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Toward ecosystem-based management (EBM) of the world's large marine ecosystems during climate change

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ABSTRACT

The approach to the assessment and management of Large Marine Ecosystems (LMEs) has been the subject of a series of seminal symposia convened at the annual meetings of the American Association for the Advancement of Science. Since 1995, a five module approach to ecosystem-based management (EBM) of LMEs has been the focus of 110 economically developing countries around the globe engaged in 22 LMEs. A sum of $3.1 billion in financial assistance from the Global Environment Facility and the World Bank has been provided to support this global movement towards recovery and sustainability of LME goods and services in partnership with several OECD countries, five UN agencies, and two NGOs. LME stressors of prime concern are nutrient over-enrichment and climate warming stress from projected levels of reduced primary productivity in LMEs located between 30°N and 30°S. Successful mitigation actions for reducing nutrient over-enrichment in LMEs, and adaptive precautionary actions for protecting fish and fisheries in LMEs in the high-risk circumglobal belt are addressed. The paper concludes with comments on the unity of approach in the linking of science and policy in advancing toward sustainability of the world's LMEs in accordance with Rio+20 goals.

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1. Introduction

The coastal oceans along the margins of Africa, Asia, Latin America, North America, and Europe are being stressed by overfishing, pollution, habitat losses, nutrient over-enrichment, acidification, and biodiversity loss. While much has been reported on these degraded conditions of coastal oceans (Doney, 2010; Hoegh-Guldberg and Bruno, 2010; Lubchenco and Petes, 2010; Hollowed et al., 2013), comparatively little is known of global movement towards recovery and sustainability of coastal ocean goods and services. Support for improving conditions of coastal ocean ecosystems has been advocated by an international community of political leaders who have put forward during the past 22 years statements of commitment to improve degraded conditions of the global environment at three world summits—the United Nations Conference on Environment and Development (UNCED) convened in Rio de Janeiro in 1992 (UNCED, 1992), the World Summit on Sustainable Development (WSSD) in Johannesburg in 2002 (WSSD, 2002), and the 2012 UN Conference on Sustainable Development known as RIO+20 (RIO+20, 2012). Goal statements from the UN summits, supporting actions for protecting and sustaining oceans and ocean resources including marine ecosystems, are summarized in Table 1.

During the 22-year UNCED—WSSD—RIO+20 period, the movement towards ecosystem-based sustainability and management of coastal ocean goods and services was accelerating in the U.S. and other countries. In 1994 the U.S. Congress was briefed on an initiative of the Ecological Society of America on the science supporting ecosystem-based management including a multisectoral and multidisciplinary approach for sustaining the production potential of ecosystem goods and services by implementing a paradigm shift from individual species to ecosystems and small spatial scales to multiple scales, and short-term to long-term perspectives of adaptive management (Lubchenco, 1994)

Table 1
Agreed-upon goals for sustainable development of the oceans from three global environmental summits, 1992–2012.

United Nations Conference on Environment & Development, Rio de Janerio, Brazil, 3–14 June 1992, AGENDA 21, Chapter 17, Protection of the oceans, seas, coastal areas and the protection, rational use and development of their living resources: Coastal States commit themselves to:	
17.22	Prevent, reduce and control degradation of the marine environment so as to maintain and improve its life-support and productive capacities
17.46	Develop and increase the potential of marine living resources to meet human nutritional needs, as well as social, economic and development goals
17.5	Integrated management and sustainable development of coastal areas and the marine environment under their national jurisdiction
World Summit on Sustainable Development, Johannesburg, 26 August to 4 September 2002. Nations commit to:	
30d	Encourage the application by 2010 of the ecosystem approach, noting the Reykjavik Declaration on Responsible Fisheries in the Marine Ecosystem and decision V/6 of the Conference of Parties to the Convention on Biological Diversity
33d	Make every effort to achieve substantial progress by the next Global Programme of Action Conference in 2006 to protect the marine environment from land-based activities
32c	Develop and facilitate the use of diverse approaches and tools, including the ecosystem approach, the elimination of destructive fishing practices, the establishment of marine protected areas consistent with international law and based on scientific information, including representative networks by 2012
31a	Maintain or restore [fisheries] stocks to levels that can produce the maximum sustainable yield with the aim of achieving these goals for depleted stocks on an urgent basis and where possible not later than 2015
United Nations Conference on Sustainable Development, Rio de Janeiro, 20–22 June 2012.	
Paragraph 158	We therefore commit to protect and restore, the health, productivity and resilience of oceans and marine ecosystems, and to maintain their biodiversity, enabling their conservation and sustainable use for present and future generations Effectively apply an ecosystem approach and the precautionary approach in the management, in accordance with international law, of activities having an impact on the marine environment.

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Table 2
Paradigm shift to ecosystem-based management (Lubchenco, 1994)

FROM	TO
Individual species	Ecosystems
Small spatial scale	Multiple scales
Short-term perspective	Long-term perspective
Humans: independent of ecosystems	Humans: integral part of ecosystems
Management divorced from research	Adaptive management
Managing commodities	Sustaining production potential for goods and services

(Table 2). A decade earlier a movement toward ecosystem-based management was advanced at the 1984 annual meeting of the American Association for the Advancement of Science (AAAS) with a symposium on the variability and management of large marine ecosystems (LMEs). The presentations on LME assessment and management were multisectoral considering effects of changing conditions in environment, fisheries, pollution, and habitat through the multidisciplinary expertise of scientists, lawyers, economists, and marine policy specialists focused on sustaining the resources of LMEs as regional management units. The papers presented were peer-reviewed and published as a selected AAAS Symposium volume in 1986 (Sherman and Alexander 1986). Twenty-four years later, the ecosystem-based management (EBM) approach to the assessment and management of LMEs became national policy. The White House Council on Environmental Quality issued the Final Recommendations of the Interagency Ocean Policy Task Force on July 19, 2010 calling for coastal ocean protection and sustainability by applying an ecosystem-based approach to assessment and management of coastal and marine resources (Lubchenco and Sutley 2010). The EBM approach became official U.S. policy through Executive Order in 2010 (Executive Order, 2010).

2. Large Marine Ecosystems are defined by nature, not politics

The world's LMEs are relatively large regions of coastal water on the order of 200,000 km^2 or greater defined by ecological criteria including bathymetry, hydrography, productivity, and trophically linked populations (Sherman, 1991, 1994; Sherman and Alexander, 1994). On a global scale, 64 LMEs produce 80% of the world's annual marine fisheries biomass yield (Pauly and Alder et al., 2008). Most of the effects of coastal ocean stressors occur within the boundaries of LMEs as they are regions of ocean space encompassing stressed coastal areas from river basins and estuaries to the seaward boundaries of continental shelves and the outer margins of major coastal currents or enclosed or semi-enclosed seas (Fig. 1).

The LME approach to EBM applies five modules of indicators of changes in ecosystem (i) productivity, (ii) fish and fisheries, (iii) pollution and ecosystem health, (iv) socioeconomics, and (v) governance to support management practices directed to recovery and sustainability of LME goods and services. The approach supports EBM by strengthening the emerging effort to relate place-based ecosystem assessments to the management of coastal ocean resources within the natural boundaries of LMEs (Wang, 2004). The LME approach is steadily becoming a preferred method for advancing EBM. In 2005, a group of 221 marine experts including scientists and policy professionals compared the advantages of EBM to the research, assessment and management of marine resources with a sector-by-sector approach. In a consensus statement they agreed that LMEs are the appropriate spatial scale for applying EBM practices (McLeod et al., 2005).

Within the span of 20 years, 1986 through 2006, marine scientists and other marine specialists (e.g., economists, lawyers, scientists and policy experts) produced 6000 pages of peer reviewed studies of LMEs published in 14 LME volumes (Fig. 2). Among economically developing nations the LME approach, since the mid-1990s, has evolved into a global movement toward EBM practice. With substantial financial support from the Global Environment Facility (GEF), the World Bank, and OECD (Organization for Economic Cooperation and Development) country donors, $3.1 billion has been

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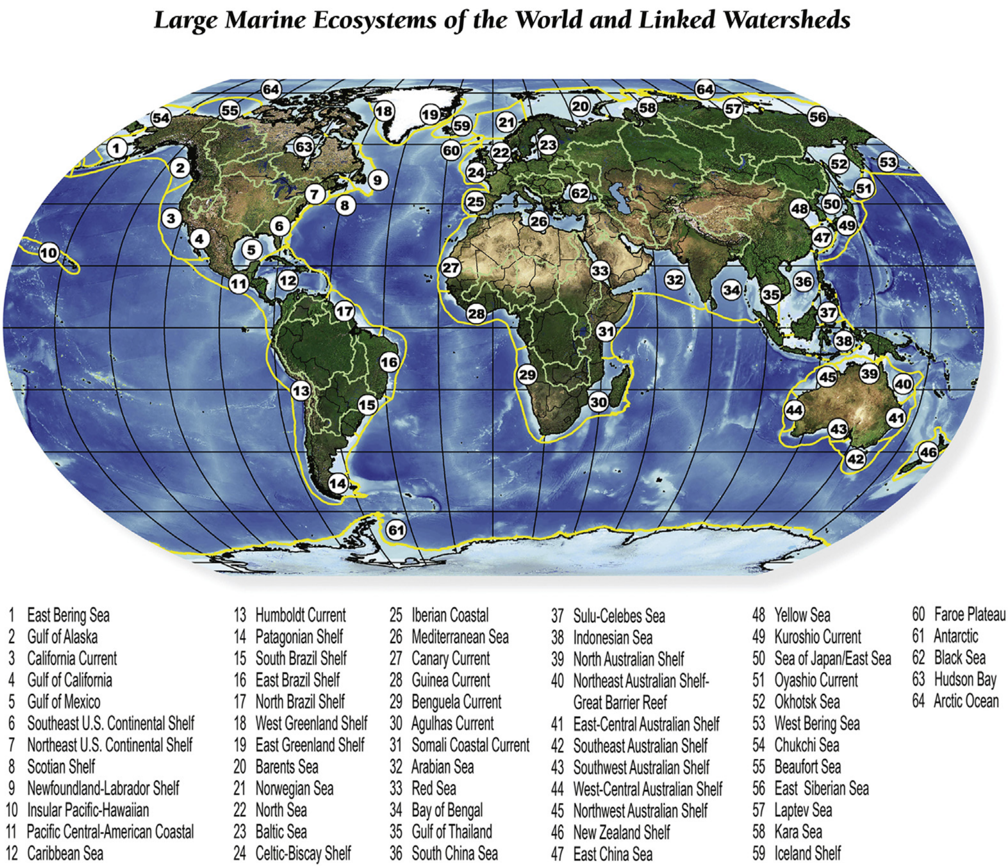

Fig. 1. Map of the 64 LMEs of the world and their linked watersheds.

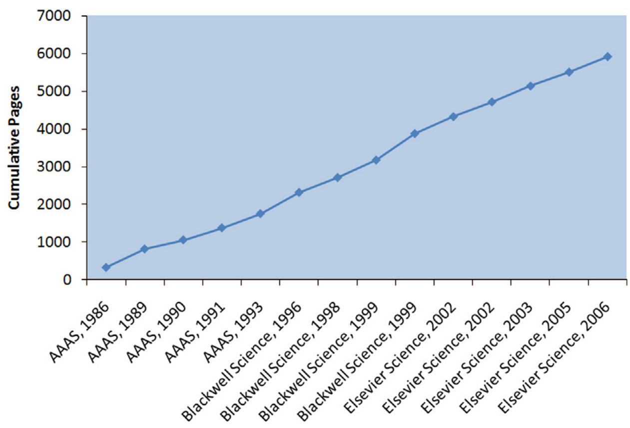

Fig. 2. Seminal LME volumes published between 1986 and 2006. Publishers and publication dates are listed along the horizontal axis, and cumulative numbers of pages are plotted along the vertical axis. Volume titles, chapters, and authors are listed in the LME program website, www.lme.noaa.gov.

