SSLME)

The Scotian Shelf LME is considered a Category II ecosystem (moderately high productivity of 150-300 gC/m^2yr) according to SeaWiFS global primary productivity estimates. Productivity in this LME is influenced by changes in environmental conditions and temperature. A decrease in ambient temperature is noted on the eastern Scotian Shelf (Zwanenburg et al. 2002). The recent changes to research vessel survey protocols broaden the collection of ecosystem monitoring data to include abundance and distribution of phytoplankton, zooplankton, as well as an increased suite of physical oceanographic parameters. A monthly Continuous Plankton Recorder Survey (CPR) is being conducted in collaboration with the Allister Hardy Foundation, Plymouth, England. A recent initiative by Canada and the United States entitled the East Coast of North America Strategic Assessment Project (Brown et al. 1996) is an attempt to gather and synthesize additional physical and biological data for the East coast of North America, from Cape Hatteras to the Labrador Shelf. Recent analyses of changes in the productivity and biomass yields of the Scotian Shelf LME revealed the consequences of the removal of top predators to the trophic structure and timeline of an ecosystem (Frank et al. 2005; Choi et al. 2004). The dominant change in the biomass yield was a sharp decline in groundfish landings and biomass during the decade from mid-1980s through the mid-1990s. Coincident to the decline was the increase of pelagic fish and also shrimp and snow crab (Figure 19). At the lower trophic levels, increases were observed for a 40-year period from 1960 to 2000 in phytoplankton concentrations based on color index values from Continuous Plankton Recorder silks, and in the increase in numbers of zooplankters, less than 2mm in length. The principal fisheries are now directed toward a pelagic fish and macroinvertebrates dominated by herring, shrimp and snow crab (Figure 19).

Fish and Fisheries (SSLME)
Systematic fishery surveys of the shelf made between the 1960s and the present are the most consistent source of information available concerning this Large Marine Ecosystem. There were significant declines in abundance and size for many commercially exploited fish species on both eastern and western subareas of the shelf, indicating that the limits of exploitation had been reached. The decrease in size, related to fishing effort, occurred both on the eastern shelf and on the western shelf (Pauly et al. 2001). The trawlable demersal biomass declined from a maximum of 450,000 metric tons in 1973 to less than 15,000 tons in 1997. The pelagic fish biomass also increased, although it showed fluctuations between 1970 and 1997. There has been an exponential increase in grey seal abundance since the 1960s. Harp, hooded, and harbor seals are found in the Gulf of St. Lawrence and so are Beluga whales.

Fishing effort increased rapidly with the establishment of Canada's 200-mile Exclusive Economic Zone in 1977. The commercially exploited fish include capelin, turbot, Atlantic halibut, white hake, silver hake, cod, haddock, and pollock. Pelagic species include the Atlantic herring and the Atlantic mackerel. Invertebrates include snow crab, northern shrimp and short fin squid. Both snow crab and northern shrimp prefer cold water and the increased landings for both those species coincide with the cooling of the eastern shelf (Zwanenburg 2003). A management scheme taking into account species interaction and biomass production is being initiated to address the overexploitation of the LME's main fisheries (cod, haddock, flounder, and other demersal fish). When the cod fishery collapsed on the Eastern shelf, a cod moratorium was imposed in 1993 and remains in effect. Overfishing led to a number of fishery closures in the early 1990s.

Pollution and Ecosystem Health (SSLME)
Environment Canada (EC) and the Canada-Nova Scotia offshore petroleum board's (CNSOPB) joint project [www.**cnsopb**.ns.ca/environment/pdf/CNSOPB_EC_DFO_MOU_2004.pdf] is an effort to protect this LME's offshore environment from marine pollution. There is a need to assess the wider ecological costs of over-exploitatoin of the fisheries resources (Hollingworth 2000).

Socioeconomics (SSLME)
The Scotian Shelf ecosystem has been exploited for hundreds of years. Exploitation intensified with the arrival of the Europeans in the 15th century. Their arrival saw the commercialization of the cod fishery. Since then, commercialization has intensified with the development of more efficient technologies and the expansion of markets. After World War 2, the development of distant-water international fleets increased the level of exploitation of the Scotian Shelf fisheries to the point of collapse in the mid 1970s. The trophic cascade has changed the structure of the Scotian Shelf LME from an economic perspective the recent value of shrimp and crab landings far exceeds the former value of the demersal fishery. With regard to other marine resources, the Canada-Nova Scotia offshore petroleum board is responsible for the regulation of petroleum affairs in the province. The presence of oil raises issues of multiple uses of the marine environment.

Governance (SSLME)
The Scotian Shelf Large Marine Ecosystem falls under the jurisdiction of the Canadian province of Nova Scotia. The fisheries of the Scotian Shelf after 1945 were regulated under ICNAF (International Commission for the Northwest Atlantic Fisheries), consisting of all the

industrialized fishing nations of the world operating in that area. ICNAF's effectiveness, however, was limited by the voluntary nature of compliance to its rules. The limited development of Canada's domestic fleet prompted Canada to establish a 200-mile Exclusive Economic Zone in 1977. Single species quota management continues, while there is a stated desire to change to an ecosystem level approach as with the Eastern Scotian Shelf Integrated Management Project (ESSIM) [http://www.mar.dfo-mpo.gc.ca/oceans/e/essim/essim-intro-e.html.]

SUSTAINABILITY AND COMPARATIVE ECOSYSTEM CONDITIONS

Sustainability and Socioeconomic Conditions

It has recently been observed by ICES (2005) that in developing an ecosystem-scale management perspective, "*it must be recognized that the objectives set will include much wider considerations than those traditionally addressed for fisheries management. The overall ecosystem objective should involve sustainability. Sustainability means different things to different people. We take it to mean that current activities do not compromise the ability of the environment to provide resources and services in the future, nor reduce the choices available to future generations. Further, we recognize that, with regard to fisheries, there are three aspects to sustainability:*

- *Sustainable fisheries. The level and composition of landings are sustainable*
- *Sustainable fishing industry. This is the socioeconomic sustainability of fishing and includes considerations of the viability of communities dependent on fisheries, the size and nature of the fishing industry and all linked economic and social activities including merchants and fish processing sectors, chandlers, vessel building and repair, etc.*
- *Sustainable ecosystems. The native species composition and functioning of the environment are not placed at risk of changes that seem long lasting and difficult to reverse.*

It is not for scientists to advise on the balance among these three, but such a consideration must form an explicit part of any ecosystem management scheme. It should, however, be understood that a number of existing international agreements (Table 3) already place a priority on sustaining the ecosystem, arguing that pursuit of social and economic sustainability cannot be allowed to result in an unacceptable risk to conservation of the ecosystem" (ICES 2005)."

The four LMEs examined in this report support significant socioeconomic activities including capture fisheries, aquaculture, shipping and related activities, oil production and tourism. Indices have been calculated for each of a range of marine and relevant not-marine activities by the Marine Policy Group at the Woods Hole Oceanographic Institution including fish landings (metric tons), aquaculture production (metric tons), ships-on-order (orderbook numbers), cargo traffic (metric tons), merchant fleet size (deadweight tons), oil production (average barrels per day), oil rig counts (numbers of facilities), and tourism (international arrivals). Each dimensionless index is normalized to fall between 0 and 1. The maximum and minimum functions are taken over the nation-specific levels of the particular activity exhibited by all nations bordering the LME.

National Activity Index

$$I_{ij} = \frac{x_{ij} - \min(x_i)}{\max(x_i) - \min(x_i)}$$

x_{ij} = output of nation j's marine activity i (*i.e.*, fish landings, aquaculture production, ships on order, cargo traffic, merchant fleet size, oil production, oil rig counts, or tourist arrivals) in relevant units

The index values for a nation's activities that depend upon a relatively clean environment, such as fisheries landings and aquaculture production can be combined into an aggregate activity index by weighting the index I_{ij} for each individual activity and summing across weighted indexes. Weights can be selected by the analyst or decision-maker. In the absence of non-arbitrary weights, such as those based on prices, we assign equal weights to the components of the fisheries & aquaculture activity index. Using the same method, we also calculate aggregate activity indexes for those combinations of activities that may lead to pollution, such as shipping (in the figures we display below, the weights are 2/3 cargo volume and 1/3 merchant fleet size) and offshore oil and natural gas production (weights are 2/3 production and 1/3 offshore rig count). We leave shipbuilding (orderbook numbers), tourism (number of international tourist visits), and the UNDP's human development index (HDI) as disaggregated indexes.

National Aggregate Activity Index

$$AI_j = \sum_{i=1}^{n} w_i I_{ij}$$

$$\sum_{i=1}^{n} w_i = 1$$

w_i = weights across n related activities (*e.g.*, fisheries landings and aquaculture production) for nation j.

We calculate a national total marine activity index by assigning weights to each of the aggregate activity indexes (AI) and summing across weighted aggregate activity indexes. The total marine activity index is a measure of the level of marine and relevant non-marine activity of all kinds in an LME or RSP. (We use the same approach to calculate a combined shipping and offshore oil marine activity index.) As before, the weights can be selected by the analyst or decision-maker, but we start with equal weights across all aggregate activity indexes. The UNDP Human Development Index (HDI) has not been included in the national total activity Index.

National Total Activity Index

$$TAI_j = \sum_{k=1}^{m} v_k AI_j$$

$$\sum_{k=1}^{m} v_k = 1$$

v_k = weights across m aggregate indexes for each nation j.

We calculate an LME (marine) activity index (MAI) for each LME by weighting each member nation's activity indexes (AI's) by the ratio of its coastline (in the LME) to the total coastline of the LME in which it participates, as measured for all s nations in an LME. We do this for each activity index (AI) and for the total activity index (TAI). Other weights, such as relative EEZ areas, could also be selected by the analyst or decision-maker. We use the same calculation to derive a socio-economic index (SEI) for each LME, using the UNDP human development index (HDI). UNDP has calculated the HDI for all nations. The HDI is itself an aggregate index comprising three key indicators: life expectancy (at birth); (2) education (i.e., the adult literacy rate and combined gross enrollment ratio for primary, secondary, and tertiary schools); and GDP per capita (expressed in the "purchasing power parity" of US dollars).

