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Food for Thought

Sustaining the world's large marine ecosystems

Kenneth Sherman*

National Oceanic and Atmospheric Administration, National Marine Fisheries, NEFSC, Narragansett Laboratory, 28 Tarzwell Drive, Narragansett, RI 02882, USA

**Corresponding author: tel: + 1 401 782 3210; fax: +1 401 782 3201; e-mail: kenneth.sherman@noaa.gov*

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In this essay, I review nearly six decades of a career in marine science and fisheries considering scientific contributions, successes, failures, and changes in my field of practice. My body of work has been in plankton research to support fisheries assessments, and in ecosystems programme development and implementation. I describe my early studies on Pacific plankton oceanography in relation to fisheries assessment, and subsequent studies of plankton oceanography and fisheries in relation to coastal ocean fisheries and management. Early in my career, realizing that applications of my published results and those of other fisheries ecologists were generally not included in fish stock assessments, I participated in a national planning group that introduced a system for marine resources monitoring, assessment, and prediction (MARMAP) that included primary productivity, ichthyoplankton, zooplankton, and oceanographic assessments as important components for large-scale fisheries ecology assessment. I joined with European colleagues in ICES to advance fisheries ecology studies in fish stock assessments in the 1970s and 1980s. In 1983, I conceived with Professor Lewis Alexander of the University of Rhode Island a system for assessing and managing marine resources within the spatial domain of ecologically delineated large marine ecosystems (LMEs). On behalf of the National Oceanic and Atmospheric Administration, and in partnership with developing countries, international financial organizations, UN agencies, and NGOs, I am currently contributing scientific and technical advice to a global network of assessment and management projects in 22 LMEs with 110 developing countries and $3.1 billion in financial support. The participating countries are applying a modular framework of natural science and social science indicators for assessing the changing states of LMEs. I conclude the essay with a retrospective viewpoint on my career and changes over half a century of practicing the application of marine science in relation to sustaining the goods and services of the ocean Commons.

Keywords: ecosystem-based assessment and management partnerships, fusion of science and management, large marine ecosystems.

Introduction

During my 55-year career in marine science, my contributions have been focused on three bodies of work: (i) plankton research; (ii) advancing the inclusion and application of plankton monitoring and assessment into the management of marine fisheries; and (iii) development of a multidisciplinary and multisectoral modular approach to monitoring, assessing, and managing marine resources within the spatial domain of large marine ecosystems (LMEs).

LMEs occupy coastal ocean space around the margins of the continents. They produce 80 per cent of the world's annual marine fish catch (Pauly *et al*., 2008), are overfished, polluted, and subject to nutrient overenrichment, acidification, accelerated warming from climate change, loss of biodiversity and key habitats under stress, including sea grasses, mangroves, and coral reefs. These stressors are impacting the sustainable development of an estimated $12 trillion annually in coastal ocean goods and services contributed by LMEs to the global economy (Costanza *et al*., 1997). In relation to global fisheries, progress is being made in rebuilding fisheries, particularly in countries with advanced economies, as recently described online in the *ICES Journal of Marine Science* (Hilborn and Ovando, 2014). Recently, it has been reported that most of the advancements in science have been evolutionary rather than

Food for Thought articles are essays in which the author provides their perspective on a research area, topic or issue. They are intended to provide contributors with a forum through which to air their own views and experiences, with few of the constraints that govern standard research articles. This Food for Thought article is one in a series solicited from leading figures in the fisheries and aquatic sciences community. The objective is to offer lessons and insights from their careers in an accessible and pedagogical form from which the community, and particularly early career scientists, will benefit.

revolutionary (Ioannidis *et al.*, 2014). My main body of scientific work has been in applying methods for sustaining the world's LMEs following an evolutionary track.

However, rebuilding fish stocks supporting small-scale coastal fisheries in developing countries remains a major challenge. In full recognition of the oceans' degraded condition and importance to society, world political leaders at the 2012 United Nations Conference on Environment and Development in Rio de Janeiro committed themselves and their countries to "... protect and restore the health, productivity, and resilience of oceans and marine ecosystems, and to monitor their biodiversity, enabling their conservation and sustainable use for present and future generations: ... and in doing so, to ... effectively apply an ecosystem approach and the precautionary approach to the management, in accordance with international law, of activities having an impact on the marine environment ... " (RIO+20, 2012).

What follows describes the evolutionary emergence of the global movement towards the sustainable development of LMEs and the contributions made during my early career to advance plankton and early life history studies in support of fisheries management practices, and contributions made in the latter half of my government research and administrative service to the development of a modular assessment strategy in support of ecosystem-based management (EBM) practice in LMEs.

Plankton studies

During my first two decades practicing as a marine scientist, beginning in the early 1960s, I was struck by the highly sectorized partitioning of fishery scientists into stock assessment specialists at the top of the analytical pyramid and the specialists in plankton, pollution, and habitat assessment at the bottom. Each of us at the bottom layer was working more or less in response to funds appropriated by national governments to address a special problem of interest to their constituents, including as examples, fish stock depletions, dumping of contaminated sediments, spatial extension, and frequency of red tide events causing closure of shellfishing. It was common practice for government fisheries agencies in the 1960s and 1970s to be rather conservatively funded and therefore allowed little flexibility to support broad-scale multidisciplinary marine science or marine fisheries programmes.

In the 1960s, very few specialists in plankton were employed by government-supported fisheries organizations, including the Bureau of Commercial Fisheries (BCF). As a plankton specialist at the Honolulu Laboratory of the BCF, I studied plankton as indicators of movement of surface water types in an early effort by tuna assessment scientists and physical oceanographers to forecast seasonal arrival of skipjack tuna, *Katsuwonus pelamis*, in the Central Pacific to the Hawaiian Islands hook and line fisheries. While I was successful in relating copepods to movements of surface waters in the Central Pacific (Sherman, 1963, 1964), I was not successful in relating my findings to any tuna assessment or management measures. Tuna research in the 1960s was in support of fisheries expansion and not limits on catch.