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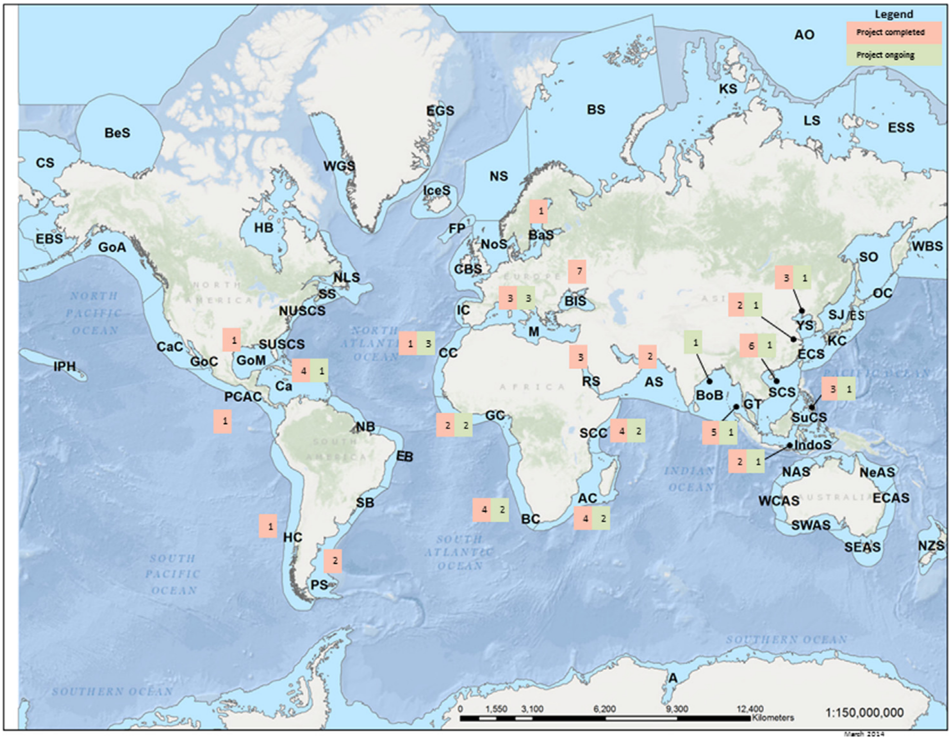

EBS: East Bering Sea
GoA: Gulf of Alaska
CaC : California Current
GoM: Gulf of Mexico
SUSCS: Southeast US Continental Shelf
NUSCS: Northeast US Continental Shelf
SS: Scotian Shelf
NLS: Newfoundland–Labrador Shelf
IPH: Insular Pacific-Hawaiian
PCAC: Pacific Central-American Coastal
CbS: Caribbean Sea
HC: Humboldt Current
PS: Patagonian Shelf
SB: South Brazil Shelf
EB: East Brazil Shelf
NB: North Brazil Shelf
WGS: West Greenland Shelf
EGS: East Greenland Shelf
BS: Barents Sea
NS: Norwegian Sea
NoS: North Sea

BaS: Baltic Sea
CBC: Celtic-Biscay Shelf
IC: Iberian Coastal
M: Mediterranean
CC: Canary Current
GC: Guinea Current
BC: Benguela Current
AC: Agulhas Current
SCC: Somali Coastal Current
AS: Arabian Sea
RS: Red Sea
BoB: Bay of Bengal
GT: Gulf of Thailand
SC: South China Sea
SuCS: Sulu-Celebes Sea
IndoS: Indonesian Sea
NA: North Australian Shelf
NeA: Northeast Australian Shelf
ECAS: East-Central Australian Shelf
SEAS: Southeast Australian Shelf
SWAS: Southwest Australian Shelf

WCS: West-Central Australian Shelf
NAS: Northwest Australian Shelf
NZS: New Zealand Shelf
ECS: East China Sea
YS: Yellow Sea
KC: Kuroshio Current
SJ: Sea of Japan / East Sea
OC: Oyashio Current
SO: Sea of Okhotsk
WBS: West Being Sea
CS: Chukchi Seas
BeS: Beaufort Sea
ESS: East Siberian Sea
LS: Laptev Sea
KS: Kara Sea
IceS: Iceland Shelf
FP: Faroe Plateau
A: Antarctica
B: Black Sea
HB: Hudson Bay
AO: Arctic Ocean

Fig. 3. Global Environment Facility (GEF) funded Projects since 1994 in 22 LMEs totaling $3.15 billion USD in project financial support. The LMEs with funded projects are listed in bold in the legend.

made available in grants and investment funds to 110 countries in Africa, Asia, Latin America, the Pacific, and eastern Europe to protect, sustain, and manage the goods and services of 22 LMEs (Duda and Sherman, 2002; Hume and Duda, 2012) (Fig. 3).

In recognition of the growing need for mitigating the effects of global scale environmental degradation, the GEF was established in 1991 to test and evaluate innovative approaches to respond to challenges of climate change, biodiversity conservation, ozone depletion and stressors on international waters. In 1994, following the commitment to UNCED Agenda 21 goals, the GEF was transformed from a pilot stage to a permanent financial mechanism, empowered with a multibillion

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dollar trust fund contributed by an international community of over 100 countries (Duda and Sherman, 2002). The GEF Council in 1995 issued its Operational Strategy on the use of GEF funding of international waters issues (GEF, 1995), using the ocean goals stated in Chapter 17 of UNCED Agenda 21. The Council included LMEs in its Operational Strategy as global management units for reversing the decline in socioeconomic benefits of large international waters coastal systems (Duda, 2005).

The GEF-supported LME projects are provided with scientific and technical support from five United Nations agencies (UNDP, UNEP, UNIDO, FAO, and IOC-UNESCO), the International Council for the Exploration of the Sea (ICES), donor countries and institutions including NOAA (U.S.), Institute of Marine Research (IMR Bergen, Norway), the German Marine Research Consortium (KDM—the Centre for Tropical Marine Ecologie (ZMT) in Bremen and the Leibnitz Centre for Tropical Marine Ecology), the Swedish International Development Cooperation Agency (SIDA), the Icelandic International Development Agency (ICEIDA), and two non-governmental organizations (WWF, IUCN). The 110 countries that have received since 1994 GEF financial support in the planning and implementation of LME projects based on EBM are listed in Table 3.

3. The Five modules assessment and management LME strategy

The five module assessment and management LME strategy links natural science assessment metrics with the human dimension of social science based management principles leading to EBM practice. The modules include suites of indicators of changing conditions of LMEs.

3.1. Productivity module

Primary productivity (g cm^2/yr^{-1}) drives the trophodynamics of the LME and can be related to the carrying capacity of marine ecosystems in relation to supporting fish resources (Pauly and Christensen, 1995; Christensen et al., 2009). Measurements of ecosystem primary productivity are also useful indicators of the growing eutrophication problem leading to an increase in the frequency and extent of dead zones in coastal waters around the globe (Diaz and Rosenberg, 2008). In several LMEs, excessive nutrient loadings have produced harmful algal blooms implicated in mass mortalities of marine resource species, emergence of pathogens (e.g., cholera, vibrios, red tides, and paralytic shellfish toxins) and population explosions of invasive species (Epstein, 2000; Sherman, 2000). Biogeochemical constituents used as indicators of changing conditions are photosynthetically active radiation, water column transparency, chlorophyll *a*, primary production, zooplankton biomass, species biodiversity, ichthyoplankton biodiversity, oceanographic variability (e.g., temperature, salinity, density, circulation, and nutrient flux) (Sherman, 1980; Sherman et al., 1998, 2009;) and acidification (Oliver et al., 2012). Plankton can be measured over decadal time scales by deploying Continuous Plankton Recorder (CPR) systems monthly across LMEs from commercial vessels of opportunity (Batten et al., 2003; Jossi et al. 2003, 2013). Advanced plankton samplers can be fitted with electronic sensors for temperature, salinity, chlorophyll, nutrients, oxygen, and light (Melrose et al., 2006). Application of satellite derived data coupled to appropriate algorithms will allow for time-series visualizations of LME-scale sea surface temperature, hydrographic fronts, chlorophyll concentrations, and primary productivity estimates (Sherman et al., 2011).

3.2. Fish and fisheries module

The LME module for fish and fisheries is focused on monitoring and assessing changes in the condition of capture fisheries, mariculture, environmental variability including climate change, and predator-prey dynamics within the fish community—from benthic components and plankton at the base of the ecosystem food web, to Apex predators at the top (Daskalov, 2003; Frank et al., 2005; Chassot et al. 2007; Fu et al. 2012; Link et al., 2012). During the past three decades, climate warming has been driving change in distribution and abundance of fish populations (Sherman et al., 2009; Blanchard et al., 2012; Cheung et al., 2012; Hollowed et al., 2013). The fish and fisheries module

Table 3
List of 110 countries that have received GEF support since 1994 for LME projects based on EBM practices to recover and sustain depleted fisheries, restore degraded habitats, conserve biodiversity, control nutrient over-enrichment and other ocean pollution, and mitigate and adapt to the effects of acidification and climate change.

List of LME projects and countries funded by the GEF ($3.15B)			
LME	***Country***	***Project name***	***Funds in US$ millions***
Agulhas Current; Somali Coastal Current	Comoros; Kenya; Madagascar; Mauritius; Mozambique; Seychelles; South Africa; Tanzania United Republic of	Programme for the Agulhas and Somali Current Large Marine Ecosystems: Agulhas and Somali Current Large Marine Ecosystems Project	30.463
Agulhas Current; Benguela Current; Canary Current; Guinea Current; Somali Coastal Current	Targets: Canary Current (West Africa), Guinea Current (Gulf of Guinea), Benguela Current (Namibia, Angola South Africa), Agulhas Current (South Africa, Mozambique, Comoro Islands, Seychelles, Madagascar, Mauritius), and Somali Current (Tanzania, Kenya, Somali)	Strategic Partnership for a Sustainable Fisheries Investment Fund in the Large Marine Ecosystems of Sub-Saharan Africa (Tranche 1, Installment 1)	80.073
Agulhas Current; Benguela Current; Canary Current; Guinea Current; Somali Coastal Current	Targets: Canary Current (West Africa), Guinea Current (Gulf of Guinea), Benguela Current (Namibia, Angola South Africa), Agulhas Current (South Africa, Mozambique, Comoro Islands, Seychelles, Madagascar, Mauritius), and Somali Current (Tanzania, Kenya, Somali)	Strategic Partnership for a Sustainable Fisheries Investment Fund in the Large Marine Ecosystems of Sub-Saharan Africa (Tranche 1, Installment 2)	127.240
Agulhas Current; Somali Coastal Current	Comoros; Kenya; Mozambique; South Africa; Tanzania United Republic of; Mauritius; Seychelles	Southwest Indian Ocean Fisheries Project	34.950
Agulhas Current, Indian Ocean, Somali Coastal Current	Comoros, Kenya, Madagascar, Mauritus, Mozambique, Seychelles, Tanzania, South Africa	Addressing Land-based Activities in the Western Indian Ocean	11.413
Baltic Sea	Estonia; Latvia; Lithuania; Poland; Russian Federation	Baltic Sea Regional Project, Phase I	12.450
Bay of Bengal	Bangladesh; India; Indonesia; Malaysia; Maldives; Myanmar; Sri Lanka; Thailand	Bay of Bengal Large Marine Ecosystem	28.468
Benguela Current	Angola; Namibia; South Africa	Implementation of the Strategic Action Programme (SAP) Toward Achievement of the Integrated Management of the Benguela Current Large Marine Ecosystem	38.564
Benguela Current	Angola; Namibia; South Africa	Implementation of the Benguela Current LME Action Program for Restoring Depleted Fisheries and Reducing Coastal Resources Degradation	67.167
Benguela Current	Angola; Namibia; South Africa	Distance Learning and Information Sharing Tool for the Benguela Coastal Areas	1.546
Black Sea	Bosnia and Herzegovina; Bulgaria; Croatia; Czech Republic; Hungary; Moldova Republic of; Romania; Serbia and Montenegro; Slovakia; Slovenia; Ukraine	Strengthening the Implementation Capacities for Nutrient Reduction and Transboundary Cooperation in the Danube River Basin-Phase I Project	11.950
Black Sea	Bulgaria, Croatia, Czech Rep., Hungary, Moldova, Romania, Slovakia Rep., Slovenia, Ukraine, Yugoslavia & Serbia	Strengthening the Implementation Capacities for Nutrient Reduction and Transboundary Cooperation in the Danube River Basin	24.878