LME Activity Indexes

$$MAI_{LME} = \sum_{j=1}^{s} l_j AI_j$$

$$SEI_{LME} = \sum_{j=1}^{s} l_j HDI_j$$

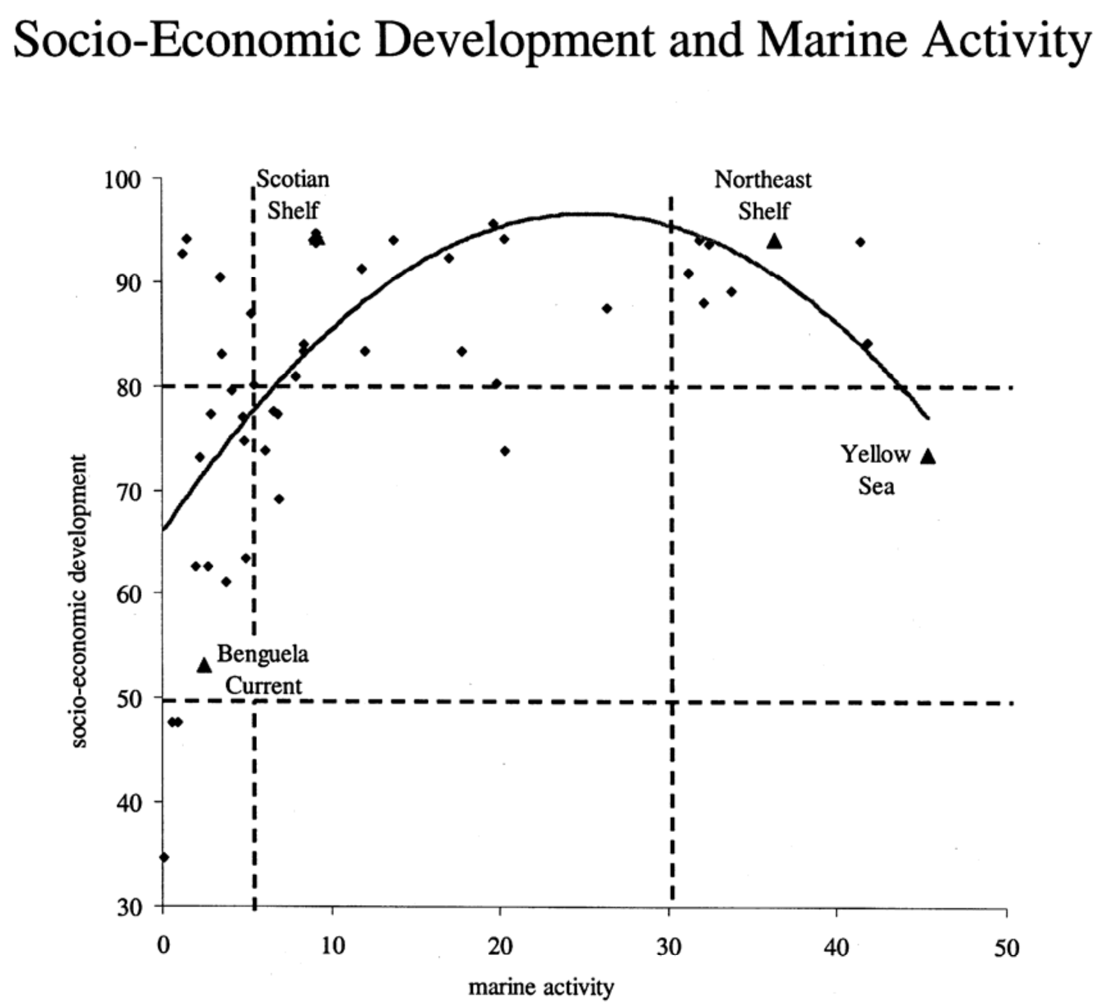
l_j = ratio of nation j's coastline length (in the LME) to the total coastline length of the LME in which it participates.

Measures of marine activity groupings can be calculated. Each of these measures is an index that relates the value of a specific LME relative to all other LMEs. The socio-economic index has been developed by UNDP, and it is not explicitly a measure of marine activity. The tourism index is a nationwide measure as well. Fisheries & aquaculture and shipping & offshore oil and gas are explicitly marine indexes. The table depicts the relatively minor levels of activity for the Benguela Current and Scotian Shelf LMEs. The Northeast Shelf and the Yellow Sea exhibit much greater levels of activity. Source: unpublished data from the WHOI Marine Policy Center (August 2005).

Aggregate Index Values for Four LMEs

LME	Socio-Economic Index (SEI)	Fisheries & Aquaculture ($MAI_{F\&A}$)	Tourism (MAI_T)	Shipping & Offshore Oil ($MAI_{S\&OO}$)	Total Marine Activity (MAI_{TOT})
Northeast Shelf	93.963	15.456	52.758	37.861	36.360
Scotian Shelf	94.300	4.880	25.351	5.262	9.204
Benguela Current	53.103	1.805	2.127	2.791	2.461
Yellow Sea	73.442	71.837	44.410	36.865	45.369

This graph depicts the values of two aggregate indexes for each LME: the socio-economic index, based on UNDP's human development index and the total marine activity index developed by the WHOI Marine Policy Center. The graph is divided up into nine sections relating to low, medium, and high values of the two indexes. All LMEs are plotted on the graph, and the four case study LMEs are identified by name. The graph suggests that moderate levels of marine activity are associated with relatively high levels of human development. More work is needed to understand any underlying causal explanations. This kind of analysis could be used to help prioritize efforts to assist in classifying LMEs in relation to conservation or sustainable development efforts. Source: unpublished data from the WHOI Marine Policy Center (August 2005).



Sustainability and Ecosystem Conditions

Based on the ICES perspective on ecosystem scale management and the definition of sustainability (ICES 2005), the fisheries of the Yellow Sea LME and the Scotian Shelf LME have become unsustainable for demersal species, given the depletions attributed principally to overfishing. With regard to the definition for a sustainable fishing industry, China has joined with South Korea in the joint $25KK GEF-supported project to “Reduce Environmental Stress in the Yellow Sea Large Marine Ecosystem,” as described in the recent release of several Working Group Reports (UNDP/GEF 2005). In addition to the moratorium enacted by China on summer fishing in the Yellow Sea by Chinese fishermen, the government has been supporting “enhancement” actions wherein juveniles of marine species are being introduced to the Yellow Sea. Expansion of caged mariculture of selected species is also being pursued (Tang 2003). It would appear that the fishing industry in China is under extreme stress and, at the present time, has not achieved a level of sustainability that is in accordance with the ICES guidelines (ICES 2005).

For the Scotian Shelf LME, the fishing industry earning capacity is apparently good. According to Frank et al. (2005), the “inflation adjusted monetary value of the combined shrimp and crab landings alone now far exceed that of the groundfishery replaced”. From an economic perspective, this may be a more attractive situation. It is not clear how the shift from groundfishery to pelagic and macroinvertebrate fishing has affected Nova Scotian coastal communities. However, in both Yellow Sea LME and the Scotian Shelf LME, the third level of the definition of sustainability, that of the sustainable ecosystem, cannot be met. Based on the changes observed in chlorophyll, zooplankton, and in the results of fishery independent stock assessments, it is clear that these two LMEs have been placed at risk of changes that seem long lasting and difficult to reverse.

In contrast to the questionable sustainability of the Yellow Sea and Scotian Shelf LMEs, the U.S. Northeast Shelf ecosystem is robust in relation to the relatively high levels of chlorophyll, primary productivity, zooplankton biomass and species diversity, and the absence of any persistent oceanographic regime shift. Evidence of a recovery trend from overfishing of demersal species is an encouraging response to significant reductions in fishing effort (Figures 17 and 18).

In the case of the Benguela LME, the short-term climate induced perturbations in fishery biomass has been compounded by overfishing and changes in the mean trophic level of fishery yields from 2.85 to 3.25 in the 80s and 3.1 in the 1990s (Heymans, Shannon and Jarre 2004). In response, the three border countries have joined together to launch a collaborative effort for promoting the recovery of depleted fish stocks, restoring degraded habitats, and controlling coastal pollution. With the assistance of a GEF grant and national and international donor contributions, the three participating countries, Angola, Namibia, and South Africa, have adopted the LME approach to assessing and managing the resources of the ecosystem. The Productivity module will include systematic assessments of plankton throughout the ecosystem from Luanda, Angola to Durban, South Africa. Systematic surveys are being conducted of pelagic and demersal fish species along with concomitant assessments of oceanographic conditions utilizing both shipboard sensors and satellite-borne remote sensors for temperature, chlorophyll, nutrients, and primary productivity. Indicators are in place to monitor harmful algal blooms and monitor the effects of offshore diamond mining and oil and gas production on marine resources and the integrity of the ecosystem. A detailed description of the effort is available at the Benguela Current LME (BCLME) website, (http://www.bclme.org).

CONCLUSION

A significant beginning is underway among developing nations for introducing the ecosystem approach in support of marine resources assessment and management. The GEF-supported LME projects in the planning and operational phases are being supported with $650 million in start-up funding from the GEF, augmented with national and donor scientific and technical support. At present, a total of 121 participating countries from Africa, Asia, Latin America and eastern Europe represent a growing network of marine scientists, managers, and ministerial leaders who are pursuing fishery and ecosystem recovery goals (Table 3). In each of the GEF-supported LME projects, the 5-module assessment and management approach is being tailored to suit the unique needs of the countries bordering the LMEs, based on the results of the transboundary diagnostic analyses.

For the four case studies examined, it would appear that the Benguela Current countries are at the threshold for initiating practical ecosystem assessment, monitoring, and management actions. From a socioeconomic perspective, it is an LME with considerable development potential. Countries bordering the Yellow Sea (China and Korea) and the Scotian Shelf LME (Canada), face formidable challenges in their efforts for reducing risks of further ecosystem degradation. The level of ecosystem unsustainability is especially acute in the case of the Yellow Sea, where the mean trophic levels of the fishery yields have been reduced from 4.1 in 1959, to a low of 3.4 in 1999. The eastern sector of the Scotian Shelf ecosystem remains perturbed with a change from fish biomass yields dominated by demersal species in the mid-1980s to a pelagic fish-macro-invertebrate dominance in fishery yield beginning in the 1990s and extending to the present.

The Northeast Shelf LME case study is an example of stewardship activities resulting in the initiation of stock recoveries for several important species, including Atlantic mackerel, herring, haddock, and Yellowtail flounder. The resilience of the ecosystem is high as measured by robust levels of primary productivity, zooplankton biomass and biodiversity. No major change in trophic level has occurred in the ecosystem. The trophic level was limited in range to between 3.6 in the 1960s, to 3.4 in the 1970s and, is once again at 3.6 in 2002 (Figure 20).

In the absence of comparable mitigation response data and actions, it is difficult to compare the condition of the four LMEs in relation to pollution effects. However, in the case of the Northeast Shelf LME, the positive steps taken toward initiating recovery of depleted demersal fish stocks have yet to be matched by a focused effort to reduce ecological degradation of estuaries in the LME. Evidence of widespread sediment contamination, fecal coloform and oxygen depletion events; benthic biodiversity perturbation, and nutrient loading leading to eutrophication, remain as problems to be more systematically addressed from an ecosystem perspective. (Figure 21). In recognition of the problem, NOAA and EPA in the United States have joined forces to extend the coastal condition monitoring and assessment of EPA to the more open waters of the Northeast Shelf LME by conducting joint ecosystem surveys on NOAA vessels to obtain the necessary data on which to base appropriate actions for mitigating further ecosystem stress and protecting the valuable economic activities of the ecosystem estimated at $234 billion annually to the US economy (Table 4).

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Table 1. Large Marine Ecosystems Published Studies and Volumes

LMEs	Vol.#	Authors	LMEs	Vol.#	Authors
Somali Coastal Current	7	Okemwa	East China Sea	8	Chen & Shen
Bay of Bengal	5	Dwividi	Yellow Sea	2,5,12	Tang
	7	Hazizi	Kuroshio Current	2	Terazaki
East Bering Sea	1	Incze & Schumacher	Sea of Japan	8	Terazaki
	8	Livingston *et al.*	Oyashio Current	2	Minoda
West Greenland Shelf	3	Hovgärd & Buch	Okhotsk Sea	5	Kusnetsov *et al.*
	5	Blindheim & Skjoldal	Gulf of Mexico	2	Richards & McGowan
	10	Rice		4	Brown *et al.*
Barents Sea	2	Skjoldal & Rey		9	Shipp
	4	Borisov		9	Gracia & Vasquez Baden
	5	Skjoldal	Southeast US Shelf	4	Yoder
	10	Dalpadado *et al.*	Northeast US Shelf	1	Sissenwine
	12	Matishov		4	Falkowski
Norwegian Shelf	3	Ellertsen *et al.*		6	Anthony
	5	Blindheim & Skjoldal		10,12	Sherman
North Sea	1	Daan	Scotian Shelf	8	Zwanenburg *et al.*
	9	Reid	Caribbean Sea	3	Richards & Bohnsack
	10	McGlade	Patagonian Shelf	5	Bakun
	12	Hempel	South Brazil Shelf	12	Ekau & Knoppers
Iceland Shelf	10	Astthorsson, Vilhjálmsson	East Brazil Shelf	12	Ekau & Knoppers
Faroe Plateau	10	Gaard *et al.*	North Brazil Shelf	12	Ekau & Knoppers
Antarctic	1	Scully *et al.*	Baltic Sea	1	Kullenberg
	3	Hempel		12	Jansson
	5	Scully *et al.*	Celtic-Biscay Shelf	10	Lavin
California Current	1	McCall	Iberian Coastal	2	Perez-Gandaras
	4	Mullin		10	Wyatt & Porteiro
	5	Bottom	Mediterranean Sea	5	Caddy
	12	Lluch-Belda *et al.*	Canary Current	5	Bas
Pacific American Coastal	8	Bakun *et al.*		12	Roy & Cury
Humboldt Current	5	Bernal	Guinea Current	5	Binet & Marchal
	12	Wolff *et al.*		11	Koranteng & McGlade
Gulf of Thailand	5	Piyakarnchana		11	Mensah & Quaatey
	11	Pauly & Chuenpagdee		11	Lovell & McGlade
South China Sea	5	Christensen		11	Cury & Roy
Indonesian Sea	3	Zijlstra, Baars		11	Koranteng
Northeast Australian Shelf	2	Bradbury & Mundy	Benguela Current	2	Crawford *et al.*
	5	Kelleher		12	Shannon & O'Toole
	8, 12	Brodie	Black Sea	5	Caddy
				12	Daskalov