It was common practice in the 1960s for marine scientists engaged in fisheries studies to publish papers in their disciplines (e.g. plankton, oceanography, pollution, and early life history studies), thereby contributing to the larger body of marine science and fisheries literature, more than contributing directly to a fish stock assessment for fisheries management and sustainability. Today, with the larger funding base, government and academic institutions can mobilize large-scale multiyear projects where team work across disciplines is a requisite for a successful career. In the 1960s, we were in effect contributing a small piece to a larger issue of fisheries sustainability that was overshadowed by an overriding interest of the fishing industry of the time to accelerate the growth of industrial scale fisheries. The negative effects of continued fishing expansion were becoming understood by senior government officials at national levels, but they were not being readily transferred from senior agency administrators downwards in clearly articulated policies to the bench scientists until the decade of the 1970s following actions prompted by legislatively extending national ownership over coastal resources.

I transferred from the BCF Honolulu Laboratory in 1963 to the BCF Laboratory in Boothbay Harbor, Maine. In the 1970s, extension by nations to legal jurisdictions over coastal ocean goods and services brought a new vitality to multisectoral marine studies. The establishment of national Fishery Economic Zones and Exclusive Economic Zones (EEZ) in the 1970s and 1980s accelerated the growth of marine institutions, agencies, and academic institutions. National ownership conditions initiated a period of growth, allowing for practice of fisheries assessment and management to undergo broadening support for fishery ecology and oceanography studies. I welcomed the change and the opportunity to test hypotheses of Hjort on spawning stock and year-class strength of fisheries (Hjort, 1914, 1926), Hardy on zooplankton and herring fisheries (Hardy *et al.*, 1936), and Glover on the continuous plankton recorder (CPR) and ocean plankton variability (Glover, 1967; Glover *et al.*, 1973). From my research position at the Boothbay Harbor Laboratory, I focused on extending zooplankton and ichthyoplankton research to generate results pertinent to fisheries assessments, with a series of papers on plankton abundance and composition in relation to the Gulf of Maine coastal fishery for Atlantic herring *Clupea harengus*, and to predator–prey studies of zooplankton, herring, and other species in the coastal waters of the Gulf of Maine (Sherman and Schaner, 1965, 1968a, b; Sherman, 1966; Sherman and Honey, 1970a, b, 1971a, b; Sherman and Perkins, 1971). However, our new scientific findings were rarely afforded significant consideration in any fishery management actions. I was able to address this disappointing situation later, when the National Marine Fisheries Service was integrated into the National Oceanic and Atmospheric Administration (NOAA) in 1970 (EOP, 1970) and with colleagues in ICES during the 1970s and 1980s. Today, foodweb-based trophic analyses are widely used to estimate sustainable fisheries yields.

Marine resources monitoring, assessment, and prediction years

In response to the formation of NOAA, the NMFS leadership initiated the planning of a more centralized and broadened, environmentally aware approach to fisheries assessment and management for the United States. It was in 1970 that I was recruited from my plankton studies of the Gulf of Maine to a 24-month stint, to champion plankton and hydrographic survey expansion, in the programme development process of a planning group at NMFS headquarters in Washington DC, led by Dr Robert Edwards. Dr Edward's strategy was for NMFS to become part of NOAA with an operational national programme. The NMFS group developed a more multidisciplinary, integrative approach to fisheries stock assessments in collaboration with TRW Corporation, a Redondo Beach California Aerospace Company. I was engaged heavily with TRW engineers, in the adoption of aerospace programme engineering to ocean sampling methodologies and to the preparation of event logic diagrams (ELDs). The ELDs were used to guide the NMFS Planning Group in the development of national plans for oceanographic, zooplankton, ichthyoplankton, and fish stock surveys in support of more informed fishery management practices. The surveys were to be operated from each of four NMFS Research Centers located in the Northeast, Southeast, Southwest, and Northwest regions of the United States. The national survey approach was called MARMAP for marine resources monitoring, assessment, and prediction, and was implemented with funding secured by the new NOAA organization. The original plans that the Planning Group prepared and edited for NMFS have been archived (TRW Systems Group, 1973a, b, 1974). The Plans remain the basis of ongoing broadly based coastal ocean assessment methods under way by most advanced OECD nations. With other Group members, I formulated the application of the ichthyoplankton and zooplankton (I&Z) survey component of MARMAP that I had advocated for previously.

Although NOAA was formed in 1970, the agencies that came together at that time are among the oldest in the Federal Government. The agencies included the US Coast and Geodetic Survey formed in 1807 under President Thomas Jefferson, the Weather Bureau formed in 1870, and the BCF formed in 1871. The Environmental Data Service, the National Oceanographic Data Center, the National Satellite Center, and the research laboratories were also included in the new NOAA. In 1970, the assumption was that these agencies could be moulded into a first-class National Oceanographic and Atmospheric Administration with responsibility for conducting fisheries and geophysical research while also monitoring and assessing changing national and global environmental conditions.