Table 3 (*continued*)

List of LME projects and countries funded by the GEF ($3.15B)			
LME	***Country***	***Project name***	***Funds in US$ millions***
Black Sea	Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Georgia, Hungary, Moldova Republic of, Romania, Russian Federation, Serbia and Montenegro, Slovakia, Slovenia, Turkey, Ukraine	Danube/Black Sea Basin Strategic Partnership on Nutrient Reduction: Tranche 1	29.555
Black Sea	Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Georgia, Hungary, Moldova Republic of, Romania, Russian Federation, Serbia and Montenegro, Slovakia, Slovenia, Turkey, Ukraine	Danube/Black Sea Basin Strategic Partnership on Nutrient Reduction Fund: Tranche 2	76.550
Black Sea	Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Georgia, Hungary, Moldova Republic of, Romania, Russian Federation, Serbia and Montenegro, Slovakia, Slovenia, Turkey, Ukraine	Strategic Partnership for Nutrient Reduction in the Danube River and Black Sea - World Bank - GEF Nutrient Reduction Investment Fund: Tranche 3	225.100
Black Sea	Bulgaria; Georgia; Romania; Russian Federation; Turkey; Ukraine	Control of Eutrophication, Hazardous Substances and Related Measures for Rehabilitating the Black Sea Ecosystem: Phase 1	7.945
Black Sea	Bulgaria; Georgia; Romania; Russian Federation; Turkey; Ukraine	Control of Eutrophication, Hazardous Substances and Related Measures for Rehabilitating the Black Sea Ecosystem, Tranche 2	11.332
Canary Current	Cape Verde; Gambia; Guinea; Guinea-Bissau; Mauritania; Morocco; Senegal	Protection of the Canary Current Large Marine Ecosystem	26.506
Caribbean Sea	Cuba; Jamaica	Demonstrations of Innovative Approaches to the Rehabilitation of Heavily Contaminated Bays in the Wider Caribbean	32.770
Caribbean Sea	Cuba; Barbados; Jamaica; Mexico; Venezuela; Antigua and Barbuda; Bahamas; Belize; Brazil; Colombia; Costa Rica; Dominica; Dominican Republic; Grenada; Guatemala; Guyana; Haiti; Honduras; Nicaragua; Panama; Saint Kitts and Nevis; Saint Lucia; Saint Vincent and the Grenadines; Suriname; Trinidad and Tobago	Sustainable Management of the Shared Marine Resources of the Caribbean Large Marine Ecosystem and Adjacent Regions	55.380
Caribbean Sea	Antigua and Barbuda, Bahamas, Barbados, Cuba, Dominica, Dominican Republic, Jamaica, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Trinidad and Tobago	Integrating Watershed and Coastal Area Management in the Small Island Developing States of the Caribbean	111.652
Caribbean Sea	Colombia; Costa Rica; Nicaragua	Reducing Pesticide Runoff to the Caribbean Sea	10.042
Caribbean Sea	Antigua and Barbuda; Barbados; Costa Rica; Guatemala; Guyana; Honduras; Saint Lucia; Suriname; Panama; Jamaica; Belize; Trinidad and Tobago	Testing a Prototype Caribbean Regional Fund for Wastewater Management	271.500
East Asia	China, Thailand, Viet Nam	Livestock waste management in East Asia	24.006
East China Sea; South China Sea; Gulf of Thailand;	Cambodia; China; Korea Democratic People's Republic of; Korea Republic of;		44.250

Table 3 (*continued*)

List of LME projects and countries funded by the GEF ($3.15B)			
LME	***Country***	***Project name***	***Funds in US$ millions***
Yellow Sea; Sulu-Celebes Sea; Indonesian Sea	Indonesia; Japan; Lao People's Democratic Republic; Philippines; Singapore; Timor-Leste; Viet Nam	Implementation of Sustainable Development Strategy for the Seas of East Asia	
East China Sea; South China Sea; Gulf of Thailand; Yellow Sea; Sulu-Celebes Sea; Indonesian Sea	Cambodia, China, Indonesia, Lao People's Democratic Republic, Malaysia, Philippines, Thailand, Viet Nam	World Bank/GEF Partnership Investment Fund for Pollution Reduction in the Large Marine Ecosystems of East Asia (Tranche 1 of 3 tranches)	464.368
East China Sea; South China Sea; Gulf of Thailand; Yellow Sea; Sulu-Celebes Sea; Indonesian Sea	Cambodia; China; Indonesia; Lao People's Democratic Republic; Malaysia; Philippines; Thailand; Viet Nam	World Bank/GEF Partnership Investment Fund for Pollution Reduction in the Large Marine Ecosystems of East Asia (Tranche 1, Installment 2)	85.870
Guinea Current	Angola; Benin; Cameroon; Congo; Cote d'Ivoire; Equatorial Guinea; Ghana; Guinea; Guinea-Bissau; Liberia; Nigeria; Sierra Leone; Togo; Gabon; Congo The Democratic Republic of; Sao Tome and Principe	Combating Living Resource Depletion and Coastal Area Degradation in the Guinea Current LME through Ecosystem-based Regional Actions	54.683
Gulf of Mexico	Mexico, USA	Integrated Assessment and Management of the Gulf of Mexico Large Marine Ecosystem	101.277
Gulf of Thailand; South China Sea	China	Biodiversity Management in the Coastal Area of China's South Sea - marine biodiversity, ecosystem management and marine biodiversity monitoring	46.605
Gulf of Thailand; South China Sea	Cambodia; China; Indonesia; Malaysia; Thailand; Viet Nam; Philippines	Reversing Environmental Degradation Trends in the South China Sea and Gulf of Thailand	32.813
Gulf of Thailand; South China Sea	Indonesia	Demonstration of Community-based Management of Seagrass Habitats in Trikora Beach East Bintan, Riau Archipelago Province, Indonesia	0.790
Humboldt Current	Chile; Peru	Towards Ecosystem Management of the Humboldt Current Large Marine Ecosystem	32.115
Mediterranean Sea	Albania; Algeria; Bosnia and Herzegovina; Croatia; Egypt; Lebanon; Libyan Arab Jamahiriya; Morocco; Montenegro; Syrian Arab Republic; Tunisia; Turkey	Strategic Partnership for the Mediterranean Large Marine Ecosystem–Regional Component: implementation of agreed actions for the protection of the environmental resources of the Mediterranean Sea and its coastal areas	49.439
Mediterranean Sea	Algeria; Albania; Bosnia and Herzegovina; Bulgaria; Croatia; Egypt; Lebanon; Libyan Arab Jamahiriya; Macedonia the former Yugoslavian Republic of; Morocco; Serbia and Montenegro; Syrian Arab Republic; Tunisia; Turkey	World Bank - GEF Investment Fund for the Mediterranean Sea Large Marine Ecosystem Partnership, Tranche 1, 1st Allocation	96.055
Mediterranean Sea	Albania; Algeria; Bosnia and Herzegovina; Bulgaria; Croatia; Egypt; Macedonia the former Yugoslavian Republic of; Lebanon; Libyan Arab Jamahiriya; Monaco; Morocco; Serbia and Montenegro; Syrian Arab Republic; Tunisia; Turkey	World Bank-GEF Investment Fund for the Mediterranean Sea Large Marine Ecosystem Partnership, Tranche 1, 2nd Installment	60.000

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Table 3 (*continued*)

List of LME projects and countries funded by the GEF ($3.15B)

LME	***Country***	***Project name***	***Funds in US$ millions***
Mediterranean Sea	Albania, Algeria, Bosnia and Herzegovina, Egypt, Lebanon, Libyan Arab Jamahiriya, Morocco, Syrian Arab Republic, Tunisia	MED Integration of Climatic Variability and Change Into National Strategies to Implement the ICZM Protocol in the Mediterranean	9.298
Mediterranean Sea	Tunisia	MED Greater Tunis Treated Wastewater Discharge in the Mediterranean Sea.	555.000
Pacific Central American Coastal	El Salvador, Honduras, Nicaragua	Integrated Ecosystem Management Pilot for the Gulf of Fonseca	26.326
Patagonian Shelf	Argentina, Uruguay	Reducing and Preventing Land-based Pollution in the Rio de la Plata/Maritime Front Through Implementation of the FrePlata Strategic Action Programme	17.870
Patagonian Shelf	Argentina; Uruguay	Environmental protection of the Rio de la Plata and its Maritime Front: Pollution Prevention and Control and Habitat Restoration	10.480
Red Sea, Arabian Sea	Djibouti; Egypt; Jordan; Saudi Arabia; Sudan; Yemen	Red Sea and Gulf of Aden Strategic Ecosystem Management	38.000
Red Sea, Arabian Sea	Djibouti; Egypt; Jordan; Saudi Arabia; Somalia; Sudan; Yemen	Implementation of the Strategic Action Programme for the Red Sea and Gulf of Aden	44.650
Red Sea, Arabian Sea	Yemen	Protection of the Marine Ecosystem of the Red Sea	2.800
Sulu-Celebes Sea	Indonesia; Malaysia; Philippines	CTI Sulu-Celebes Sea Sustainable Fisheries Management Project	6.310
Yellow Sea	China; Korea Republic of	Reducing Environmental Stress in the Yellow Sea Large Marine Ecosystem	24.696
Total number of countries with GEF-funded projects: 110		**TOTAL FUNDS**	**3155.195**

indicators are derived from fisheries independent bottom-trawl surveys and acoustic surveys for pelagic species. Both surveys have been deployed for decades by NOAA's National Marine Fisheries Service (AFSC, 2006; NEFSC, 2006) where access to large vessels is limited or unavailable, standardized sampling methods can be deployed from small calibrated trawlers (Sherman and Laughlin, 1992). Time-series collections of fish catch samples provide biological specimens for stock identification, age and growth, fecundity, and pathological data, as well as data for preparing stock assessments. Survey vessels are used to obtain fish population demographic data, while also serving as platforms for environmental sampling for water, sediments, benthos, oxygen, harmful algal blooms, emergent diseases, specimens for acidification assessments and changes in plankton and benthic biodiversity. A more detailed description of fish and fisheries indicators for applications in EBM is given in Liu et al. (2014) and Jennings and Brander (2010), among others (Jennings, 2005; Fogarty, 2014; Liu et al., 2014).

For GEF supported projects, a partnership between the Norwegian government, and the FAO Fisheries Division is providing opportunity for scientists and technicians engaged in the Bay of Bengal LME, Canary Current LME, Guinea Current LME, Benguela Current LME, and the Agulhas Current LME & Somali Current LME projects, to conduct bottom trawling and acoustic surveys of fish and simultaneous sampling of plankton and benthic communities and their biogeochemical environments (see EAF-Nansen project activities at ⟨http://www.eaf-nansen.org/nansen/topic/18013/en⟩). Time-series profiles from 1950 to 2004 of fish and fisheries indicators for the world's LMEs depicting mean-annual catch by species and species groups, landed value, primary production required to sustain fisheries, marine trophic indices and fisheries-in-balance indices have been produced with descriptive diagnostics by

Daniel Pauly and his associates at the University of British Columbia (Pauly et al., 2008). The descriptions can be downloaded from the Sea Around Us Project website at www.seaaroundus.org.