Vol. 1 1986. *Variability and Management of Large Marine Ecosystems*. Sherman & Alexander, eds. AAAS Symposium 99. Westview Press, Boulder,CO. 319p

Vol. 2 1989. *Biomass Yields and Geography of Large Marine Ecosystems*. Sherman & Alexander, eds. AAAS Symposium 111. Westview Press, Boulder, CO. 493p

Vol. 3 1990. *Large Marine Ecosystems: Patterns, Processes, and Yields.* Sherman, Alexander and Gold, eds. AAAS Symposium. AAAS, Washington, DC. 242p

Vol. 4 1991. *Food Chains, Yields, Models, and Management of Large Marine Ecosystems*. Sherman, Alexander and Gold, eds. AAAS Symposium. Westview Press. Boulder, CO. 320p

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Vol. 6 1996. *The Northeast Shelf Ecosystem: Assessment, Sustainability and Management*. Sherman, Jaworski and Smayda eds. Blackwell Science, Cambridge, MA. 564p

Vol. 7 1998. *Large Marine Ecosystems of the Indian Ocean: Assessment, Sustainability and Management.* Sherman, Okemwa and Ntiba, eds. Blackwell Science, Malden, MA. 394p

Vol. 8 1999. *Large Marine Ecosystems of the Pacific Rim: Assessment, Sustainability and Management.* Sherman and Tang, eds. Blackwell Science, Malden, MA. 455p

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Table 2. 121* Countries Participating in GEF/Large Marine Ecosystem Projects

Approved GEF Projects

LME	Countries
Gulf of Guinea (6)…………………………	Benin, Cameroon, Côte d'Ivoire, Ghana, Nigeria, Togo
Yellow Sea (2)……………………….....	China, Korea
Patagonia Shelf/Maritime Front (2)…………..	Argentina, Uruguay
Baltic (9)………………………………………	Denmark, Estonia, Finland, Germany, Latvia, Lithuania, Poland, Russia, Sweden
Benguela Current (3)………………………….	Angola, Namibia, South Africa
South China Sea (7)……………………………	Cambodia, China*, Indonesia, Malaysia, Philippines, Thailand, Vietnam
Black Sea (6)…………………………………..	Bulgaria, Georgia, Romania, Russia*, Turkey, Ukraine
Mediterranean (19)…………………………….	Albania, Algeria, Bosnia-Herzegovina, Croatia, Egypt, France, Greece, Israel, Italy, Lebanon, Libya, Morocco, Slovenia, Spain, Syria, Tunisia, Turkey*, Yugoslavia, Portugal
Red Sea (7)…………………………………….	Djibouti, Egypt* Jordan, Saudi Arabia, Somalia, Sudan, Yemen
Western Pacific Warm Water Pool-SIDS[a] (13)…	Cook Islands, Micronesia, Fiji, Kiribati, Marshall Islands, Nauru, Niue, Papua New Guinea, Samoa, Solomon Islands, Tonga, Tuvalu, Vanuatu
	Total number of countries: 70*

GEF Projects in the Preparation Stage

Canary Current (7)...	Cape Verde, Gambia, Guinea, Guinea-Bissau, Mauritania, Morocco*, Senegal
Bay of Bengal (8)……………………………..	Bangladesh, India, Indonesia*, Malaysia*, Maldives, Myanmar, Sri Lanka, Thailand*
Humboldt Current (2)…………………………	Chile, Peru
Guinea Current (16)…………………………..	Angola*, Benin*, Cameroon*, Congo, Democratic Republic of the Congo, Côte d'Ivoire*, Gabon, Ghana*, Equatorial Guinea, Guinea*, Guinea-Bissau*, Liberia, Nigeria*, São Tomé and Principe, Sierra Leone, Togo*
Gulf of Mexico (3)…………………………….	Cuba, Mexico, United States
Agulhas/Somali Currents (8)………………….	Comoros, Kenya, Madagascar, Mauritius, Mozambique, Seychelles, South Africa*, Tanzania
Caribbean LME (23)…………………………..	Antigua and Barbuda, The Bahamas, Barbados, Belize, Colombia, Costa Rica, Cuba*, Grenada, Dominica, Dominican Republic, Guatemala, Haiti, Honduras, Jamaica, Mexico*, Nicaragua, Panama, Puerto Rico[b], Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Trinidad and Tobago, Venezuela
	Total number of countries: 51*

*Adjusted for multiple listings

[a] Provisionally classified as Insular Pacific Provinces in the global hierarchy of LMEs and Pacific Biomes (Watson *et al*. 2003)

.[b] A self-governing commonwealth in union with the United States

Table 3. From the ICES Cooperative Research Report No. 272, July 2005. Ecosystem Effects of Fishing: Impacts, Metrics, and Management Strategies, Dr. Jake C. Rice, ed.

An overview of the main global conventions, laws and treaties applying to the conservation and management of marine living resources. These are often given regional specificity in 'local' conventions such as Annex V of the OSPAR Convention which covers protection of species and habitats.

Convention or treaty	Year	Main objective
UN Law of the Sea	1982	Regulation of the management and authority of all living marine resources. Establishment of an Exclusive Economic Zone
Bonn Convention	1983	Protection of migratory stocks of wild species (species moving across national borders)
CITES and GATT		General Treaties governing prevention of trade in endangered species (CITES) on reduction of environmental impact (GATT)
Convention on Biological Diversity (CBD)	1992	Result of UNCED Conference. Protection of biodiversity at level of genetics, species and ecosystems
Agenda 21 - Chapter 17	1992	Result of UNCED Conference. Protection of all marine and coastal areas by rational use and development of living resources
FAO Code of Conduct	1995	Code of Conduct for Responsible Fisheries by considering ecosystem and socio-economic aspects of fisheries and the precautionary approach
Jakarta Mandate	1997	Elaboration of CBD for marine systems in which Marine Protected Areas form a major issue
UN Convention on Migratory and Straddling Fish Stocks	not in force	Conservation and protection of border crossing and high seas fish stocks

Table 4. Valuation to US economy of the Northeast Shelf LME (from Hoagland et al. 2005).

Northeast Shelf LME: Economic Impacts

BROAD INDUSTRY	TIER	IMPLAN SECTOR	OUTPUT ($\$ \times 10^6$)	EMPLOYMENT (Jobs $\times 10^3$)
Fisheries	1°	Commercial Fishing	855	18
		Canned and Cured Seafoods	234	2
		Prepared Fresh or Frozen Fish and Seafoods	1,187	8
	2°	Miscellaneous Livestock	250	11
		Agricultural, Forestry, Fishery Services	1,457	45
Shipbuilding	1°	Ship Building and Repairing	4,872	50
		Boat Building and Repairing	735	7
	2°	Search and Navigation Equipment	6,554	35
Shipping	1°	Water Transportation	7,694	37
Water Quality	2°	Water Supply and Sewerage Systems	878	4
Tourism	2°	Eating and Drinking	38,993	1,042
		Hotels and Lodging Places	18,563	265
		Amusement and Recreation Services	5,413	171
Real Estate	2°	Real Estate	146,250	619
TOTALS			233,935	2,314