Following decades of experiencing separate sector-by-sector efforts at managing coastal marine resources, it became apparent that NMFS could move forward with the senior officials of the newly established NOAA already conversant with the importance of research and time-series monitoring of the planet's atmospheric and oceanographic space. NOAA's Ocean and Atmospheric research focused on short- and long-term climate forcing of weather conditions in an effort to improve weather forecasting of the National Weather Service. The NOAA Corps operated a fleet of ocean-class vessels, while the National Environmental Satellite Data Information Service partnered with NASA in developing and gathering global scale environmental data from satellite-borne ocean sensors. The coastal-zone management and pollution assessment responsibilities of the National Ocean Service provided opportunities for NMFS to move fisheries research, assessment, and management towards a more comprehensive, multidisciplinary, and multisectoral ecosystems approach to coastal ocean assessment and management of marine goods and services.

ICES connection

The research and policy planning experience at NOAA–NMFS headquarters was instructive and personally transformative. On return to the NEFSC and its Narragansett Laboratory as a leader of a fishery ecology group, and national coordinator for MARMAP, I was strategically positioned to advance the application of plankton studies and assessments into the NEFSC fisheries assessment programme. I focused on encouraging the fisheries science community to broaden from a principal focus on stock assessment to include studies of fisheries ecology time-series assessments and I&Z in relation to early life history of fish, predator–prey interactions, spawning variability, as well as ecosystem productivity, biomass yields, and biodiversity studies. From 1976 to 2003, results of our studies of the Northeast Shelf plankton and fisheries were regularly reported to the ICES community in a continuous body of results presented to the Plankton and Biological Oceanography Committees where I served as US participant and as Chair. During the 1980s, I continued to support implementation and operation of time-series surveys of I&Z and other marine species as a member and editor of the SCOR sampling methods group for the Antarctic (Biomass, 1982a, b) and as the US-NMFS scientific advisor to the Commission for the Conservation of Antarctic Living Marine Resources (Sherman and Ryan, 1988).

Two ICES reports based on symposia results document the initiation of a European movement towards ecosystem-based assessment and management. In the first report entitled, "North Sea Fish Stocks—Recent Changes and Their Causes", Professor Gotthilf Hempel, the convener of the same named ICES Symposium, addressed long-term causes of changes in fish stocks of the North Sea. Among the authors of the multidisciplinary contributions were European hydrographers, planktologists, biogeochemical specialists, pollution experts, benthologists, and fishery stock assessment biologists and demographers (Hempel, 1978). This was followed with publication of the results of four symposia held during the Joint Oceanographic Assembly in Edinburgh in 1976 and published as "Marine Ecosystems and Fisheries Oceanography" in the ICES *Procès Verbaux* series. The volume was edited by Parsons, Tomsson, Longhurst, and Sætersdal, with contributions from an international gathering of multidisciplinary marine scientists (Parsons *et al.*, 1978). Professor Hempel's contributions to forging linkages between the ICES community and the fishery ecology community were notable (Hempel and Sherman, 1993; Hempel and Sherman, 2003). The 43 I&Z-related papers from 1976 to 2003 that I presented at ICES Annual Meetings are listed at www.lme.edc.uri.edu.

Early life history studies

One of the study areas of fishery sciences that benefitted from the post-EEZ increased investments of national governments was early life history studies (ELH) of fish. In an effort to bring the results of these studies into the emergent thinking about the role of I&Z in growth and survival of young stages of fish, I joined with Reuben Lasker to convene an ICES Symposium on The Early Life History of Fish in 1979. The venue was the Marine Biological Laboratories in Woods Hole, Massachusetts, where the 343 participants representing 21 countries contributed important papers on ELH pollution, modelling, enclosure studies, distribution and abundance, physiological ecology, rearing and aquaculture, and systematics and development (Lasker and Sherman, 1981).

In the published volume, the overview remarks of Alan Saville and Deitrich Schnack on the application of I&Z surveys and studies to the advancement of fisheries stock assessments in 1981 are quite relevant to inclusion of time-series surveys in support of EBM in LMEs today. They argued that:

> There are many reasons for wanting to know something about the distribution and abundance of the early life history stages of fish. Most marine fish species grow during their early development through a planktonic phase and thus affect, and are affected by the interspecific relationships of plankton communities. The temporal and regional occurrence of the eggs and larvae of fish is, therefore, of interest in relation to basic research on the dynamics of plankton communities, as well as with respect to the life history conditions during the development of the early stages when they are subject to rather

> different factors than at later ages. To some extent, basic ecological studies of this kind satisfy intrinsic intellectual curiosity, and this may be an adequate reason for most inquiries. However, these basic studies receive much greater motivation from the practical demands of the fisheries to further our knowledge of, and ability to control, the factors governing the yields which can be taken from the fish stocks. They can provide a means of predicting the effects of man's activities in the sea, other than fishing, on potential yields of fish. These applied aspects produce the main forces and financial backing necessary for the study of the distribution and abundance of the early life history stages of fish on an adequate scale.

They conclude their overview paper with the following:

> Judging from the contributions presented to this symposium, continuing effort is aimed at defining factors and time periods during the early life history of fish which may be critical for year-class success. At the present time, however, studies of distribution and abundance are being directed in two major directions:
>
> (a) determining spatial and temporal distributions in the near coastal zone chiefly to provide background information against which the effects of industrial interference with the environment can be evaluated:
>
> (b) obtaining some fisheries-independent measure of exploited stocks.
>
> A better understanding of the complex of ecological relationships into which the early life stages of fish are integrated is required before prediction of recruitment becomes less problematic.
>
> Rapp.P.-v. Réun. Cons. Int. Explor. Mer, 178: 153–157. 1981.