3.3. *Pollution and ecosystem health module*

Ecosystem health is a concept of wide interest for which a single precise scientific definition is difficult (Borja and Rodríguez, 2010; Tett et al., 2013). The health paradigm is based on multiple-state comparisons of ecosystem resiliency and stability and is an evolving concept. To be healthy and sustainable, an ecosystem should maintain its metabolic activity level and its internal structure and organization and should resist external stresses over space and time relevant to the ecosystem (Costanza, 1992). The pollution and ecosystem health module indicators recommended for LME applications are based on the monitoring strategy of the US Environmental Protection Agency's (EPA) water quality, sediment quality, benthic, coastal habitat and fish tissue indices (USEPA, 2004). The LME-series of metrics used for producing the five classes of indices include pathobiological examination of fish and fish tissue, estuarine and nearshore monitoring of contaminants and the effects of contaminants in the water column, substrate, and selected groups of organisms. Bioaccumulation and trophic transfer of contaminants are assessed and critical life history stages of selected food web organisms are examined for levels of exposure to and effects from contaminants, effects of impaired reproductive capacity, organ disease, and contaminant impaired growth. EPA health indices are connected into “stoplight” assessment values for communicating results to coastal resource managers and the general public (USEPA, 2004).

Assessments are made of contaminant impacts at species and population levels to assess the multiple ecological disturbances (Sherman, 2000). The number and frequency of multiple marine ecological disturbances (MMEDS) can be used as indicators of ecosystem health (Sherman, 2001). Nutrient over-enrichment of LMEs is a growing problem (NRC, 2000). Total dissolved inorganic nitrogen (DIN) loads and yield to LMEs was determined by Seitzinger et al. (2008) (Fig. 4). Included in the assessment were natural biological N_2 fixation, agricultural biological N_2 fixation, fertilizer, manure, atmospheric deposition, and sewage. Export of Nitrogen to LMEs is predicted to increase 3 times the 1990 baseline by 2050 (Seitzinger and Harrison, 2008). In the absence of substantial effort to control the sources of excessive nitrogen levels from human activities, serious water quality degradation is predicted for LMEs globally, with the greatest increases in eastern and southern Asia by 2050 (Fig. 5) (Seitzinger and Kroeze, 1998).

An approach to the assessment of comparative ecosystem health for meeting the needs of the European Union has focused on a multidisciplinary and multiscale strategy that defines general ecosystem health as the condition of a system that is self-maintaining, vigorous, resilient, and with the capacity to sustain services to humans (Tett et al., 2013). A more pragmatic approach toward improved ecosystem health can be found in the indicators of ocean health based on benefits humans derive from ecosystems where assessments of comparative ecosystem health have focused on multidisciplinary and multiscale indicators of the well-being of coupled human-natural systems (Rapport et al., 1998). A quantitative standard index of ocean health based on ten specified goals has recently been published (Halpern et al., 2012). The index analysis considers index goals including (i) food provision (fisheries, mariculture), (ii) artisanal fishing opportunity, (iii) natural products, (iv) carbon storage, (v) coastal protection, (vi) tourism and recreation, (vii) coastal livelihoods and economies, (viii) sense of place (iconic species, lasting special places), (ix) clean water, and (x) biodiversity (habitats, species). Questions raised regarding sources of bias in the food provision index (Branch et al., 2013) have been addressed (Halpern et al., 2013)

3.4. *Socioeconomics module*

The value of LMEs to the community of nations represented at UNCED, WSSD and RIO+20 is quite high. Annually the coastal and marine areas encompassed by LMEs contribute an estimated $12.6 trillion to the global economy (Costanza et al., 1997). The socioeconomics module emphasizes the practical application of scientific findings to managing LMEs and the explicit integration of social and

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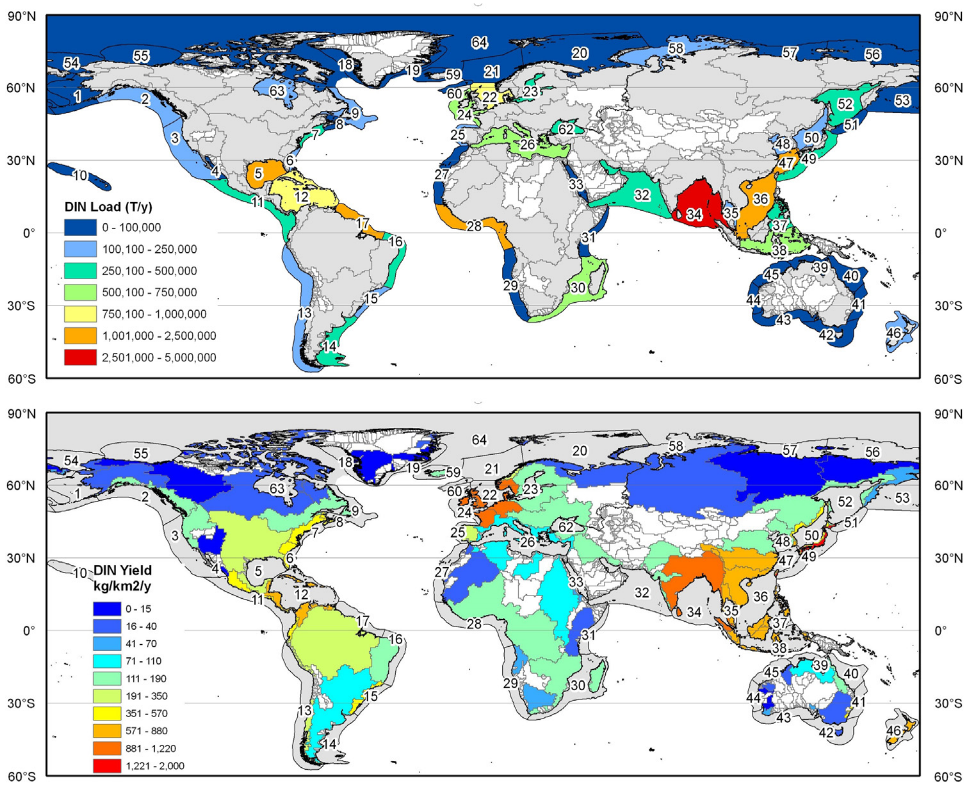

Fig. 4. DIN load (top) and yield (bottom) from land-based sources to LMEs predicted by the NEWS DIN model. Watersheds discharging to LMEs are grey; watersheds with zero coastal discharge are white (from Seitzinger and Lee, 2008). LMEs are identified by numbers as given in Figure 1.

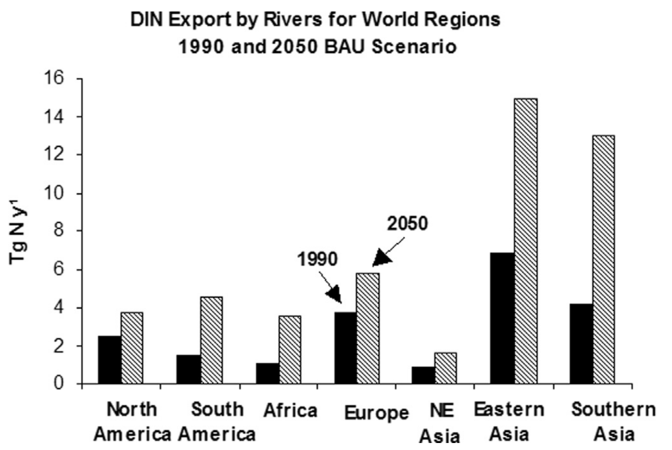

Fig. 5. Predicted DIN export to coastal systems in 1990 (black) and 2050 under a business-as-usual (BAU) scenario (from Seitzinger and Kroeze 1996).

Table 4
Steps for socioeconomic monitoring and assessment of LMEs Sutinen et al. (2005)

1. Identify LME resource users and their activities
2. Identify governance mechanisms influencing LME resource use
3. Assess the level of LME-related activities
4. Assess interactions between LME-related activities and LME resources
5. Assess impacts of LME-related activities on other users
6. Assess the interactions between governance mechanisms and resource use
7. Assess the socioeconomic importance of LME-related activities and economic and sociocultural value of key uses and LME resources
8. Identify the public's priorities and willingness to make trade-offs to protect and restore key natural resources
9. Assess the cost of options to protect or restore key resources
10. Compare the benefits with the costs of protection and restoration options
11. Identify financing alternatives for the preferred options for protecting and restoring key LME resources

economic indicators and analyses to assure that prospective management measures are cost effective. Economists and policy analysts work closely with ecologists and other scientists to quantify and evaluate management options that are both scientifically credible and economically practical and sustainable with regard to the use of ecosystem goods and services. In order to respond adaptively to changing ecological conditions, socioeconomic considerations must be closely integrated with science-based assessments (Tallis et al., 2008). The Department of Environmental and Natural Resource Economics at the University of Rhode Island has developed a framework for monitoring and assessing the human dimensions of LMEs, allowing for the integration of socioeconomic considerations to support ecosystem-based adaptive management actions (Sutinen et al., 2005). Eleven steps are included in the time-series process of monitoring and assessing the human dimensions of an LME and utilization of its resources (Table 4). The time-series data are derived from monitoring of user socio-cultural and economic activity in relation to user benefits and ecosystem sustainability. Assessment of cost options for the recovery and protection of key resources and comparisons of benefits with costs of resource protection and restoration are key elements of management strategy.

An initial step toward comparative socioeconomic conditions among LMEs was made by Hoagland and Jin at the Marine Policy Center of the Woods Hole Oceanographic Institution using indices of socioeconomic activity based on data from fish landings, aquaculture production, ship building, cargo traffic, merchant fleet size, oil production, oil rig counts, and tourism (Hoagland and Jin, 2006). Hoagland and Jin compared three sectors, fisheries and aquaculture, tourism, and shipping and offshore oil, with socioeconomic condition as represented by the UN's human dimension index (HDI) for the Yellow Sea. The LME economic sector activity was compared against the global average. Three of the sectors exceeded the world average (shipping and offshore oil, fisheries and aquaculture, and tourism) (Fig. 6), suggesting that the YSLME has much higher than average marine activity levels for most of its major marine industries. An implication of this comparison, according to Hoagland and Jin, is that the YSLME environment is being utilized at levels that may be unsustainable (Hoagland and Jin, 2006).

3.5. Governance module

The relationships between the United Nations Law of the Sea provisions and the legal basis for transboundary international agreements for the assessment and management of the world's LMEs has been examined and found fully compatible (Belsky, 1986, 1989, 1992; Somers, 1998; Wang, 2004). Large Marine Ecosystems with a history of being managed from an ecosystem perspective include the Antarctic under the jurisdiction of the Commission for the Conservation of Antarctic Marine Living Resources (Scully et al., 1986) and the Great Barrier Reef (Kelleher, 1993). The governance module provides the intergovernmental framework for nations committed to developing and practicing EBM to plan and implement LME projects that consider three key governance components: (i) the marketplace, (ii) the government, and (iii) non-governmental institutions and arrangements that interact through patterns of dynamic interrelationships (Juda and Hennessey, 2001). In the

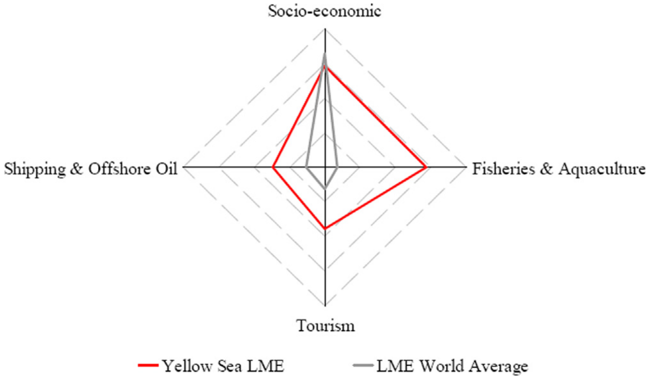

Fig. 6. Yellow Sea LME activity index values for three major marine sectors and the socioeconomic sector in comparison to the LME world average (from Hoagland and Jin 2006).

marketplace, considerations are given to law, the environment, and to resources usually utilized for a profit incentive. Government policy and regulation are mechanisms affecting human behavior, and non-governmental and social institutions usually serve as advocates of particular courses of action by government or societal behavior, including behaviors based on scientific considerations. The three components of governance are considered in the guidance provided by the GEF to countries coming together to protect, recover, and sustain the goods and services of LMEs (GEF, 1995). The GEF strategy requires countries to consider the root causes of stressors on LME goods and services and actions for their recovery and sustainability based on agreed upon Transboundary Diagnostic Analysis, (TDA) that is prioritized and serves as the basis for implementing a Strategic Action Plan (SAP). The SAP is focused on mitigating ecosystem stress and sustaining shared goods and services within the framework of LME productivity, fish and fisheries, pollution and ecosystem health, socioeconomics and governance through mutually agreeable ecosystem-based management practices (Carlisle, 2013).