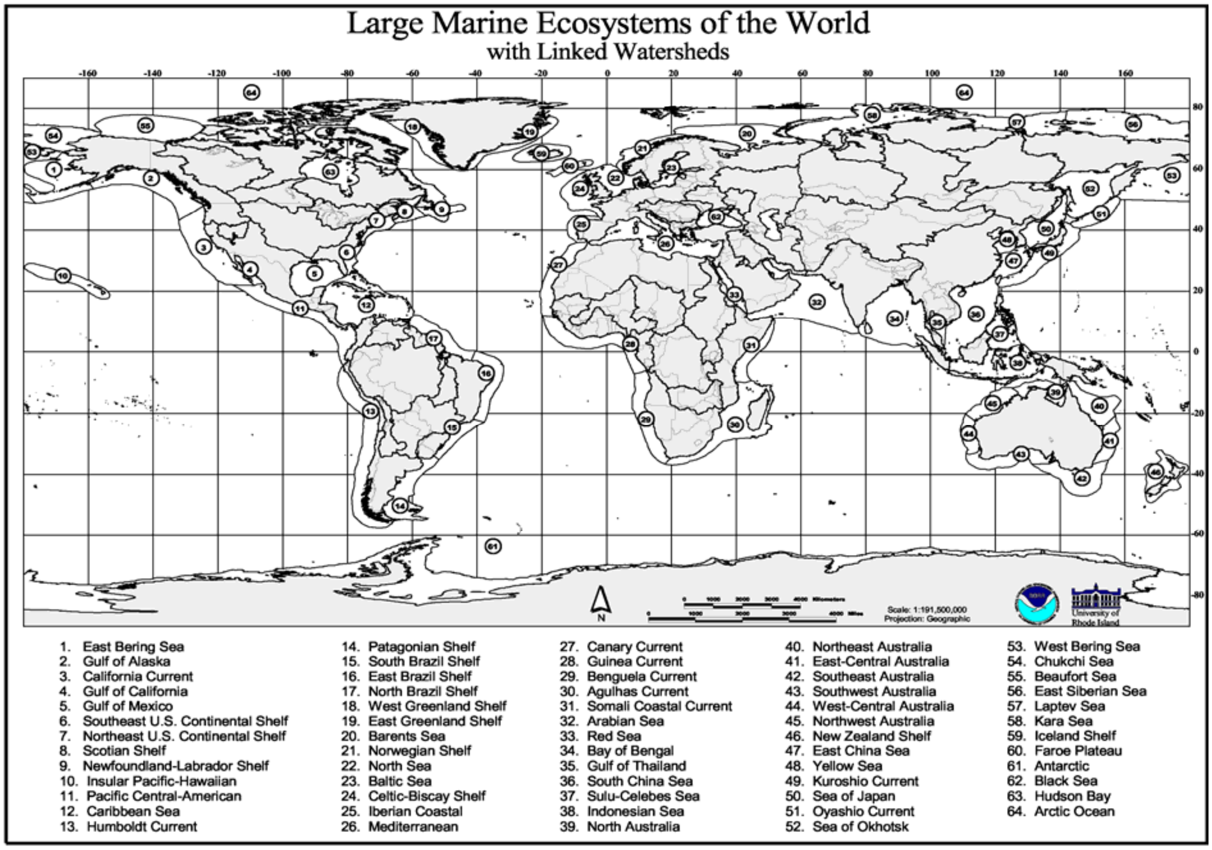


Figure 1. Map showing 64 large marine ecosystems and linked watersheds

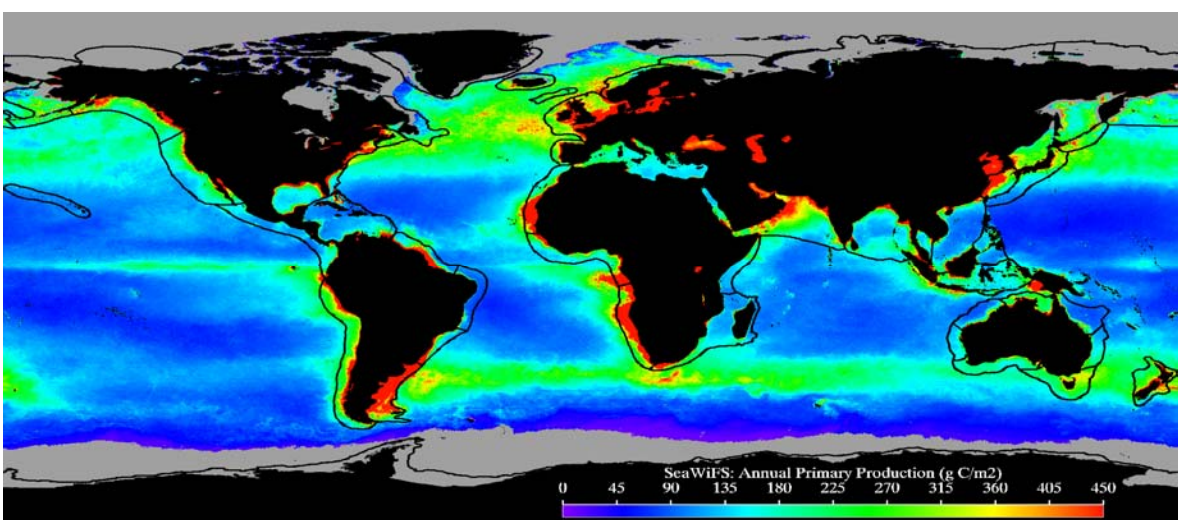


Figure 2. Global map of average primary productivity and the boundaries of the 64 Large Marine Ecosystems (LMEs) of the world, available at www.lme.noaa.gov. The annual productivity estimates are based on SeaWiFS satellite data collected between September 1998 and August 1999, and the model developed by M. Behrenfeld and P.G. Falkowski (Limnol.Oceangr. 42(1):1997,1-20). The color-enhanced image provided by Rutgers University) depicts a shaded gradient of primary productivity from a high of 450 gCm^2yr^{-1} in red to less than 45 gCm^2yr^{-1} in purple.

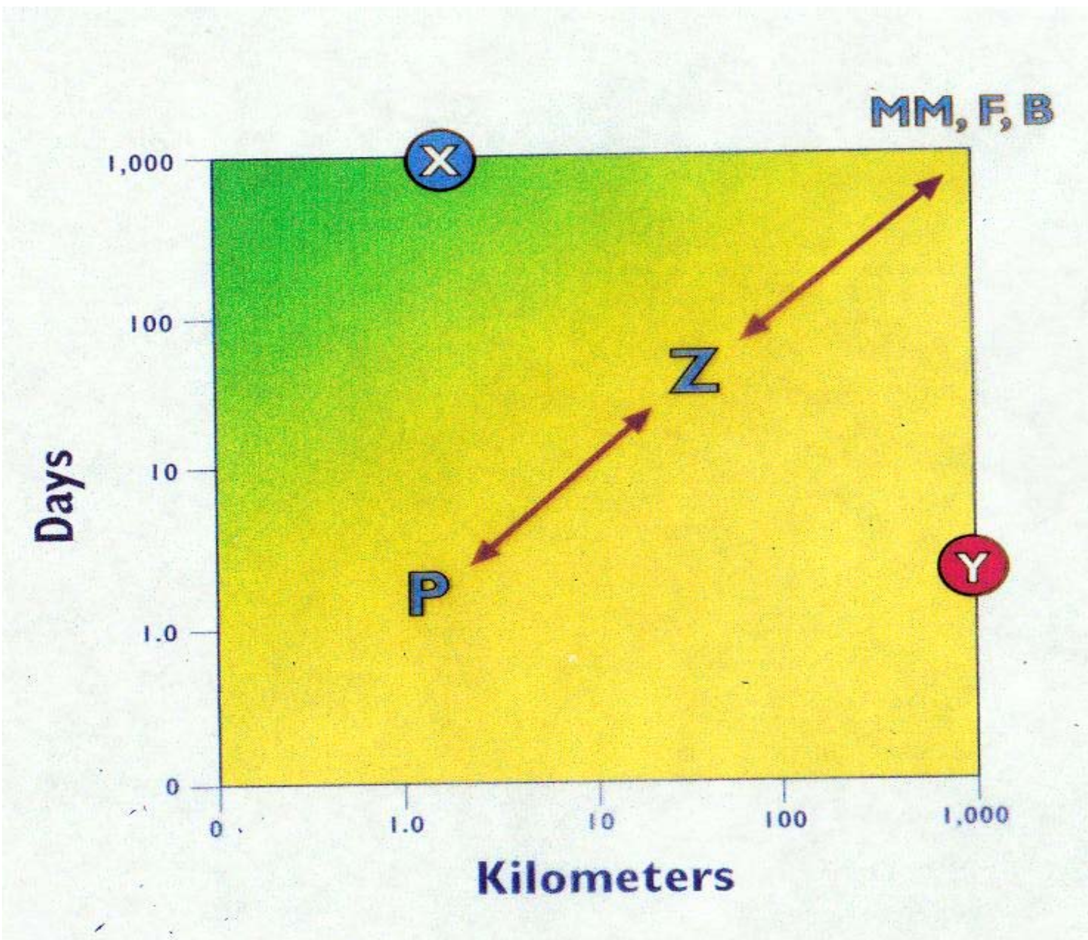


Figure 3. A simple set of scale relations for the pelagic food web. (P) Phytoplankton, (Z) zooplankton, (F) fish, (MM) marine mammals, (B) birds. Two physical processes are indicated by (X) Predictable fronts with small cross-front dimensions, and (Y) weather events occurring over relatively large scales. (Adapted from Steele 1988)

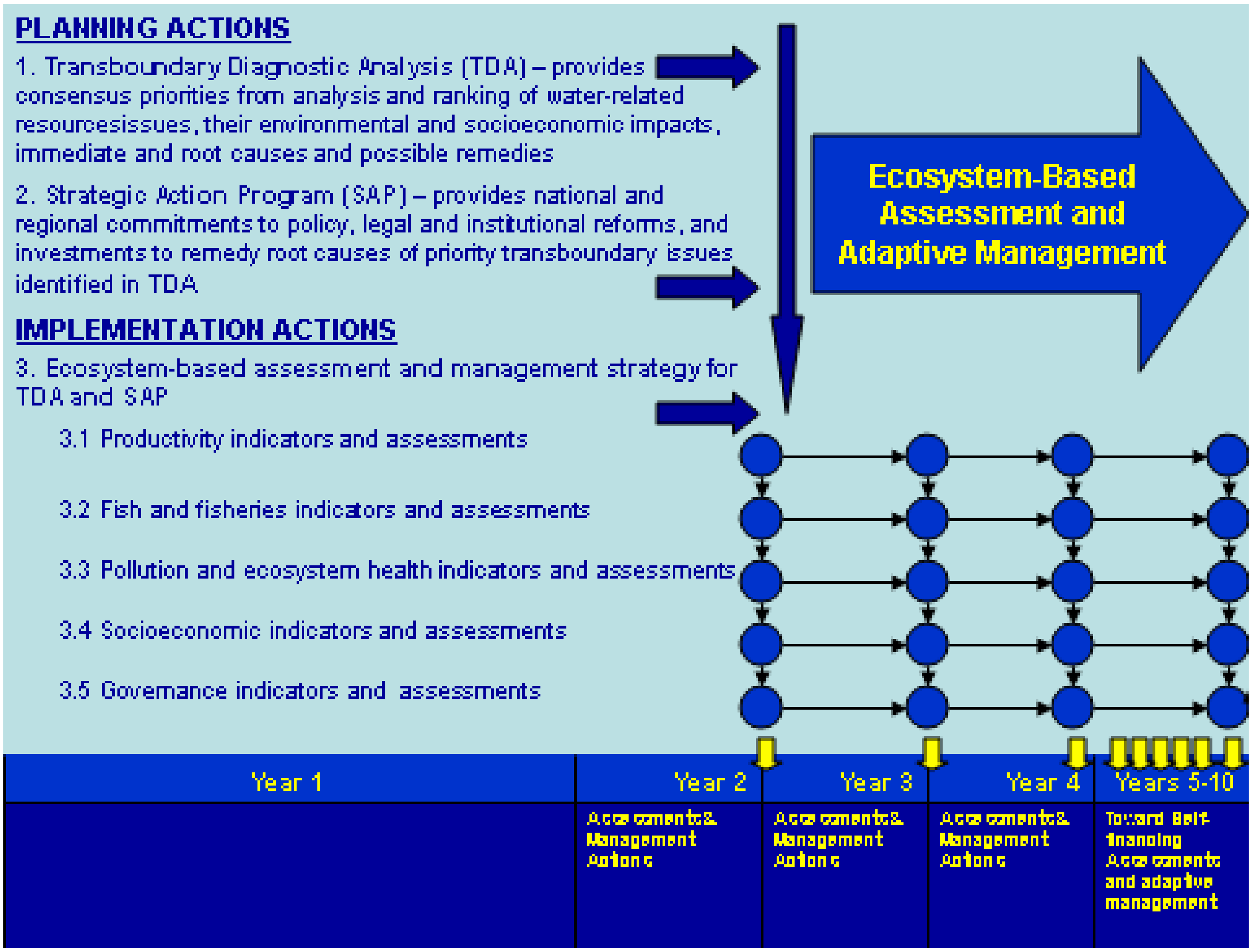


Figure 4. The LME approach: assessments and management practices incorporated through the TDA and SAP process, supported in phased, benchmarked increments, to adaptive management and self-financing sustainability for ecosystem-wide marine resources, goods, and services.

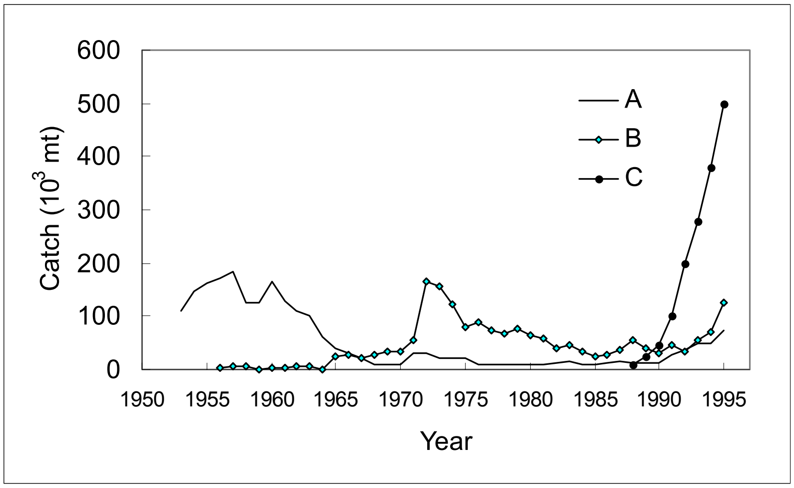


Figure 5. Annual catch of dominant species in the Yellow Sea LME: (A) small yellow croaker and hairtail, (B) Pacific herring and Japanese mackerel, and (C) anchovy and half-fin anchovy (Tang 2003).

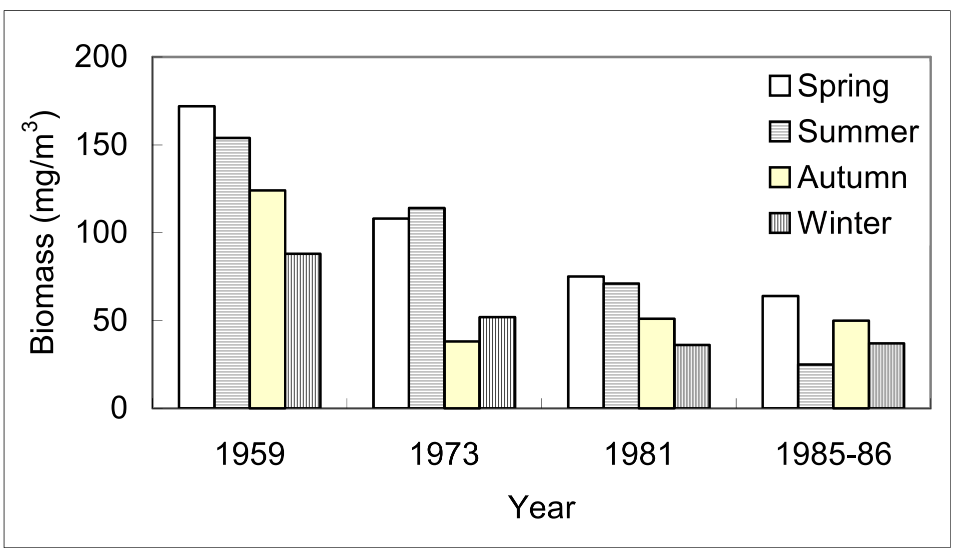


Figure 6. Changes in zooplankton biomass in the Yellow Sea.