Both objectives remain valid reasons for continuing time-series surveys of I&Z in support of EBM in LMEs. Later, large-scale studies on the recruitment process including GLOBEC were more sharply focused on the biological and oceanographic processes controlling fisheries year-class success as reviewed recently by Rothschild (2015). During the present and next decades, I&Z surveys are important to support, as the effects of climate change realign spatial and temporal trophic foodweb links. As was the case in the 1980s with the emergence of fisheries ecology studies, broad-scale I&Z assessments throughout the spatial extent of LMEs are important indicators of ecosystem conditions that need to be taken into consideration in relation to EBM options for sustaining marine goods and services (McClatchie *et al.*, 2014; Sheffield-Guy *et al.*, 2014). Time, the expense of sampling, and the expense in identification and enumeration of species in the samples are problems in the applications of I&Z data and information in the fishery assessment process. To overcome survey expense, we deployed paired bongo nets of different mesh sizes to collect I&Z on MARMAP bottom trawl surveys (Sherman, 1980). Through a bilateral joint fishery study with Poland's Sea Fisheries Institute, an arrangement was made with our Polish colleagues to establish a Plankton Sorting and Identification Center (PSIC) in Szczecin, Poland. Since 1974, the staff of the PSIC has expertly processed 280 000 bongo samples providing investigators species-specific data on 33 million eggs and larvae, and 19 million zooplankters (Ejsymont and Sherman, 2013). Annual reports of the US–Poland Fishery Ecology Studies Advisory Committee, including lists of hundreds of important I&Z publications relative to Fisheries Ecology, are on file at the NOAA, NEFSC Narragansett Laboratory.

Fusion of science and policy at the LME scale goes global

While the ICES ELH Symposium results, and the MARMAP type I&Z surveys were continued, few of the published findings in the 1960s and 1970s were well enough advanced from an ecosystem perspective to be incorporated into actual stock assessments leading to management decisions. This situation led me to conclude that in the absence of an acceptable ecologically based assessment and management system for marine resources, the gap between marine science and improved EBM practices for fisheries and other marine sectors (e.g. pollution, habitats, energy production, shipping, tourism, and mining) would remain. It became somewhat of a personal challenge to overcome the gap and earlier disappointment in not realizing any significant management outcomes of earlier I&Z fisheries studies. It was the location of the national MARMAP activity at the Narragansett Laboratory of the NEFSC that provided ready opportunity for me to interact with the co-located University of Rhode Island Graduate School of Oceanography research programmes and the URI Marine Affairs policy-oriented programme. This propinquity and convergence of marine science and policy at the national and regional scales led to discussions and analyses with Professor Lewis Alexander on the delineation of LMEs as comparatively large areas of ocean space defined by ecological criteria including bathymetry, hydrography, productivity, and trophic linkages. These discussions and analyses proved quite productive. My science experience with plankton, fisheries, and MARMAP were well complemented with Lew Alexander's training and experience as a marine geographer and Professor of Marine Affairs. Together we collaborated on fusing marine resources management, based on Lew's conversance with Law of the Sea principles and my approach using ecological criteria for defining LME boundaries, providing opportunity for the convergence of science and management at the scale of LMEs. The fusion of science-based, multidisciplinary, and multisectoral assessment methodology with management policy within the spatial domains of LMEs as global management units proved to be of interest to marine scientists as well as to marine policy experts and their colleagues in law, governance, and economics. To provide a forum for open discussion of the LME approach, we convened the first Symposium on LMEs at the Annual Meeting of the American Association for the Advancement of Science in 1984 in New York. The Symposium was selected by the AAAS for inclusion in the AAAS Symposium series and the results published in the seminal LME volume entitled, *Variability and Management of Large Marine Ecosystems* (Sherman and Alexander, 1986). This volume was followed by three others between 1986 and 1991 (Sherman and Alexander, 1989; Sherman *et al.*, 1990, 1991).

The MARMAP studies served as the foundation of a modular strategy for monitoring and assessing the changing states of ecological conditions in LMEs. In 1991 and 1992, I convened with Professor Simon Levin two NOAA-sponsored workshops at Cornell University and one at the NEFSC Narragansett Laboratory to consider the theoretical and practical basis for monitoring the changing states of LMEs. Among the topics examined were data analysis from the Great Lakes (H. Regier), measuring eutrophication in the North Sea (H. Skjoldal), scales for measuring biophysical dynamics of marine ecosystems (J. Steele and S. Levin), fisheries assessments (M. Sissenwine and J. Pope), time-series and ecosystem perturbation (A. Solow), and the CPR and ocean physics and climatology (R. Williams). Concurrent to the workshops, expert lectures were being presented at Cornell on the topic of long time-series analyses that included presentations on ocean-driven climate change effects (W. Broecker), long-term biophysical plankton relationships (R. Dickson), analyses of time-series (A. Solow), coupled ocean models (J. Sarmiento), long-term population variability (S. Pimm), biophysical coupling (J. Steele), and time-scales ecology vs. evolution (S. Levin). The results of the Cornell and Narragansett Workshops and lectures and meeting of experts at a 1991 meeting at IOC-UNESCO, and an earlier meeting on LME assessment strategy with a similar outcome convened at IOC-UNESCO, provided input to the formulation of the five-module framework for monitoring and assessing changing ecological states of LMEs (Sherman and Laughlin, 1992a, b; Sherman, 1993). A list of all 28 reports and publications supporting the five-module approach is available at www.lme.edc.uri.edu.

Following the printing and circulation of the first four LME volumes, I received an invitation in 1992 to brief senior executives at the Global Environment Facility (GEF) in Washington DC and followed up with a briefing on LMEs at the World Bank (WB). The outcome of the briefings was an invitation to NOAA to provide scientific and technical assistance to a funded port expansion project in Korea, and to a UNEP pollution reduction effort under way in West Africa. The express purpose of the former was to assist the GEF and WB in providing advice to representatives of the People's Republic of China and the Republic of Korea in adapting an LME-wide assessment and management strategy for the Yellow Sea LME. For West Africa, the GEF and WB requested NOAA assistance to six Gulf of Guinea countries to transform a pollution project into a multisectoral Gulf of Guinea ecosystem-based assessment and management project. The six countries engaged in the pollution project were Nigeria, Ghana, Ivory Coast, Benin, Cameroon, and Togo.