From the governance module perspective, considerable progress has been made by Angola, Namibia, and South Africa for recovering, developing and sustaining the shared goods and services of the Benguela Current LME. Following GEF operational guidelines, the Project produced a prioritized TDA, identifying transboundary stressors. The outcome of the TDA process was an agreed-upon SAP endorsed by the three governments in 2002, followed by the establishment of an interim Benguela Current Commission in August 2008. The Benguela Current Commission formalized two decades of transboundary, 3-country cooperation in introducing an ecosystem-based approach to the assessment and governance of Benguela Current LME resources based on the five modules for monitoring and assessing the BCLME (Hamukuaya and Willemse, 2013).

The BCLME governance module is unique in its establishment in March 2013 of the first Convention for monitoring a coordinated regional approach to the long term conservation, protection, rehabilitation, enhancement, and sustainable use of the BCLME to provide economic, environmental, and social benefits to the people of Angola, Namibia, and South Africa. The Convention's mandates are carried forward under 10 Articles by 3 Commissioners, and 3 permanent Committees committed to a governance framework. The framework is organized to reach decisions that apply results of analyses that consider science-based assessments of changing ecological conditions with optimizing the human dimensions of socioeconomic benefits in recovering and sustaining BCLME goods and services as put forward in Articles 4, 7, and 10. The full text of the BCLME governance document can be downloaded from www.DLIST-Benguela.org.

Among the 110 countries that have received GEF support since 1994 for LME projects, 21 countries including the three supporting the BCLME Convention, are implementing ecosystem-based governance regimes. Sixteen countries have together established an Interim Commission for the protection, recovery, and sustainability of the Guinea Current LME (Honey and Elvin, 2013). The two countries participating in the UNDP/GEF Yellow Sea LME Project, the People's Republic of China and the Republic of Korea, have included plans for the establishment of a Yellow Sea LME Commission for

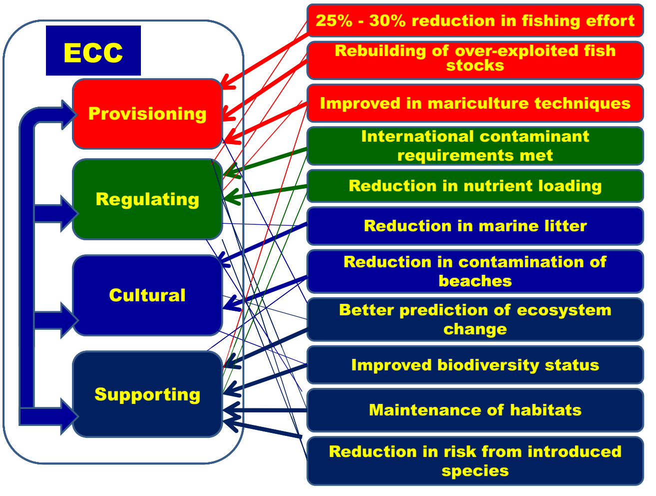

Fig. 7. Management actions for maintaining carrying capacity of the Yellow Sea LME for ecosystem services, and targets for sustaining services (from the Yellow Sea SAP, UNDP 2009).

reducing environmental stress on the goods and services of the Yellow Sea LME (UNDP/GEF, 2009). From a governance perspective, important actions are underway to improve YSLME conditions based on data analyses from the fish and fisheries and pollution and ecosystem health indicator metrics. Actions include reduction in capture fishing effort of 30% by 2020 to rebuild overfished stocks, improvements in coastal water quality with new water treatment facilities reducing nutrient loading, and improvement of mariculture methods through extension of integrated multitrophic aquaculture practices (Fig. 7).

4. LMEs and climate change

The most highly productive areas of the ocean are located within the boundaries of the world's LMEs (Fig. 8) (Behrenfeld and Falkowski, 1997). Annual levels of primary productivity are highest in the LMEs around the margins of continents where an estimated 80% of the annual global marine fisheries catch is produced. The world's fish populations are responding to climate change. Since the 1980s, decadal averages of global temperatures have been progressively warming (Fig. 9) (NOAA, 2009). For the period 1982–2006, sea surface temperatures in 61 LMEs warmed two to four times faster than the global average reported by the IPCC (Belkin, 2009). Fifteen of the fastest warming LMEs ranged from 0.71 °C in the Mediterranean Sea LME, to 1.35 °C in the Baltic Sea LME (Belkin, 2009). Warming has been correlated with fisheries biomass yields (catches) in six LMEs in the northeast Atlantic—Norwegian Sea LME, Faroe Plateau LME, Iceland Shelf LME, North Sea LME, Celtic Biscay LME, and Iberian Coastal LME (Sherman et al., 2013).

A rise in fisheries yield from 1982 to 2006 was most pronounced among zooplanktivorous pelagic fish species including herring and blue whiting in the biomass yields of the Norwegian Sea, Faroe Plateau, and Iceland Shelf LMEs. In contrast, in the more southern northeast Atlantic LMEs (North Sea, Celtic Biscay Shelf, and Iberian Coastal LMEs), fisheries biomass yields declined (Sherman et al., 2009). As the sea-surface temperatures warmed in the North Sea, Celtic Biscay and Iberian LMEs, the nutrient enrichment of the upper water layers was reduced from the effects of strong thermocline formation, less nutrient mixing from the subsurface to the upper surface layers of the water column, reduced overall primary productivity and zooplankton production (Richardson and Schoeman, 2004). These results are consistent with modeling results of climate warming and increased stratification leading to reductions in subsurface nutrient contributions to upper water layers and declining levels of primary

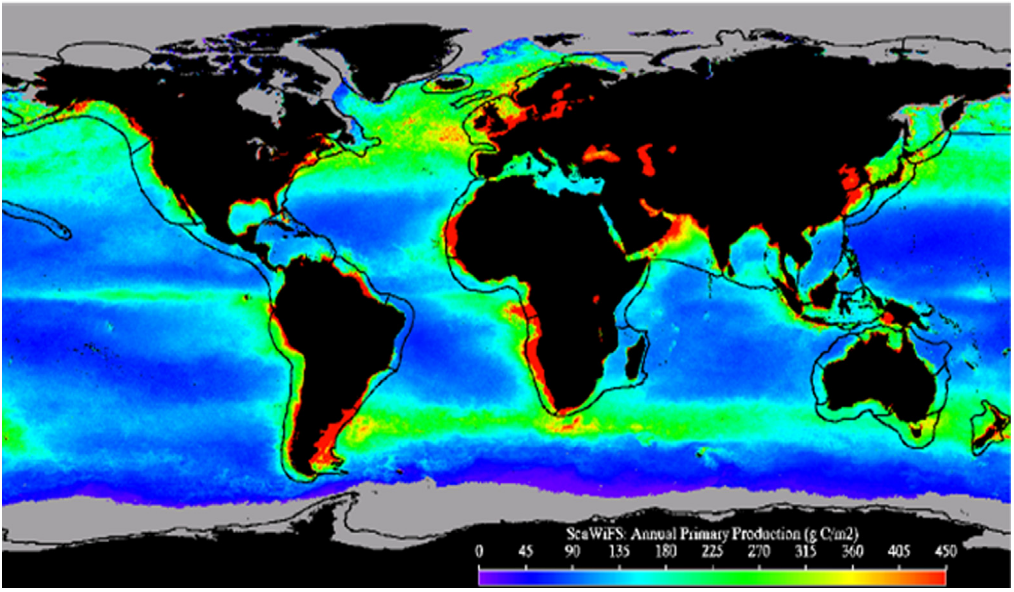

Fig. 8. A global map of average primary productivity and the boundaries of the 64 Large Marine Ecosystems (LMEs) of the world available at www.lme.noaa.gov. The annual productivity estimates were based on Sea WiFS satellite data collected between September 1998 and August 1999 and the model developed by M. Behrenfeld and P.G. Falkowski in 1997. The color enhanced image provided by Rutgers University depicts a shaded gradient of primary productivity from a high of 450 gCm2yr-1 in red to less than 45 gCm2yr-1 in purple.

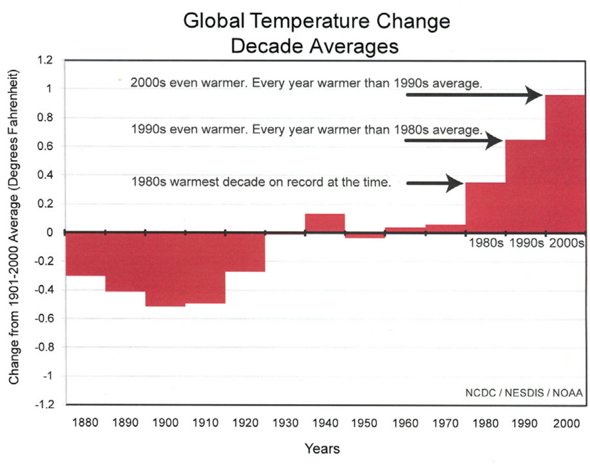

Fig. 9. Decadal averages of Global Temperature Change, 1880–2000. From NOAA (2009) report, “State of Climate Change”.

productivity (PP) (Sarmiento et al., 2004; Doney, 2006; Steinacher et al., 2010; Falkowski, 2012). The results are consistent with projections of six model outputs for 2040–2060 that depict increasing PP in polar latitudes and lowered PP levels in tropical and subtropical latitudes (Fig. 10).

The model projections would place at risk fishing yields of 29 LMEs located in a circumglobal belt between 30°N and 30°S, representing an estimated average annual yield of 40.6 mmt, constituting 50.7% of the global marine fisheries biomass yield based on 2006 estimates computed from the University of British Columbia Sea Around Us Project data (www.seaaroundus.org) (Table 5). Within

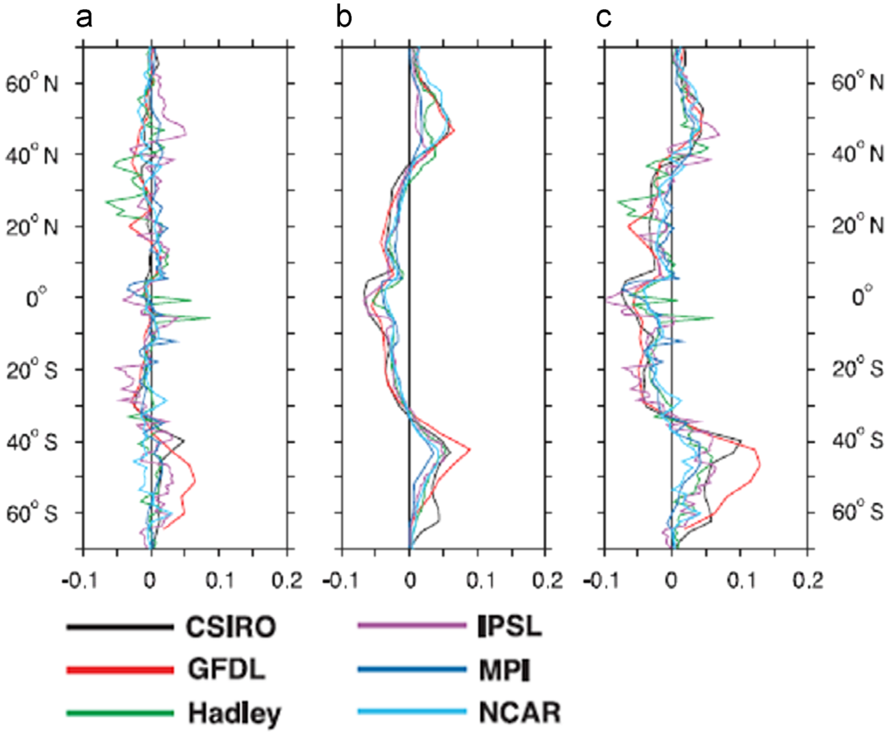

Fig. 10. Zonally integrated response of primary production (PP) calculated with the Behrenfeld and Falkowski (1997) algorithm using chlorophyll calculated from the empirical model. The figure shows the difference between the warming and the control simulation for each of the six AOGCMs averaged over the period 2040 to 2060 (except for MPI, which is for the period 2040 to 2049). (a) The increase in primary production that occurs in response to the chlorophyll change only, with temperature kept constant at the control scenario. (b) The increase in primary production that occurs in response to the temperature increase only, with chlorophyll kept constant at the control scenario. (c) The increase in primary production that occurs in response to the combined effect of the chlorophyll change and temperature increase (from Sarmiento et al. 2004).

the high-risk, circumglobal belt are 20 LMEs off the coasts of developing countries populated with poor coastal communities dependent on marine fish and fisheries for food security and livelihoods (Table 5). At the higher latitudes depicted in Fig. 10, where PP is expected to increase, fish and fishery yields are projected to increase poleward in relation to global warming, loss of sea ice, and extended length of seasonal plankton production (Perry et al., 2005; Cheung et al., 2010; Hollowed et al., 2013; Sherman et al., 2013). Within the waters of 19 of the 20 LMEs off the coasts of developing countries, future declining productivity and fisheries biomass yields are expected. Therefore, EBM practices should include application of FAO's fisheries precautionary principle, where 30% or more of the fisheries yields have already been assessed as fully exploited and overexploited (Table 5). Annual limits on total allowable catches for dominant pelagic species are presently in place for the Humboldt Current (Akester, 2013).