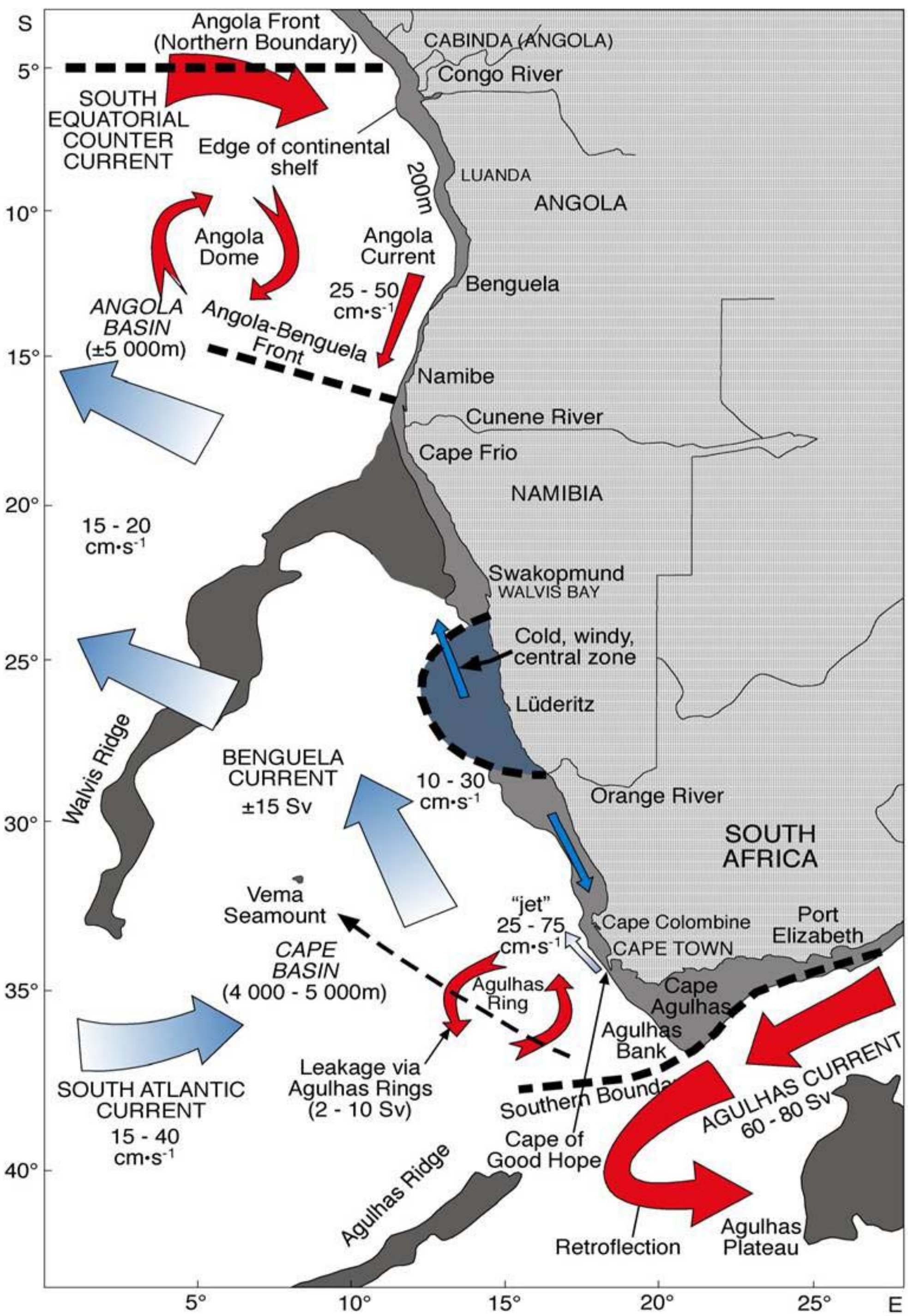


Figure 7. Map of the Benguela Current LME (O'Toole, IOC 2005)

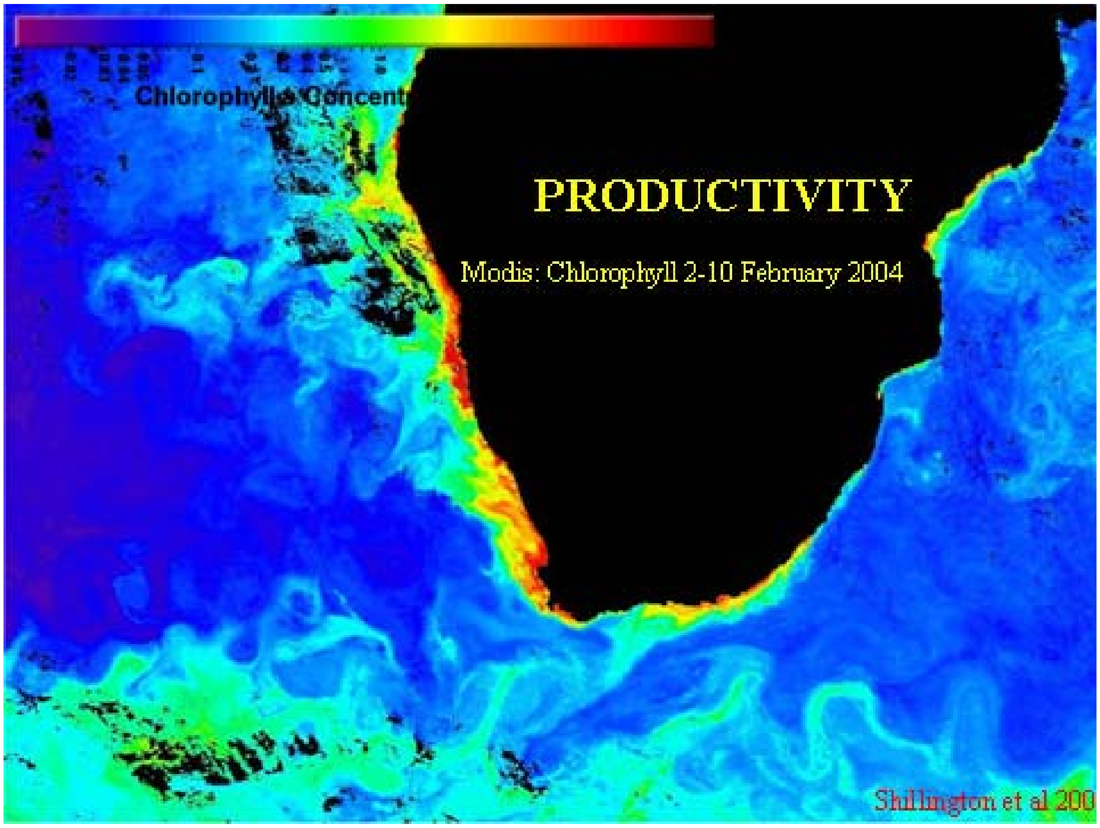


Figure 8. Benguela Current LME Productivity as measured by MODIS, February 2004. (O'Toole, IOC 2005)

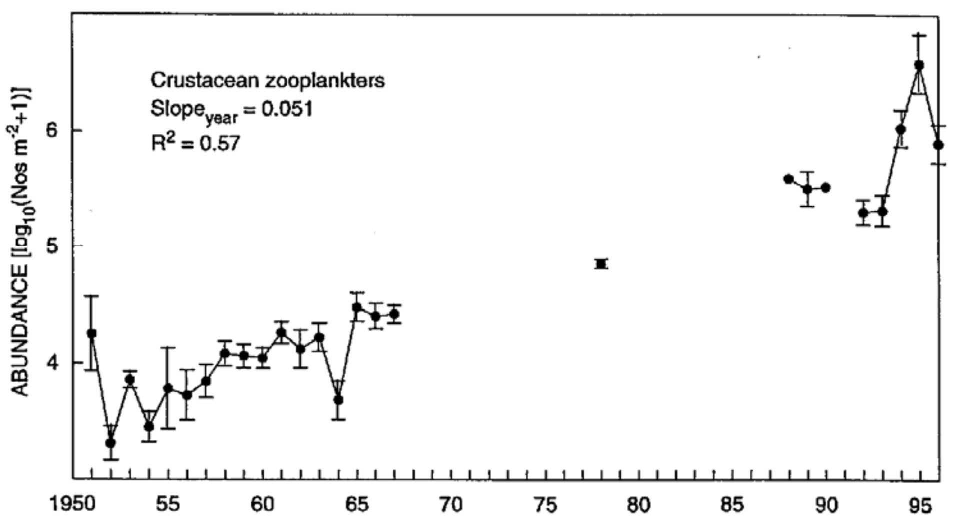


Figure 9. Change in crustacean zooplankton abundance, St. Helena Bay area (southern Benguela), March-June, 1951-1995 from Verheye et al. 1998 (ICES J. Mar.Sci. 55:803-807).

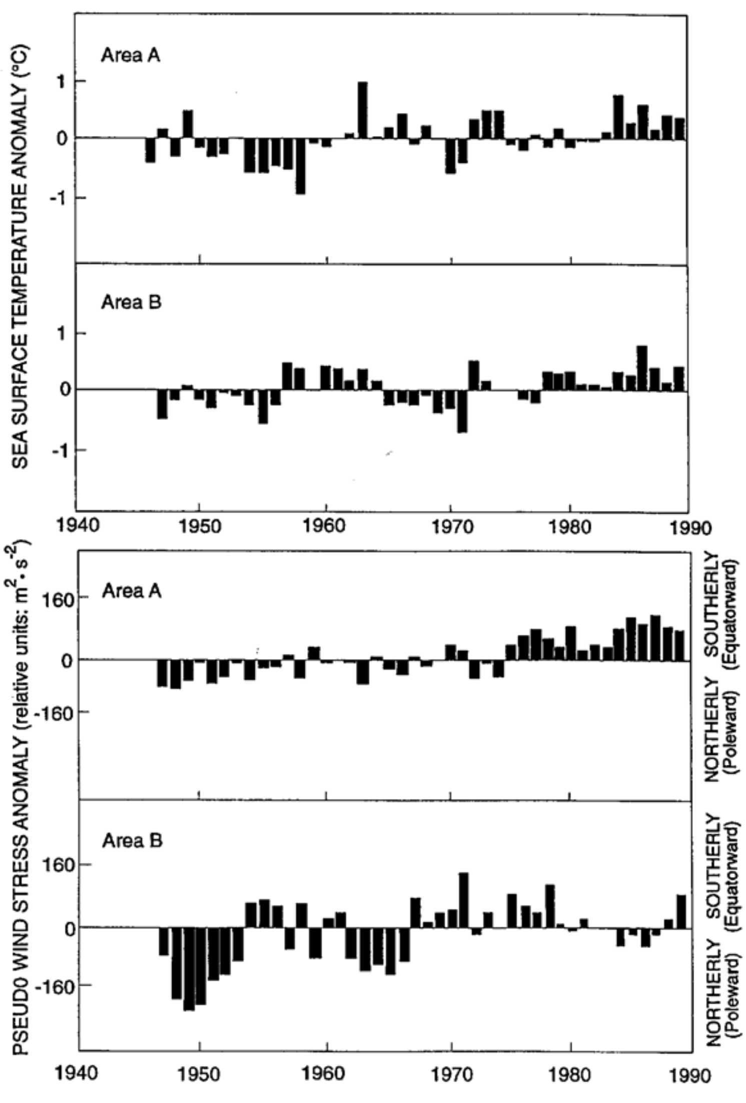


Figure 10. Sea surface temperature (°C) and pseudo windstress ($m^2 \cdot S^{-2}$) anomalies in the offshore northern Benguela and southern Benguela (from Shannon and O'Toole 2003)