I was advised by executives at the GEF and WB that the LME approach, described in the volumes, for including multidisciplinary and multisectoral inputs of both natural and social scientists towards EBM practice was key to their interest in proceeding with providing financial assistance to developing countries. In the cases of the Yellow Sea and Gulf of Guinea, the participating countries were committed at national government ministerial levels to the application of the LME approach to the sustainable development of their coastal ocean marine resources.

Natural and social science LME foundations

The interest in providing financial support to developing countries by international financial institutions, to advance ecosystem-based assessment and management practices, was an unexpected outcome of the publication of LME volumes by the AAAS, Blackwell Science, and Elsevier Science. As a result of the wide circulation of the LME volumes and journal publications, I and others on behalf of NOAA have been providing scientific and technical advice to LME projects conducted by developing countries around the globe since the mid-1990s (Sherman, 1995, 2006; Sherman and Duda, 1999b, c, 2001; Ajayi *et al.*, 2002; Duda and Sherman, 2002; Sherman *et al.*, 2003, 2005, 2009, 2013; Sherman and Duda, 2007; Sherman, 2014b). Since 1995, in response to growing interest in the LME approach, I joined with the network of professionals engaged in LME projects in publishing a number of journal articles. Much of the application of marine science studies and results from which the LME approach has advanced can be found in the chapters of 14 published LME volumes. In the 20-year period between 1986 and 2006, 450 marine scientists, economists, lawyers, and policy specialists contributed chapters that resulted in strengthening the natural science and social science base of LME assessment and management practice. The application of science to the governance of LMEs was predicated on the legal standing of ecologically defined domains of LMEs as global units for the management of coastal ocean goods and services (Belsky, 1986, 1989, 1992). The LME volumes are listed along with chapter titles and authors and selected journal articles on LMEs at www.lme.edc.uri.edu.

One of the important highly visible and most controversial papers on comparative LME studies of fisheries yields was published in *Science* by Worm *et al.* (2006), indicating severe fisheries consequences from overexploitation by 2045. In a subsequent comparative study, this extreme overexploitation postulate was modified significantly (Worm *et al.*, 2009). Other LME studies have compared expected positive results from rights based fisheries management practice (Costello *et al.*, 2008), comparative length relationships (Fisher *et al.*, 2010), total biomass yield models (Christensen *et al.*, 2009), and more recently sustainable yield forecasts for LMEs based on trophic modelling (Rosenberg *et al.*, 2014). In addition to the publications, another important focus was to maintain the capability for responding rapidly to opportunities for catalysing financial support to the most populated and poorest economically developing coastal ocean communities in the world. Within the countries along the coasts of these LMEs, there is critical need and political will to halt and reverse the downward spiral of ecological stress on the shared transboundary goods and services.

Modular LME framework

Application of an operational five-module framework for assessing changing ecological states of LMEs applying indicators of changes in LME (i) productivity,(ii) fish and fisheries, (iii) pollution and ecosystem health, (iv) socio-economics, and (v) governance has strong appeal to developing countries seeking LME projects, largely attributed to transparency of the modules to the scientists, resource managers, and ministerial representatives of participating countries and their United Nations partners (e.g. UNDP, UNEP, UNIDO, FAO, and IOC-UNESCO) serving as implementing agencies or executing agencies for LME projects. The modular LME framework supporting EBM management has been well reported in the literature (Sherman and Duda, 1999a, b; Wang, 2004a, b; Carlisle, 2014; Sherman, 2014a, b). The first three modules require time-series metrics on the changing conditions of productivity in relation to chlorophyll, primary productivity in an average value of gCm^2 year^{-1} (Sherman, 2014b); sea surface temperature (Belkin, 2009); fish and fisheries (Pauly *et al.*, 2008); and pollution and ecosystem health, pertaining to nutrient overenrichment and multiple marine ecological disturbances (Sherman, 2000; Seitzinger and Lee, 2008; Seitzinger *et al.*, 2008). The remaining two modules are focused as socio-economic benefits to be derived from healthy LMEs and governance practices supporting LME management (Juda and Hennessey, 2001; Wang, 2004a; Hoagland *et al.*, 2005; Sutinen *et al.*, 2005).

In moving countries towards EBM and sustainable development of LME goods and services, developing countries participating in LME projects are practising a strong bottom-up country-driven planning process. Working together partnering countries sharing transboundary goods and services of an LME complete a transboundary diagnostic analysis (TDA) that describes root causes of ecological stress and prioritizes a series of actions to recover from the stress and move forward to a more sustainable development of LMEs. Countries sharing LME resources proceed to implement actions to relieve stress and pursue EBM through the preparation by the countries of an agreed-upon strategic action plan (SAP) that carries governmental approvals from the multiple ministries responsible for LME goods and services including ministries of fisheries, mining, energy, environment, tourism, shipping, development, and finance (Carlisle, 2014).