5. GEF-supported nutrient over-enrichment mitigation actions

5.1. The Baltic Sea LME

The growing problem of nutrient over-enrichment is being addressed under the pollution and ecosystems health module by countries participating in the GEF-supported LME projects. During the

Table 5
The 29 LMEs located within the 30°N–30°S circumglobal belt at risk from projected lowered primary productivity based on 6 model projections for 2040–2060. Information on fisheries yield status is from Pauly et al. (2008). Sea Around Us Project, available online at http://www.seaaroundus.org. In 19 of the 20 LMEs bordering countries eligible for GEF financial assistance, designated with an x, thirty percent or more of fishery biomass yields is either fully exploited or overexploited.

LMEs bordering GEF-eligible countries	LME name	5-yr Mean fisheries biomass in tonnes	Fisheries biomass yield status – % fully exploited	Fisheries biomass yield status – % overexploited
	Insular Pacific Hawaiian	6121.00	1	54
	California Current	634,669.00	N/A	N/A
x	Gulf of California	134,297.00	45	48
x	Pacific Central American	788,191.00	42	18
x	Gulf of Mexico	987,865.00	36	60
x	Caribbean Sea	370,231.00	40	58
	Southeast US Continental Shelf	89,216.00	54	26
x	Humboldt Current	10,617,103.00	N/A[a]	N/A[a]
x	South Brazil Shelf	130,669.00	20	40
x	East Brazil Shelf	127,969.00	40	48
x	Canary Current	2,229,215.00	72	6
x	Guinea Current	1,010,453.00	71	24
x	Benguela Current	1,307,649.00	50	8
x	Agulhas Current	295,364.00	30	32
x	Somali Coastal Current	58,961.00	45	50
x	Arabian Sea	2,486,227.00	84	11
x	Red Sea	129,206.00	88	10
x	Bay of Bengal	3,062,147.00	83	15
x	Gulf of Thailand	676,304.00	37	50
x	South China Sea	6,454,043.00	83	13
x	Sulu-Celebes Sea	1,207,946.00	82	17
x	Indonesian Sea	2,392,818.00	88	12
	North Australian Shelf	159,572.00	78	18
	Northeast Australian Shelf	36,310.00	46	30
	East Central Australian Shelf	29,095.00	18	64
	West Central Australian Shelf	19,079.00	75	10
	Northwest Australian Shelf	62,842.00	59	18
x	East China Sea	4,339,890.00	77	21
	Kuroshio Current	823,035.00	48	42
SUM		**40,666,487.00**		

[a] Annual limits on total allowable catches for dominant pelagic species are presently in place for the Humboldt Current.

initial phase of the Baltic Sea LME project, effort was directed by Estonia, Latvia, Lithuania, Poland, and the Russian Federation to improve agricultural practices in controlling the application of fertilizers, including the storage and recycling of manure to reduce nutrient runoff from watersheds into the BSLME, through environmentally sustainable farm practices (Thulin, 2009). The initial GEF supported phase of the BSLME project that implemented all five modules in a multinational coordinated ICES/HELCOM partnership from 2003 to 2007, was followed by an action plan for the Baltic Sea EBM-based BONUS program, supported by 100 million Euros contributed by the European Union and by the countries bordering the Baltic (Brusendorff, 2013).

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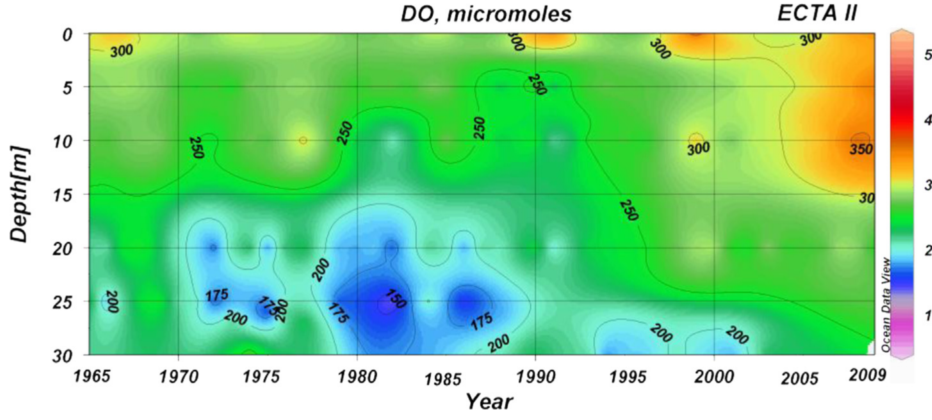

Fig. 11. Reversal of eutrophication and hypoxia in the NW shelf of the Black Sea LME as indicated in oxygen concentrations (umol/l) off Constanta, Romania (blue and green correspond to low oxygen areas during periods of greatest hypoxia; orange illustrates return of more oxygenated waters) (from Hudson and Vandeweerd 2013).

5.2. The Black Sea

Excessive nutrient loadings into the Black Sea LME from the countries along the Danube River drainage basin have been addressed by the Black Sea LME program and have reduced the frequency and extent of eutrophication and hypoxic events. Nitrogen loadings have been reduced through Black Sea program actions by an estimated 25,000 metric tons per year and phosphorus by 4000 mt/yr. The best practices for controlling nutrient over-enrichment resulted from policy and regulatory reforms and three billion dollars in nutrient reduction investments for water treatment and improved farming practices (Hudson and Vandeweerd, 2013). The transition from extreme eutrophication and hypoxia from the mid-1960s to the mid 1990s, into a period of more highly oxygenated waters from 2005 to 2009 is depicted in Fig. 11. The partnering between the GEF and World Bank in catalytic funding and EBM program support to countries bordering the western Black Sea LME, led to the reduction in excessive nutrient loading to the NW Black Sea LME (Hudson and Vandeweerd, 2013).

5.3. The Yellow Sea LME

During the planning phase of the GEF-supported Yellow Sea Large Marine Ecosystem project, the results of the Joint People's Republic of China and Republic of Korea TDA analysis identified the growing problem of eutrophication as a high priority target for mitigation. Since 1970, the size of the hypoxic area of the YSLME has increased to occupy a large area of the west central YSLME (Fig. 12) (Tang, 2009).

The YSLME is vulnerable to eutrophication. A thermohaline front, coupled with weak circulation, results in a flushing time of 7 years. In recognition of the problem, the YSLME Strategic Action Plan (SAP) established an action plan for reducing the loading of nutrients from a 2006 baseline. The SAP requires an assessment of water treatment capacity by treatment facility, on a 5-year schedule for purposes of encouraging the construction of new waste treatment plants. China's target for continuing reduction of point source nutrient loads into the YSLME is 10% at 4-year intervals (UNDP/GEF, 2009). The GEF in partnership with the World Bank, in recognition of the need to reduce excessive nutrient loading and other pollutants into the LMEs of East Asian Seas, has designated grants and investment funds of $1.5 billion for the LMEs of the East Asian Seas (GEF, 2005). East Asian Seas LMEs include: Yellow Sea LME, East China Sea LME, South China Sea LME, Gulf of Thailand LME, Sulu-Celebes LME and Indonsesian Sea LME projects.

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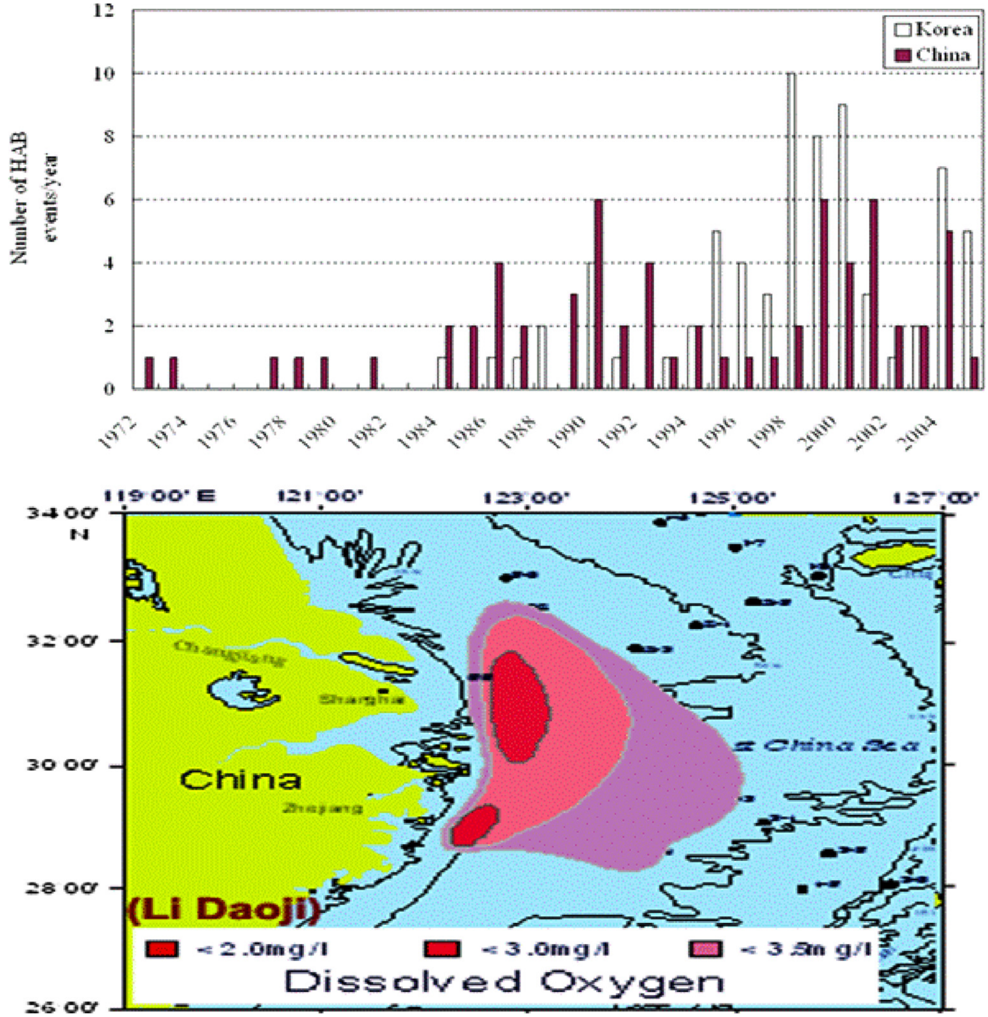

Fig. 12. Hypoxic area (lower panel) and increasing frequency of occurrence of harmful algal bloom events, 1972-2004 (upper panel) (from Tang, 2009) From Tang (2009).