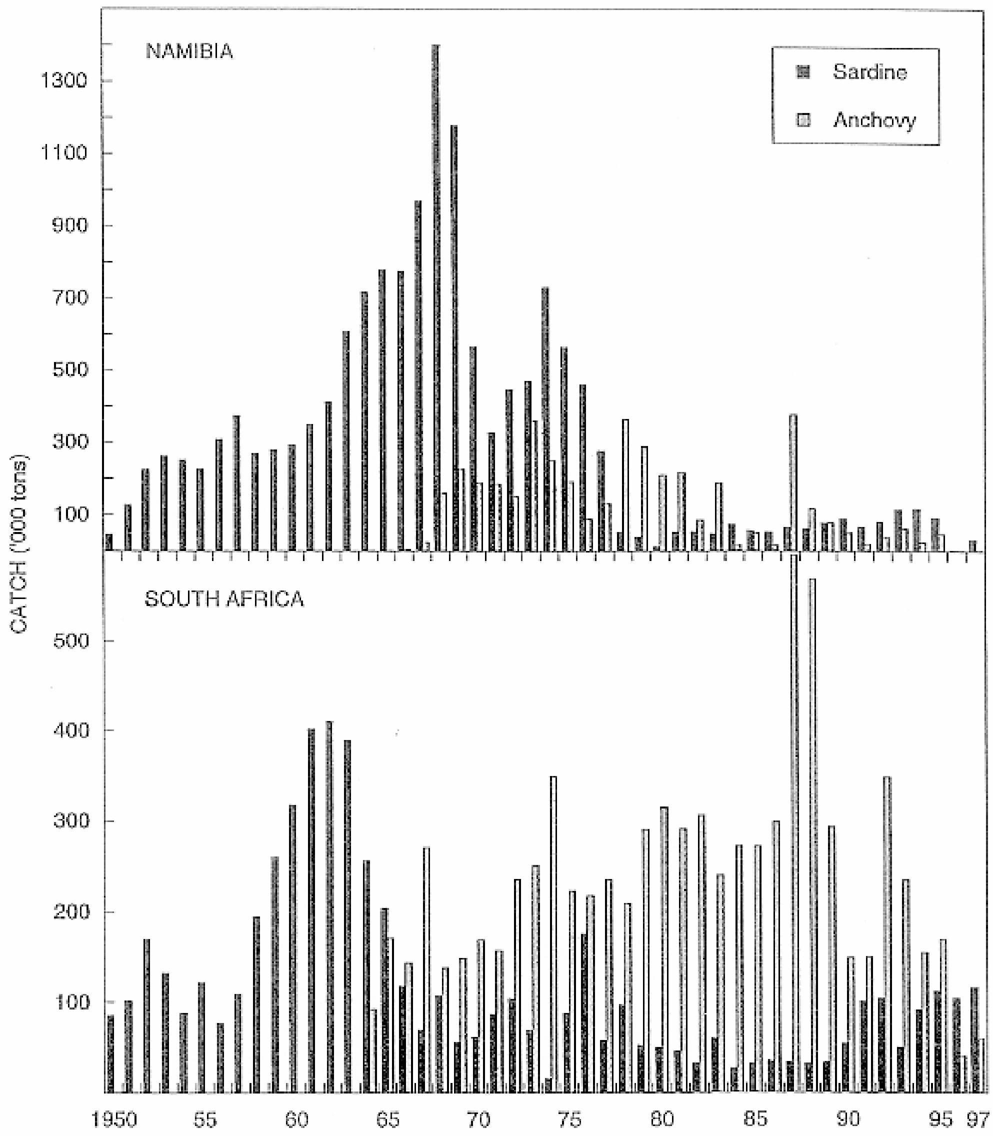


Figure 11. Sardine and anchovy catches off Namibia and South Africa, 1950-1997, modified from Crawford (1999).

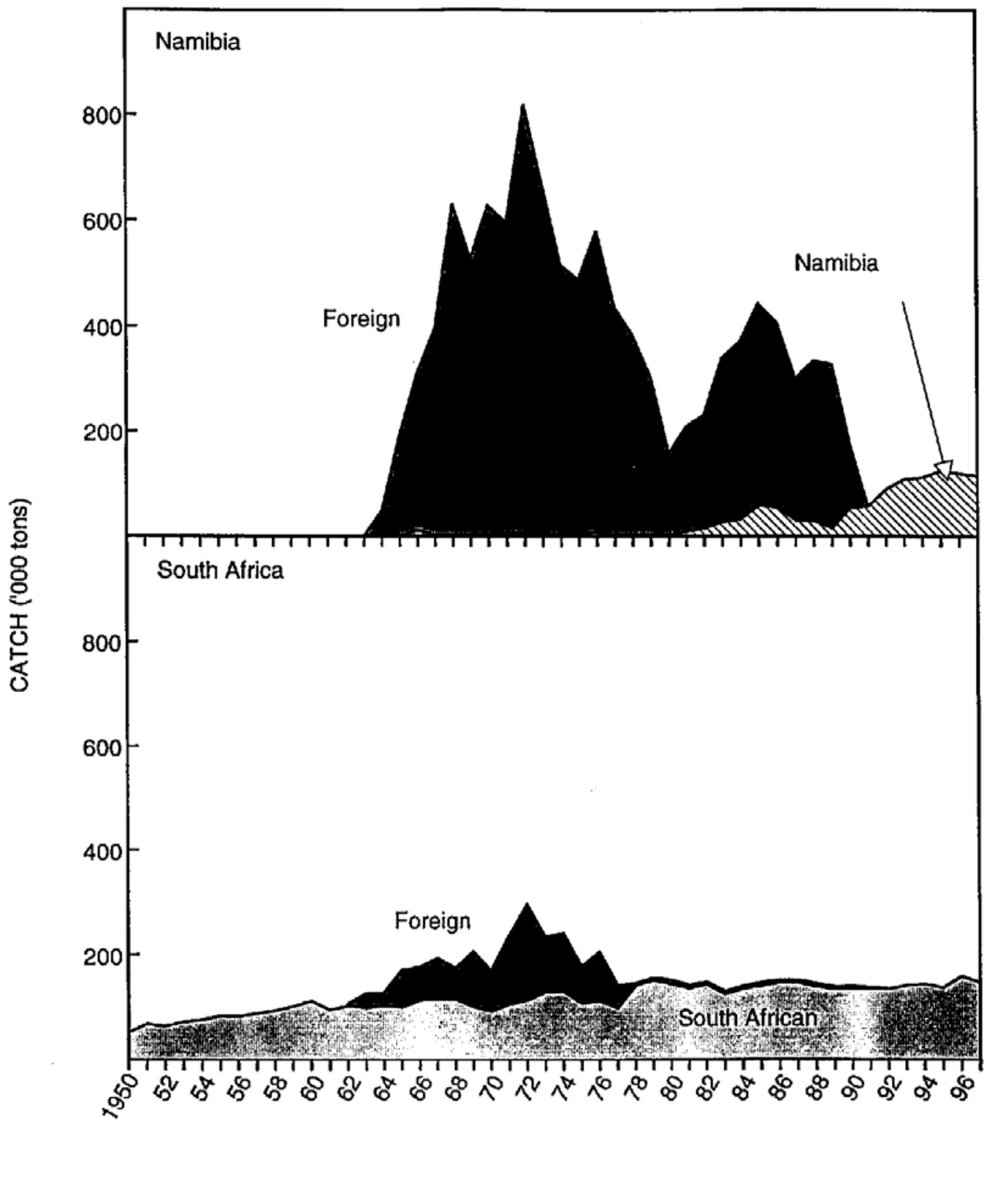


Figure 12. Catches of hakes off Namibia and South Africa from 1950. Note the extent of foreign exploitation of Namibia's resources prior to independence in 1990.(from Shannon and O'Toole 2003)

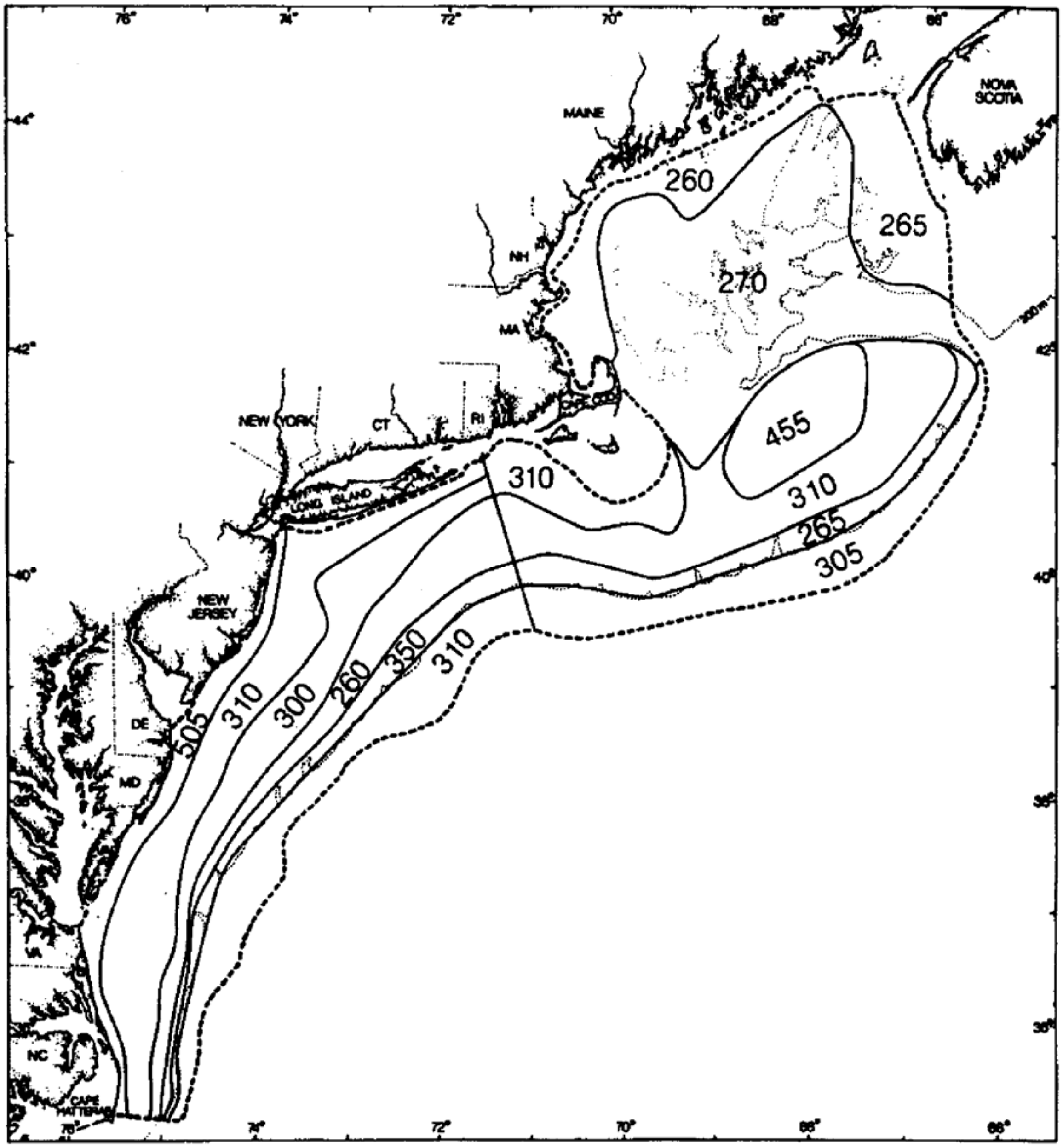


Figure 13. Map of estimated annual primary production for the Northeast Shelf LME (from Sherman 2003)