The TDA and SAP process is little known beyond the UN agencies responsible for carrying forward the goals set forth for improving the oceans of the world in language crafted and signed off on at the three global environmental summits important to the LME sustainability movement: the United Nations Conference on Sustainable Development (UNCED) of 1992, the World Summit on Sustainable Development in 2002, and the Rio +20 UNCED summit of 2012 (UNCED, 1992, 2012; WSSD, 2002). The language affecting coastal and ocean ecosystems can be downloaded from online copies of the Summit reports published by the United Nations, summarized in Table 1. The importance of the Summit declarations is seen in the positive responses of world governments in providing funds to international financial institutions including the GEF and WB, to support the TDA and SAP implementation plans for LME projects. Having engaged in the top-down planning and implementation of broad-scale marine resources assessments like MARMAP, I favour the bottom-up application applying the TDA and SAP planning process for bringing multinational science and economic stakeholder interests together from the earliest phase of project conception through the full implementation phase. Providing substantial financial support to participating countries for an average 12-month planning phase by the GEF has proved to be an effective means to build a firm international project foundation leading to innovative EBM assessment and governance regimes. Participating in this process results in consensus agreement on priorities for orchestrating actions for reducing human-induced and environmental stressors on LME goods and services. I have observed the TDA and SAP process successfully deployed in Asia, Africa, and Latin America, and recommend its application in the OECD countries where, up to now, the application of EBM practices remains quite limited (MEAM, 2015).

LME pathway to EBM

At present, marine resource ministries in 110 developing countries are in various phases of introducing and practicing EBM in 22 of the world's LMEs supported with $3.1 billion in financial assistance from the GEF, WB, and other donors (Sherman, 2014b). Six of these countries participated in the pilot project in the Gulf of Guinea in the mid-1990s. The project was expanded to encompass the full 16-country Guinea Current LME extending over the entire ocean space of the LME, from Guinea Bissau in the northwest of Africa to Angola in the southwest (Honey and Elvin, 2013). Planning is now under way for a third-phase SAP for this project. Similarly, a ports project of Korea has been expanded to a TDA- and SAP-supported, multimillion dollar EBM project for the Yellow Sea LME, jointly conducted by the People's Republic of China and the Republic of Korea. In the Guinea Current LME and Yellow Sea LME and in other LME projects, the combined TDA and SAP process, developed within the five-module framework of metrics on changing LME conditions, allows sufficient transparency for common understanding among civil society, scientists, and policy-makers to advance their LME projects towards EBM practice. The lesson learned is that transparency is critical to multisector project approval. A list of projects supporting the EBM approach to LME assessment and management is published and can be downloaded (Sherman, 2014b).

As the global LME movement for introducing EBM practice by developing countries advances around the globe, another lesson learned becomes apparent. The bottom-up country-driven TDA and SAP planning and implementation of LME projects has proved a practical pathway for closing the global digital North-South divide, of concern to a growing community of

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

United Nations Conference on Environment and 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 for 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

Sustainability Science proponents (Kates *et al.*, 2001) in developing and developed countries.

The global movement towards sustaining LMEs is on a robust financial pathway during the 2014–2018 period. A sum of $2.8 billion is being allocated for initiating new LME projects and augmenting other projects. These projects are focused on fisheries recovery and management, pollution reduction and control, coastal-zone management, biodiversity conservation, reduction of nutrient over-enrichment, acidification control, and establishment of marine protected areas. The funds are available from the GEF and WB to support project proposals submitted by developing countries in partnership with accredited UN or other agencies and organizations including NGOs. Among the OECD countries, the United States is partnering with Mexico and Caribbean Sea Island States in the joint planning and implementation of a second 5-year phase of the GEF-supported Gulf of Mexico LME and Caribbean Sea LME Projects. Using similar framework planning, the US is engaged with the Russian Federation in a GEF-supported LME project for the West Bering Sea LME. Although not a GEF-supported project, the Russian Federation and Norway are managing the greatly expanding fisheries of the Barents Sea from an ecosystem perspective. Also, in accordance with the Obama administration's Ocean Policy, the United States is moving towards EBM practices in 11 LMEs along the US coasts—NE Shelf, SE Shelf, Gulf of Mexico, Caribbean Sea, California Current, Gulf of Alaska, East Bering Sea, West Bering Sea, Chukchi Sea, Beaufort Sea, and Insular Pacific Hawaiian.

The emergence of a global movement towards EBM of LMEs over the three decades, since the first AAAS symposium in 1984, has generated positive results. For the highly degraded Yellow Sea LME, the People's Republic of China and the Republic of Korea are enlarging their capacity to control and clean-up coastal pollution to recover depleted fisheries and deploy EBM practices. Examples of the forward movement can be found in the successes in reducing fishing effort on overfished stocks and in the implementation of integrated multi-trophic aquaculture (IMTA; Fang *et al.*, 2009; Walton and Jiang, 2009). Strides are being made in Africa for stronger links between science and governance of LME goods and services with the establishment of interim LME Commissions. The Interim Guinea Current LME Commission was established to address assessment and management of goods and services of 16 countries (Honey and Elvin, 2013). The Benguella Current LME countries of Angola, Namibia, and South Africa have established both a Commission and a Convention for sustainable development of the BCLME (Hamukuaya and Willemse, 2013).