6. Unity in looking forward

The LME approach to the assessment and management of coastal ocean goods and services has provided, and will continue to provide, unifying strategy for meeting the global goals for sustainable development that were put forward for the oceans by the international community of nation representatives at three global summits. Their June 2012 Rio+20 commitment to: "... protect and restore the health, productivity and resilience of oceans and marine ecosystems, and to maintain their biodiversity, enabling their conservation and sustainable use for present and future generations..." provides a challenging goal for linking ocean science to the practical needs of seven billion people inhabiting the planet.

To help meet the challenge of Rio+20, leaders directing several of the world's top financial, scientific, and technical institutions engaged in sustainable development of the oceans, converged in February 2013 from Copenhagen, New York, Paris, and Washington DC, at Boston's John F. Kennedy

Library and Museum. They convened to discuss the recovery and sustainability of LMEs during climate change. Attendees included invited guests, scientists in Boston for the annual meeting of the American Association for the Advancement of Science, the public and the press. The five leaders who weighed in on LMEs included: Dr. Jane Lubchenco, Under Secretary of Commerce for Oceans and Atmosphere and NOAA Administrator; Dr. Naoko Ishii, Chief Executive Officer of the Global Environment Facility; Dr. Anne Christine Brusendorff, General Secretary of the International Council for the Exploration of the Sea; Dr. Andrew Hudson, Head of UNDP's Water and Ocean Governance Programme; and Dr. Wendy Watson-Wright, Executive Secretary of IOC-UNESCO and Assistant Director General of UNESCO. Other speakers addressed LMEs from the perspective of marine spatial planning and the results of case studies of the Humboldt Current LME, the Yellow Sea LME, and the Benguela Current LME. The full peer-reviewed edited text of the presentations has been published by the GEF and UNDP under the title: Stress, Sustainability, and Development of Large Marine Ecosystems During Climate Change: Policy and Implementation. The volume can be downloaded from http://on.undp.org/pbj03 and from www.lme.noaa.gov.

The unity of the global LME approach is maintained through annual Consultative Committee meetings convened at IOC-UNESCO. The 15th Annual LME Consultative Committee Report for 2013 can be downloaded from www.lme.noaa.gov. Additional movement forward toward the Rio+20 ocean goals by developing nations will be generated during the 2014 to 2017 replenishment of GEF funds to support implementation and augmentation of GEF–LME assessment and management projects.

7. Comparing future states of LMEs

Given the coastal ocean challenges of the three global environmental summits, it is important to access and monitor ecological conditions in LMEs to measure progress in fisheries recovery and sustainability, habitat restoration, pollution reduction and control, nutrient over-enrichment mitigation, biodiversity conservation, and adaptation and mitigation of the effects of acidification and climate change on LME goods and services. Presently, the GEF is supporting an IOC-UNESCO and UNEP effort to establish a global baseline of LME ecological conditions based on updating comparative metrics and analyses from the five LME suites of modular indicators of changing ecological conditions (Barbiere et al., 2013).

The IOC-UNESCO/UNEP baseline assessment of ecological conditions of the world's LMEs is scheduled for completion in 2014. A list of IOC/UNEP indicators of changing ecological states of LMEs will be given for each of the five modules. The crosswalk analysis between the five-module indicator assessment strategy and the GEF-supported TDA and SAP LME project planning and implementation process (Carlisle, 2013) is indicative of the continuing effort for extending the comparability of results from GEF supported LME projects in the pipeline for the 2014-2017 replenishment period (Ishii, 2013).

The concurrence expressed among leaders of the GEF, NOAA, IOC-UNESCO, ICES, and senior representative of UNDP, at the 2013 JFKennedy Library LME Conference in Boston, is serving as a unifying pathway for assisting developing nations towards the coastal ocean goals of Rio+20. While it is inevitable that the 7 billion people inhabiting the planet will leave their mark, it is still possible to make individual and collective choices that will result in restoring and sustainably developing the oceans' full potential for present and future generations.

References

AFSC,2006. Cooperative Acoustic Surveys. NOAA, NMFS, Alaska Fisheries Science Center. Year index available for all years online at: 〈http://www.afsc.noaa.gov/quarterly/amj2006/divrptsREFM7.htm〉.

Akester, M.J., 2013. The resilience and robustness of the humboldt current large marine ecosystem. In: Sherman, K., Adams, S. (Eds.), Stress, Sustainability, and Development of Large Marine Ecosystems During Climate Change: Policy and Implementation, 106–116. UNDP and GEF, New York and Washington, DC. (146. p.).

Barbiere, J., Heileman, S., et al., 2013. Large Marine Ecosystems, TWAP, Transboundary Waters Assessment Programme, vol. 2. IOC-UNESCO. Paris, France. www.unesco.org/new/.../brochure_TWAP_LMEs_2013.pdf.

Batten, S., Clark, R., et al., 2003. CPR sampling—the technical background, materials and methods, consistency and comparability. Prog. Oceanogr. 58, 175–191.

Behrenfeld, M., Falkowski, P.G., 1997. Photosynthetic rates derived from satellite-based chlorophyll concentration. Limnol. Oceangr. 42 (1), 1–20.
Belkin, I., 2009. Rapid warming of large marine ecosystems. Prog. Oceanogr. 81 (1–4), 207–213.
Belsky, M.H., 1986. Legal constraints and options for total ecosystem management of large marine ecosystems. Variability and management of large marine ecosystems. In: Sherman, K., Alexander, L.M. (Eds.), Proceedings of the AAAS Selected Symp. 99. Westview Press, Inc., Boulder, CO. pp. 241–260.
Belsky, M.H., 1989. The ecosystem model mandate for a comprehensive United States ocean policy and Law of the Sea. San Diego Law Rev. 26 (3), 417–495.
Belsky, M.H., 1992. Interrelationships of law in the management of large marine ecosystems. In: Sherman, K., Alexander, B.D., Gold, B.D. (Eds.), Large Marine Ecosystems: Patterns, Processes, and Yields. AAAS Press, Washington, DC, pp. 224–233.
Blanchard, J.L., Jennings, S., et al., 2012. Potential consequences of climate change for primary production and fish production in large marine ecosystems. Philos. Trans. R. Soc. B 367 (1605), 2979–2989.
Borja, Á., Rodríguez, J.G., 2010. Problems associated with the 'one-out, all-out' principle, when using multiple ecosystem components in assessing the ecological status of marine waters. Mar. Pollut. Bull. 60, 1143–1146.
Branch, T.A., Hively, D.J., et al., 2013. Is the ocean food provision index biased. Nature 495 (7442), E5–E6.
Brusendorff, A.C., 2013. Accelerated warming and sustainability of the baltic sea large marine ecosystem stress. In: Sherman, K., Adams, S.P. (Eds.), Sustainability, and Development of Large Marine Ecosystems during Climate Change, 24–33. UNDP, GEF, New York and Washington DC. (146 p.).
Carlisle, K.M., 2014. The large marine ecosystem approach: application of an integrated, modular strategy in projects supported by the global environment facility. Environ. Dev. (Special International Waters issue) http://dx.doi.org/10.1016/j.envdev2013.10.003, in press.
Chassot, E., Mélin, F., et al., 2007. Bottom-up control regulates fisheries production at the scale of eco-regions in European seas. Mar. Ecol. Prog. Ser. 343 (2007), 45–55.
Cheung, W., Lam, V., et al., 2010. Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. Glob. Change Biol. 16, 24–35.
Cheung, W.W.L., Sarmiento, J.L., et al., 2013. Shrinking of fishes exacerbates impacts of global ocean changes on marine ecosystems. Nat. Clim. Change 3, 254–258. (Published online 30 September 2012).
Christensen, V., Walters, C.J., et al., 2009. Database-driven models of the world's large marine ecosystems. Ecol. Model. 220, 1984–1996.
Costanza, R., 1992. Toward an operational definition of ecosystem health. In: Costanza, R., Norton, B.G., Haskell, B.D. (Eds.), Ecosystem Health: New Goals for Environmental Management. Island Press, Washington, DC, pp. 239–256.
Costanza, R., d'Arge, R., et al., 1997. The value of the world's ecosystem services and natural capital. Nature 387, 253–260.
Daskalov, G.M., 2003. Overfishing drives a trophic cascade in the Black Sea. In: Hempel, G., Sherman, K. (Eds.), Large Marine Ecosystems of the World: Trends in Exploitation Protection, and Research, 12. Elsevier Science, The Netherlands, pp. 171–191.
Diaz, R.J., Rosenberg, R., 2008. Spreading dead zones and consequences for marine ecosystems. Science 321, 926–929.
Doney, S.C., 2006. Plankton in a Warmer World. Nature 444, 695–696.
Doney, S.C., 2010. The growing human footprint on coastal and open-ocean biogeochemistry. Science 328 (5985), 1512–1516.
Duda, A.M., 2005. Targeting development assistance to meet WSSD goals for large marine ecosystems and small island developing states. Ocean Coast. Manag. 48, 1–14.
Duda, A.M., Sherman, K., 2002. A new imperative for improving management of large marine ecosystems. Ocean Coast. Manag. 45, 797–833.
Epstein, P.R., 2000. Algal blooms and public health. World Resource Review, 1993: The State of the World Fisheries and Aquaculture. 5. FAO, Rome190–206 (142 p.).
Executive Order, 2010. President Obama, Executive Order 13547: Stewardship of the Ocean, Our Coasts, and the Great Lakes. Washington, DC.
Falkowski, P., 2012. The power of plankton. Nature 483, S17–20.
Fogarty, M.J., 2014. The art of ecosystem-based fishery management. Can. J. Fish. Aquat. Sci. 71 (3), 479–490.
Frank, K.T., Petrie, B., et al., 2005. Trophic cascades in a formerly cod-dominated ecosystem. Science 308, 1621–1623.
Fu, C., Gaichas, S., et al., 2012. Relative importance of fisheries, trophodynamic and environmental drivers in a series of marine ecosystems. Mar. Ecol. Prog. Ser. 459, 169–184.
GEF, 1995. GEF Operational Strategy, Washington, DC. Global Environment Facility.
GEF, 2005. World Bank-Global Environment Facility Partnership Investment Fund for Pollution Reduction in the LMEs of East Asia. GEF Project ID 2454, Regional Project, Tranche 1 of 3 tranches.
Halpern, B.S., Gaines, S.D., et al., 2013. Halpern et al. reply. Nature 495 (7442), E7.
Halpern, B.S., Longo, C., et al., 2012. An index to assess the health and benefits of the global ocean. Nature 488, 615–620.
Hamukuaya, H., Willemse, N.E., 2013. Science to governance in the benguela current large marine ecosystem. In: Sherman, K., Adams, S. (Eds.), Stress, Sustainability, and Development of Large Marine Ecosystems During Climate Change: Policy and Implementation. UNDP and GEF, Washington and New York, pp. 129–146.
Hoagland, P. and D. Jin, 2006. Accounting for economic activities in Large Marine Ecosystems and Regional Seas, UNEP Regional Seas Reports and Studies, vol. 181. UNEP Regional Seas Programme, Nairobi, Kenya.
Hoegh-Guldberg, O., Bruno, J.F., 2010. The impact of climate change on the world's marine ecosystems. Science 328, 1523–1528.
Hollowed, A.B., Barange, M., et al., 2013. Projected impacts of climate change on marine fish and fisheries. ICES J. Mar. Sci. 70 (5), 1023–1037.
Hollowed, A.B., Planque, B., et al., 2013. Potential movement of fish and shellfish stocks from the sub-Arctic to the Arctic Ocean. Fish. Oceanogr. 22 (5), 355–370.
Honey, K., Elvin, S., 2013. Towards Ecosystem-based Management of the Guinea Current Large Marine Ecosystem (synthesis report). New York, United Nations Development Programme. 36 p. ⟨http://www.undp.org/content/undp/en/home/librarypage/environment-energy/water_governance/towards-ecosystem-based-management-of-gclme/⟩.