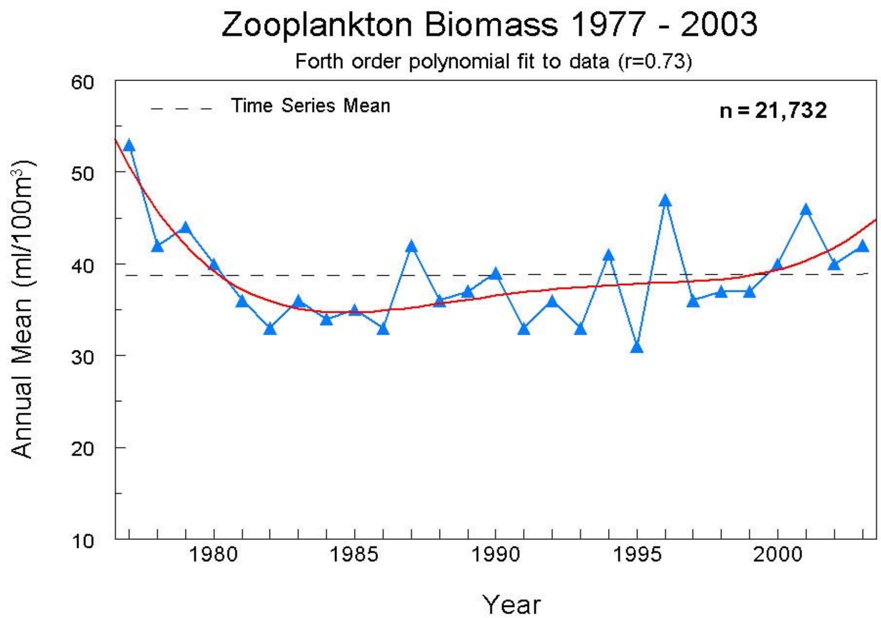


Figure 14. Northeast Shelf LME zooplankton biomass from mean annual oblique 15 minute tows , 1977 to 2002; wet displacement volume from 0.333µ mesh bongo nets.

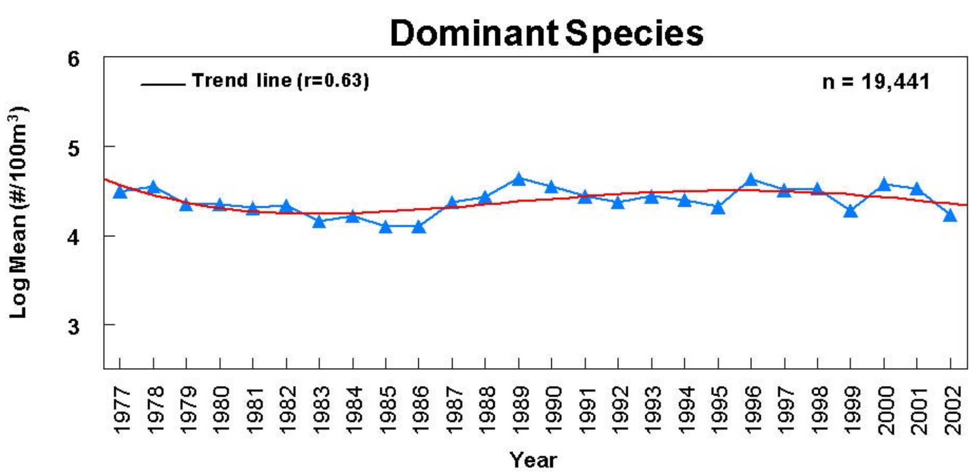


Figure 15. Northeast Shelf LME combined mean annual numbers of three dominant zooplankton species (*Calanus finmarchicus*, *Pseudocalanus* spp, and *Centropages typicus* (courtesy J. Kane, NOAA Fisheries, Narragansett Laboratory).

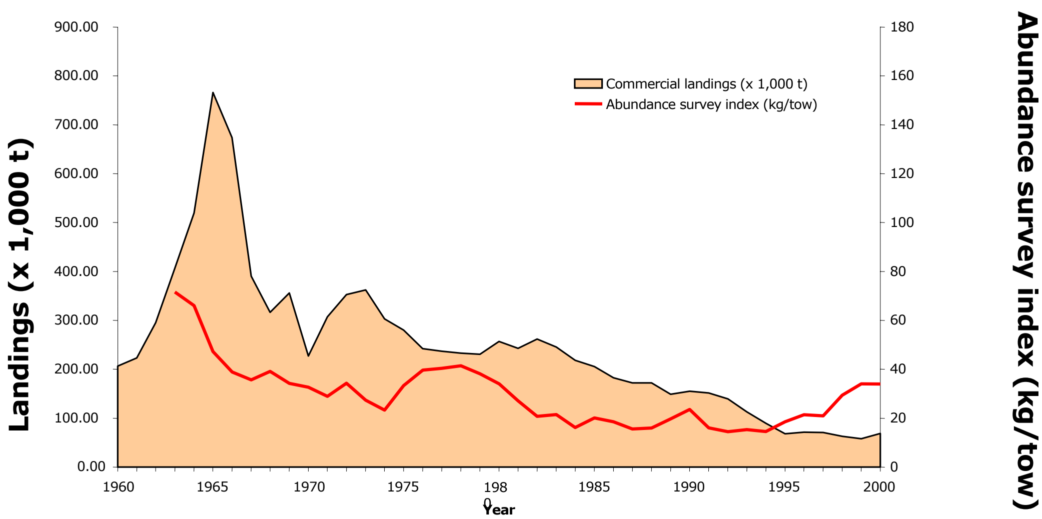
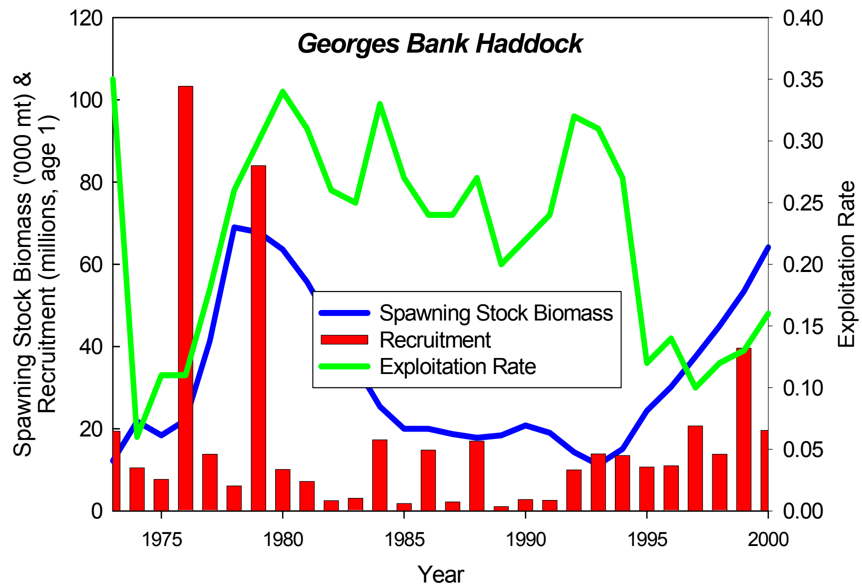


Figure 16. Northeast Shelf LME landings in metric tons (t) and abundance index of principal groundfish and flounders, 1960-2000 (from Sherman et al. 2003).



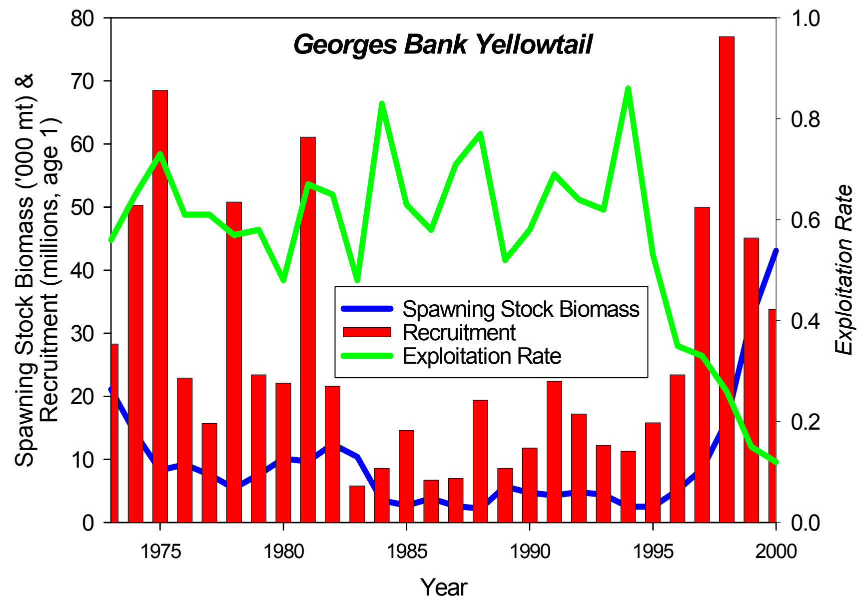
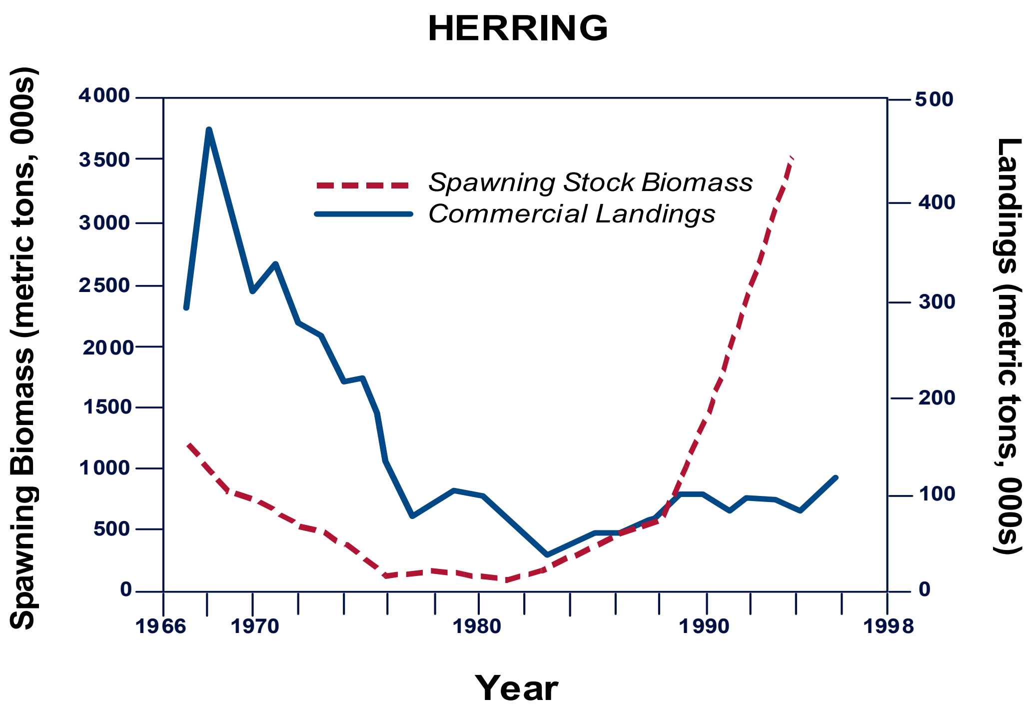


Figure 17. Increase in biomass of the Northeast Shelf LME, Georges Bank sub-area yellowtail flounder and haddock following reduction in fishing effort (exploitation rate) (from Sherman et al. 2003).