On behalf of NOAA and in cooperation with IOC-UNESCO, I co-chaired with IUCN a series of 14 IOC-LME Annual Consultative Committee meetings from 1999 to 2013 to compare results of LME project assessment and management practices. The results reported to the meetings with regard to fish and fisheries were encouraging for the Yellow Sea, Benguella Current, Canary Current, and Humboldt Current LMEs where fisheries catch limits were being implemented in an effort to rebuild depleted stocks and maintain them as sustainable resources. Also, recent results were shared on the likely negative impacts on fishery yields from an expected lowering in primary production from climate warming being forecasted for 29 LMEs in a circumglobal belt between 30°N and 30°S. These results have been shared with the policy experts from the affected LMEs to allow for consideration of precautionary management options (Sherman, 2014b). In another report, UNDP representatives described a successful approach to catalysing substantial amounts of ocean finance for LME recovery and sustainability (Hudson and Vandeweerd, 2013). Other presentations important to the global movement towards EBM practice in LMEs were on recent trends in climate change effects on LMEs (Sherman and McGovern, 2012). The IOC-LME meeting reports and other sources listed here can be downloaded from the LME website: www.lme.edc.uri.edu. At the 2013 annual meeting, 47 scientists and policy advisors and project managers participated from Asia, Africa, Latin America, eastern Europe, North America, and the Pacific. The LMEs from which results were reported included the Humboldt Current LME, Guinea Current LME, Gulf of Mexico LME, Canary Current LME, Bay of Bengal LME, Agulhas Current LME, Somali Current LME, Benguella Current LME, Yellow Sea LME, South China Sea LME, SuluCelebes Sea LME, West Bering Sea LME, Indonesian Sea LME, Mediterranean Sea LME, and Caribbean Sea LME. To enhance exchanges resulting from the movement towards EBM as practiced by the industrialized countries of ICES with the economically developing countries and their LME projects, ICES has organized a Working Group on LME Best Practices. The WGLMEBP is co-chaired by Hein Rune Skjoldal (IMR Bergen, Norway) and Rudy Hermes (Chief Technical Officer of the Bay of Bengal LME project). The WGLMEBP is providing an important platform for exchanging results, ideas, and sharing progress aimed at sustaining the world's LMEs. In early 2016, IOC-UNESCO will release the first global Transboundary Waters Assessment that will include five classes of international waters—groundwater (aquifers), rivers, lakes, open ocean, and LMEs. The LME global assessments will be focused on the five-module LME assessment and management framework (www.geftwap.org).

In retrospect

In relation to lessons learned, I subscribe to the notion that ecological science is far more evolutionary than revolutionary in its application to improving the present global environmental condition. Among the lessons learned in advancing the LME approach towards the sustainable development of coastal oceans are: (i) new ideas should be brought forward in open scientific fora to debate and advance the concept. (ii) Concentrate focus on the concept in peer-reviewed volumes, and in journal publications. It was, in fact, the strong base of tightly linked natural science and social science contributions to the peer-reviewed LME volumes that constituted the multidisciplinary and multisectoral base of the LME approach that caught the attention and support of international financial institutions and United Nations environmental agencies. The substantial funding subsequently supporting LME projects in developing countries served to elevate the application of the LME approach to address the United Nations' environmental mandates. (iii) Another important lesson learned is the advantage, in science-policy interactions, of maintaining credibility of an active I&Z researcher while networking a new ecosystem-based concept with a community of like-minded individuals and institutions in partnerships along a common pathway. (iv) Multidisciplinary and multisectoral management of marine goods and services can be achieved within the spatial domains of LMEs as evidenced by the accomplishments of hundreds of scientists and others engaged in meeting the daily challenges of LME assessment and management practice.

From the perspective of a plankton fisheries ecologist and oceanographer, as I take a look at marine science and its contribution to fisheries and other marine sectors, I am encouraged by the steady evolution towards multidisciplinary and multisectoral EBM practice. My outlook for the future of EBM practice in LMEs is quite positive. I am pleased with the progress that has been achieved in the monitoring and assessment of I&Z in LMEs along with other biogeochemical and physical constituents of coastal ocean waters in support of sustainable development of marine resources. Prospects for good progress under the framework of EBM can be found in the recently published pertinent review papers on behalf of I&Z time-series surveys (McClatchie *et al.*, 2014); early life history studies appear continuing at a healthy pace (Llopiz *et al.*, 2014), as are studies of the recruitment process during climate change (Sheffield-Guy *et al.*, 2014). From the results reported by Peterson *et al.* (2014), it is clear that inferences from zooplankton surveys of the California Current LME can be instructive for predicting salmon biomass yields (Peterson *et al.*, 2014). The clarion call has, however, been sounded by Koslow and Couture for extending the I&Z time-series into more coastal waters than are currently covered by surveys (Koslow and Couture, 2013, 2015). I concur with their call for action and have indeed, since 1995, included I&Z indicators in the modular approach to LME monitoring and assessment in support of EBM practice in LME projects around the globe.

My interest in contributing my expertise in plankton biology and ecology to fisheries assessment and management, although thwarted in the 1960s and early 1970s, did serve to establish a professional foothold on a pathway where I could envision a way forward towards a more broadly based ecosystem approach to fisheries stock assessment in the late 1970s. With the ownership of marine resources accrued to coastal nations through EEZ legislation in the mid-1970s, the pathway grew wider and smoother with national funding augmentation that spurred NOAA in the Northwest Atlantic and ICES in the Northeast Atlantic to greater support for me and like-minded supporters of I&Z and ELH studies and assessments as integral components of evolving systems approaches to multisectoral ecosystems-oriented management. As part of the fishery ecology movement of the 1970s and early 1980s, my interest in advancing the ecological movement led to open dialogue with colleagues in marine policy and marine affairs. We were able to formulate within the spatial domain of the LME approach, a basis for linking multisectoral science-based assessment to support the policy of sustainable development of the oceans declared at three world environmental summits. Through application of the five-module LME approach, developing countries in Asia and Africa have demonstrated the successful application of EBM towards sustainable development of their coastal ocean goods and services. Much remains to be accomplished. However, the LME pathway towards EBM and ocean sustainable development has been cleared and opened for advancing EBM practice.

I have had the unique privilege of observing and participating in a paradigm shift from multiscale marine resources assessment and management practices generally applied to single marine sectors in the 1960s and 1970s to the present emergent movement towards EBM from the mid-1990s to the 2000s as expressed by Lubchenco (1994) and McLeod *et al.* (2005). The most notable drivers towards this paradigm shift were (i) the policy decisions among the global community of nations to extend national jurisdictions to 200 miles in the mid-1970s, (ii) the expanding global populations increasing market demands for marine products, and (iii) the recognition by the 1980s of coastal ocean limits to renewable resources.