Hudson, A., Vandeweerd, V., 2013. Catalysing ocean finance: transforming markets to restore and protect the global ocean. In: Sherman, K., Adams, S.P. (Eds.), Stress, Sustainability, and Development of Large Marine Ecosystems During Climate Change: Policy and Implementation, 34–50. UNDP and GEF, New York and Washington DC. (146 p.).
Hume, A.C., Duda, A.M., 2012. Global environment facility strategy for assessing and managing large marine ecosystems during climate change. In: Sherma, K., McGovern, G. (Eds.), Frontline Observations on Climate Change and Sustainability of Large Marine Ecosystems. United Nations Development Programme, New York, pp. 1–15.
Ishii, N., 2013. GEF support toward sustainable development of large marine ecosystems. In: Sherman, K., Adams, S.P. (Eds.), Stress, Sustainability, and Development of Large Marine Ecosystems During Climate Change: Policy and Implementation, 20–23. UNDP and GEF, New York and Washington DC. (146 p.).
Jennings, S., 2005. Indicators to support an ecosystem approach to fisheries. Fish Fish. 6, 212–232.
Jennings, S., Brander, K., 2010. Predicting the effects of climate change on marine communities and the consequences for fisheries. J. Mar. Syst. 79, 418–426.
Jossi, J., John, A., et al., 2003. Continuous plankton recorder sampling off the east coast of North America—history and status. In: Reid, BC, Matthews, JBL, Smith, MA (Eds.), Achievements of the continuous plankton recorder survey and a vision for its future "Progress in Oceanography", 58; 2003, pp. 313–325.
Jossi, J.W., Kane, J., 2013. An atlas of the dominant zooplankton collected along a Continuous Plankton Recorder transect between Massachusetts USA and Cape Sable NS, 1961–2008. US Dept Commer, Northeast Fish Sci Cent Ref Doc. 13-12. NOAA, NMFS, Northeast Fisheries Science Center, Woods Hole, MA. 104 p.
Juda, L., Hennessey, T., 2001. Governance profiles and the management of the uses of large marine ecosystems. Ocean Dev. Int. Law 32, 41–67.
Kelleher, G., 1993. Sustainable development of the Great Barrier Reef as a large marine ecosystem. In: Sherman, K., Alexander, L. M., Gold, B.D. (Eds.), Large Marine Ecosystems: Stress, Mitigation, and Sustainability. AAAS Press, Washington, DC, pp. 272–279.
Link, J.S., Gaichas, S., et al., 2012. Synthesizing lessons learned from comparing fisheries production in 13 northern hemisphere ecosystems: emergent fundamental features. Mar. Ecol. Prog. Ser. 459, 293–302.
Liu, H., Fogarty, M.J., et al., 2014. Modeling dynamic interactions and coherence between marine zooplankton and fishes linked to environmental variability. J. Mar. Syst. 131, 120–129, http://dx.doi.org/10.1016/jmarsys.2013.12.003.
Lubchenco, J., 1994. The scientific basis of ecosystem management: Framing the context, language, and goals. In: Zinn, J., Corn, M.L., Ecosystem management: Status and potential. 103rd Congress, 2d Session, Committee Print. U.S. Government Printing Office, Superintendent of Documents. pp. 33–39.
Lubchenco, J., Petes, L.E., 2010. The interconnected biosphere: science at the ocean's tipping points. Oceanography 23 (2), 115–129.
Lubchenco, J., Sutley, N., 2010. Proposed U.S. policy for ocean, coast, and great lakes stewardship. Science 328, 1485–1486.
McLeod, K.I., Lubchenco J., et al., 2005. Scientific Consensus Statement on Marine Ecosystem-based Management. Signed by 221 Academic Scientists and Policy Experts with Relevant Expertise, 2014. Available from: ⟨www.compassonline.org/pdf_files/EBM_Consensus_Statement_v12.pdf⟩.
Melrose, D.C., Oviatt, C.A., et al., 2006. Comparisons of fast repetition rate fluorescence estimated primary production and ^{14}C uptake by phytoplankton. Mar. Ecol. Prog. Ser. 311, 37–46.
NEFSC, 2006. Northeast Fisheries Science Center Research Vessel Groundfish Surveys Overviews. A description of the Alaskan Fisheries Science Center 2006 Aleutian Islands. www.nefsc.noaa.gov/sos/vesurv/vesurv.html.
NOAA, 2009. State of the Climate. Department of Commerce.
NRC, 2000. Clean Coastal Waters: Understanding and Reducing the Effects of Nutrient Pollution. National Research Council, National Academy Press, Washington, DC.
Oliver, J.R.D., Widdicombe, S., et al., 2012. Large marine ecosystems at risk from acidification during climate change. In: Sherman, K., McGovern, G. (Eds.), Frontline Observations on Climate Change and Sustainability of Large Marine Ecosystems. United Nations Development Programme and Global Environment Facility, New York, pp. 188–203.
Pauly, D., Alder, J., et al., 2008. Fisheries in large marine ecosystems: descriptions and diagnoses. In: Sherman, K., Hempel, G. (Eds.), The UNEP Large Marine Ecosystems Report: A Perspective on Changing Conditions in LMEs of the World's Regional Seas.
Pauly, D., Christensen, V., 1995. Primary production required to sustain global fisheries. Nature 374, 255–257.
Perry, A.L., Low, P.J., et al., 2005. Climate change and distribution shifts in marine fishes. Science 308 (5730), 1912–1915.
Rapport, D.J., Costanza, R., et al., 1998. Assessing ecosystem health. Trends Ecol. Evol. **13**, 397–402.
Richardson, A.J., Schoeman, D.S., 2004. Climate impact on plankton ecosystems in the Northeast Atlantic. Science 305, 1609–1612.
RIO+20, 20–22 June 2012. The United Nations Conference on Sustainable Development. Future We Want – Outcome Document A/RES/66/288. United Nations Department of Economic and Social Affairs, Division for Sustainable Development. Rio de Janeiro. p. 24.
Sarmiento, J.L., Slater, R., et al., 2004. Response of ocean ecosystems to climate warming. Glob. Biogeochem. Cycles 18 (GB3003), 002004, http://dx.doi.org/10.1029/2003GB002134.
Scully, R.T., W.Y. Brown, et al., 1986. The convention for the conservation of antarctic marine living resources: a model for large marine ecosystem management. In: K. Sherman and L.M., AlexanderVariability and Management of Large Marine Ecosystems. Proceedings of the AAAS Selected Symposium 99. Westview Press, Boulder, CO, vol. 281–286. 319 p.
Seitzinger, S., Sherman, K., et al., 2008. Filling Gaps in LME Nitrogen Loadings Forecast for 64 LMEs, Intergovernmental Oceanographic Commission Technical Series 79. UNESCO, Paris, France. 62 p.
Seitzinger, S.P., Harrison, J.A., 2008. Land-based nitrogen sources and their delivery to coastal systems. In: Capone, C., Bronk, D.A., Mulholland, M.R., Carpenter, E. (Eds.), Nitrogen in the Marine Environment 2nd edition Elsevier, Amsterdam, pp. 469–510.
Seitzinger, S.P., Kroeze, C., 1998. Global distribution of nitrous oxide production and N inputs in freshwater and coastal marine ecosystems. Glob. Biogeochem. Cycles 12 (1), 93–113.
Sherman, B., 2000. Marine ecosystem health as an expression of morbidity, mortality, and disease events. Mar. Pollut. Bull. 41 (1–6), 232–254.

Sherman, B.H., 2001. Assessment of multiple marine ecological disturbances: applying the North American prototype to the Baltic Sea Ecosystem. Hum. Ecol. Risk Assess. **7** (5), 1519–1540.

Sherman, K., 1980. MARMAP, a fisheries ecosystem study in the NW Atlantic: fluctuations in ichthyoplankton–zooplankton components and their potential impact on the system. In: Diemer, F.P., Vernberg, F.J., Mirkes, D.Z., Belle, W. (Eds.), Advanced Concepts in Ocean Measurements for Marine Biology. Baruch Institute for Marine Biology and Coastal Research, University of South Carolina Press Columbia, South Carolina (S.C.). (572 p.).

Sherman, K., 1991. The large marine ecosystem concept: a research and management strategy for living marine resources. Ecol. Appl. 1 (4), 349–360.

Sherman, K., 1994. Sustainability, biomass yields and health of coastal ecosystems: an ecological perspective. Mar. Ecol. Prog. Ser. 112, 277–301.

Sherman, K., Alexander, L.M. (Eds.), 1986. Variability and Management of Large Marine Ecosystems. In: Proceedings of the AAAS Symposium 99. Westview Press, Boulder, CO.

Sherman, K., Alexander, L.M., 1994. Management of large marine ecosystems. In: Nierenberg, W.A. (Ed.), Encyclopedia of Environmental Biology. Academic Press, Inc., San Diego, CA.

Sherman, K., Belkin, I., et al., 2013. Changing states of North Atlantic large marine ecosystems. Environ. Dev. 7, 46–58.

Sherman, K., Belkin, I., et al., 2009. Accelerated warming and emergent trends in fisheries biomass yields of the world's large marine ecosystems. AMBIO 38 (4), 215–224.

Sherman, K., Laughlin, T.L., 1992. Large Marine Ecosystems Monitoring Workshop Report: 13–14 July 1991, Cornell University, Ithaca, New York. NOAA Tech. Mem. NMFS-F/NEC-93. Department of Commerce, Woods Hole, MA.

Sherman, K., O'Reilly, J., et al., 2011. The application of satellite remote sensing for assessing productivity in relation to fisheries yields of the world's large marine ecosystems. ICES J. Mar. Sci. 68 (4), 667–676.

Sherman, K., Solow, A., et al., 1998. Biodiversity and abundance of the zooplankton of the Northeast Shelf ecosystem. ICES J. Mar. Sci. 55, 730–738.

Somers, E., 1998. Legal constraints and options for total ecosystem management of large marine ecosystems: assessment, sustainability, and management. In: Sherman, K., Okemwa, E.N., Ntiba, M.J. (Eds.), Large Marine Ecosystems of the Indian Oceans. Blackwell Science, Malden, MA, pp. 41–74.

Steinacher, M., Joos, F., et al., 2010. Projected 21st century decrease in marine productivity: a multi-model analysis. Biogeosciences 7 (3), 979–1005.

Sutinen, J.G., Clay, P., et al., 2005. A framework for monitoring and assessing socioeconomics and governance of large marine ecosystems. In: Hennessey, T., Sutinen, J. (Eds.), Sustaining Large Marine Ecosystems: The Human Dimension, 27–81. Elsevier. (368 p.).

Tallis, H., Kareiva, P., et al., 2008. An ecosystem services framework to support both practical conservation and economic development. Proc. Natl. Acad. Sci. USA 105 (28). (9, 457–459, 464).

Tang, Q., 2009. Changing states of the Yellow Sea large marine ecosystem: anthropogenic forcing and climate impacts. In: Sherman, K., Aquarone, M.-C., Adams, S. (Eds.), Sustaining the World's Large Marine Ecosystems, 77–99. IUCN, Gland, Switzerland. (142 p.).

Tett, P., Gowen, R.J., et al., 2013. Framework for understanding marine ecosystem health. Mar. Ecol. Prog. Ser. 494, 1–27.

Thulin, J., 2009. The recovery and sustainability of the Baltic Sea large marine ecosystem. In: Sherman, K., Aquarone, M.-C., Adams, S. (Eds.), Sustaining the World's Large Marine Ecosystems, viii + 140. IUCN, Gland, Switzerland.

UNCED, 3–14 June 1992. Report of the United Nations Conference on Environment and Development. Rio de Janeiro.

UNDP/GEF, 2009. Project: Reducing Environmental Stress in the Yellow Sea Large Marine Ecosystem. Strategic Action Programme for the Yellow Sea Large Marine Ecosystem. ⟨www.yslme.org⟩.

USEPA, 2004. National Coastal Condition Report. 286. United States Environmental Protection Agency, Washington, DC.

Wang, H., 2004. Ecosystem management and its application to large marine ecosystem management: science, law, and politics. Ocean Dev. Int. Law 35, 41–74.

WSSD, 2002. Report of the World Summit on Sustainable Development, Johannesburg, South Africa, 26 August–4 September 2002. New York, United Nations. p. 167.

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