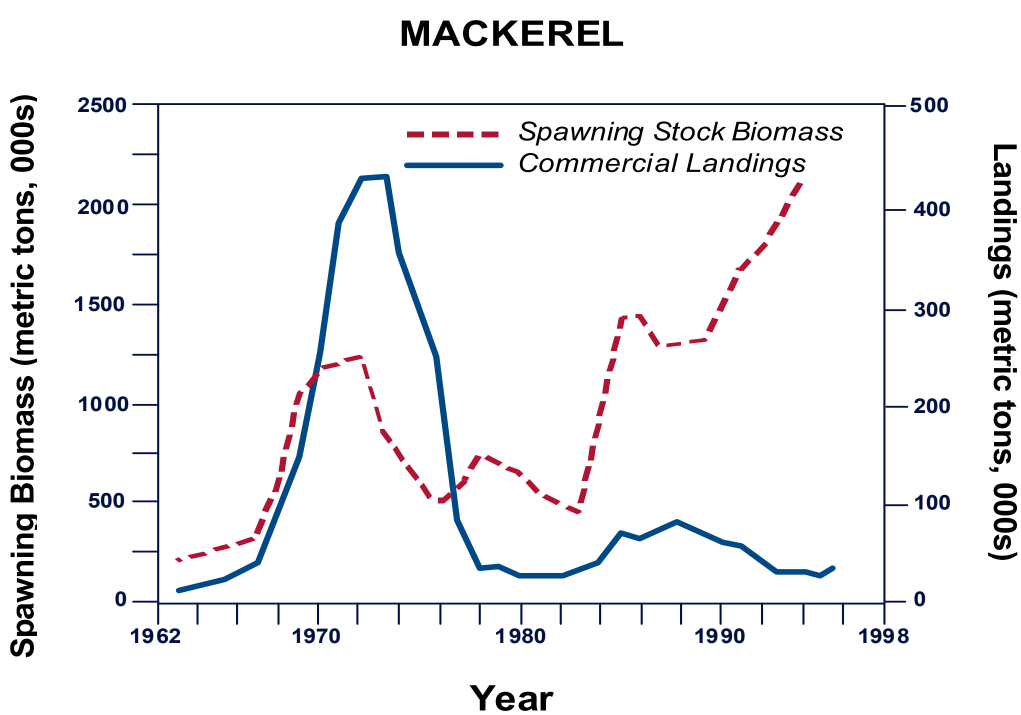


Figure 18. Top – Atlantic herring commercial l andings and spawning stock biomass, 1967 through 1996 (thousand metric tons). Bottom – Atlantic mackerel landings and spawning stock biomass, 1963 through 1996 (thousand metric tons).

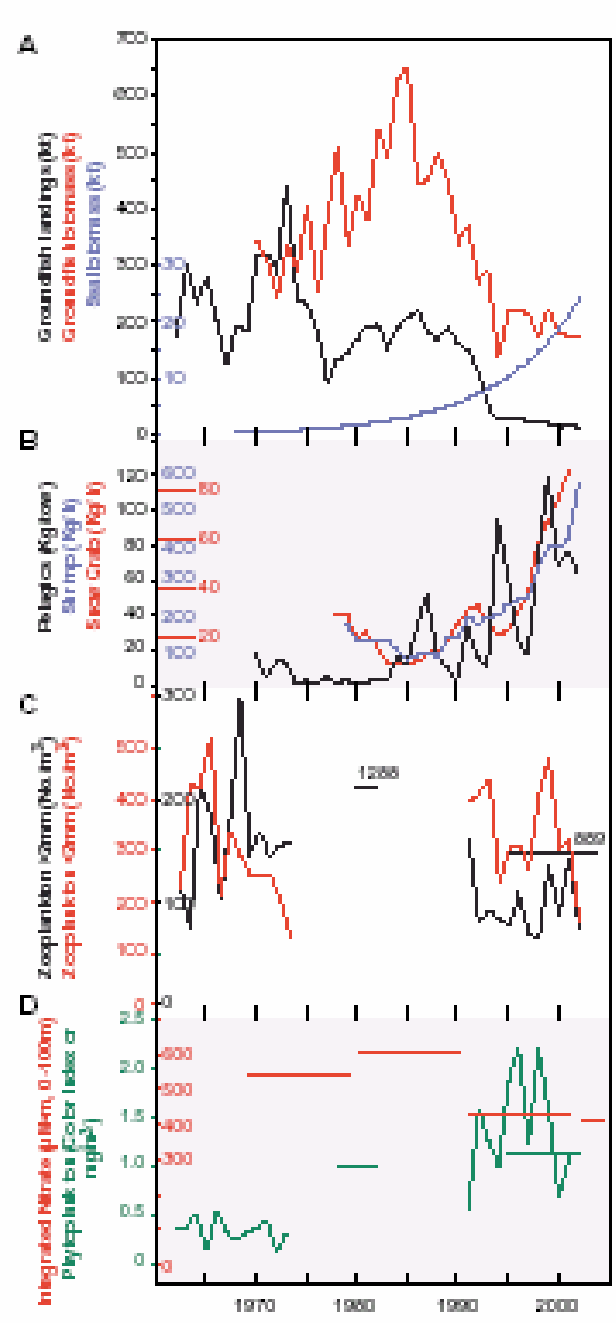


Figure 19. Illustration of a trophic cascade on the eastern Scotian Shelf across four levels and nutrients. **(A)** Commercial landings of benthic fish species, fishery-independent survey estimates of benthic fish, and population biomass estimates of grey seals. **(B)** The forage base of benthic fish species (and seals) including small pelagic fish species and benthic macroinvertebrates. **(C)** Large (>2mm) zooplankton combined abundance of copepodite and adult stages of Calanus finmarchicus, C. glacialis, and C. hyperboreous; small zooplankton, represented by the combined abundance of Calanoid copepods (28 species) other than Calanus sp. With body lengths < 2 mm, and large Calanus sp. (average number per m3) from two ancillary sampling programs shown as horizontal lines. (D) Phytoplankton color, 0 to 50 m average in situ chlorophyll (mg chlorophyll/m^3), shown as horizontal lines, and 0 to 100 m integrated, dissolved nitrate (from Frank et al. 2005).

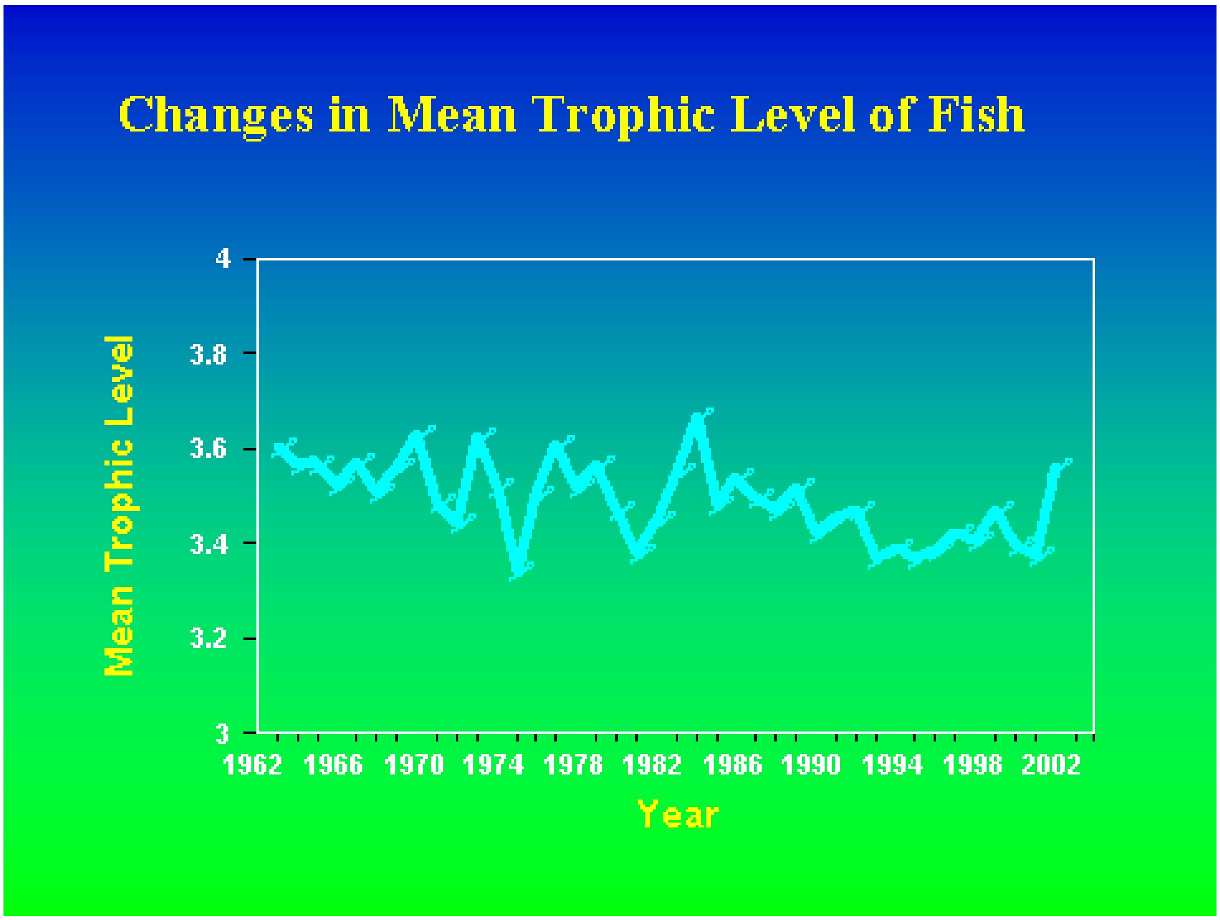
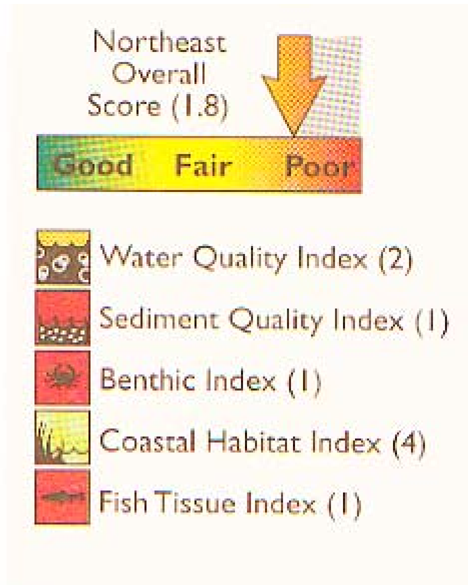


Figure 20. Mean annual trophic levels fish yields for the Northeast Shelf LME, 1962-2002 (Courtesy of M. Fogarty, NOAA Fisheries Northeast Fisheries Science Center, Woods Hole Laboratory).



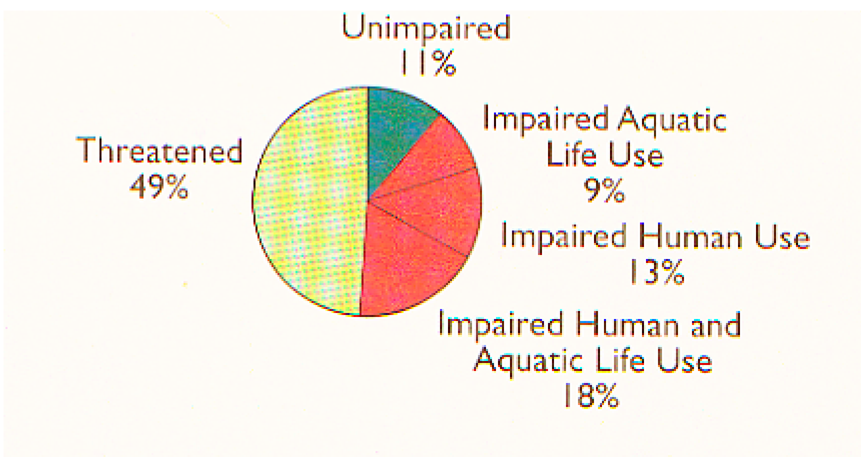


Figure 21. Northeast Shelf LME estuarine condition (adapted from EPA 2004).