Recent reports of fish stock depletions, nutrient overenrichment leading to oxygen depletions and fuelling harmful algal blooms, emerging hypoxic events, habitat degradation from sewage, oil spills and blowouts; acidification; biodiversity losses; and climate change-induced sea level rise, bring an unprecedented level of public and private sector awareness and support in favour of multisectoral EBM practice. This new awareness can be attributed in part to the widely circulated scientific and public press reports from three global environmental summits (1992 UNCED, 2002 WSSD, 2012 Rio+20) exerting a positive influence on international financial organizations to support EBM practices for the long neglected economically developing countries around the globe. By virtue of what may be called due-diligence over a half-century career, the application of methodologies for monitoring and assessing changing coastal ocean conditions in support of renewable coastal ocean resources management from an ecosystem perspective, marine scientists from both the OECD and developing countries communities now have sufficient financial support to initiate a more deliberately planned movement towards EBM. As one of those closely engaged in supporting EBM practice, I believe that we have the opportunity to extend scientific and technical assistance to those hundreds of million of people inhabiting economically developing coastal nations around the globe whose government leaders welcome the assistance. Among the poorest countries are those bordering the Somali Coastal Current, the Agulhas Current, Guinea Current, Benguella Current, and Bay of Bengal LMEs. These countries have already successfully completed their first 5-year LME-EBM projects and are in the process of planning and implementing additional 5-year phases. It is most fitting, in this regard, that the ICES LME Best Practices Working Group will be engaged with IOC-UNESCO and the aforementioned countries and their UN partnering agencies on the best practice for supporting EBM.

As I look back on my career, I should like to underscore several lasting impressions. The first is on the importance of mentoring. As a graduate student at the University of Rhode Island, it was the enthusiastic inspiring lectures of Professor David Mariotti Pratt on plankton ecology that led me to a fascination and professional commitment to the study of marine plankton. Later, as a young marine biologist, my one-on-one periodic conversations on the Gulf of Maine zooplankton with Henry Bigelow at the Museum of Comparative Zoology, comparing my findings in the early 1960s with his pioneering "Calanus Community" results of the 1920s through 1940s, brought a new level of enthusiasm for my plankton work at the BCF Boothbay Harbor Laboratory. To this day, I remember his salty and direct descriptions of "Calfin" and "Pmin" seasonal abundance cycles, and the surprising arrival in the mail of a personal copy of the Plankton of the Gulf of Maine accompanied by a short note. The note simply stated, "Dear Sherman, I find that I still have two copies of my paper on the plankton of the Gulf of Maine, so I am sending you one of them. It will do a lot more good in your hands than it would in mine! Yours, Henry BB. 4 October 1965". I was indeed fortunate to have benefitted from the personal inspiration of these two marine scientists and their lasting career-shaping legacies. The importance of mentoring was not forgotten later in my career in encouraging and supporting staff towards advanced academic studies, and in serving as adjunct faculty guiding graduate theses at the University of Rhode Island, and lecturing at the University of Massachusetts, Dartmouth Campus. In fact, on several trips to China and Korea, I was delighted to be greeted by senior officials who remembered my LME lectures while attending graduate school at URI.

Another impression is that studies in marine science and fisheries have shifted from a period in the 1960s, 1970s, and 1980s from limited spatial and temporal national and regional issues to the more broadly based ecological goals focused on recovery and sustainability of coastal ocean goods and services from a global perspective. Much of today's literature considers the global effects of climate change, excessive fishing effort, nutrient overenrichment, pollution, habitat degradation, biodiversity loss, acidification, and productivity. Unlike the earlier decades, the 2000s have brought forward a revitalized United Nations system with agencies actually assisting developing countries with introduction and practice of the ecosystems approach to sustaining coastal ocean goods and services.

When I served as a consultant on I&Z surveys for the FAO Fisheries Division in the 1960s as a means to improve fisheries assessments in developing countries in Africa and South America, I observed research vessels gifted to countries rusting at the dock from the lack of equipment and operating funds. I was listened to politely by in-country experts, but rarely experienced any follow-up actions. The sense of inertia was due in large part to the patronizing top-down approach of the UN system in the 1960s. In contrast, my experience in the 2000s has been in EBM planning and implementation workshops, allowing up to 12 months for country-driven planning to go forward among well trained in-country representatives of engaged key multisectoral ministries to prioritize transboundary issues stressing shared ecosystems. The workshops are producing through consensus, TDA and SAP planning documents subjected to approval by a GEF Council of peers in a very much bottom-up approach to sustainable development. The UN agencies serve the countries' interests, wherein partnerships among the UNDP, UNEP, UNIDO, FAO, and IOC-UNESCO, NGOs (WWF, IUCN), and donor institutions including Sweden's SIDA, Norway's NORAD, US-NOAA, Germany's GIZ, and others serve as LME project implementing or executing agents.

In the 1960s, there was no significant bottom-up UN system in place. In the 2000s, in response to the three World Environmental Summits, the reorganized UN environmental agencies have been empowered as a substantial World force in an institutionalized matrix. The GEF and WB contribution of \$3.1 billion between 1995 and 2013 is augmented by \$2.8 billion committed in the 2014–2018 pipeline representing in all \$5.9 billion. These funds support EBM activity in LME projects around the globe. Following a substantial period of underfunding, the billions of dollars now being catalysed are generating a positive and quantifiable outlook for the global movement towards sustainable development.

Is this a lucky circumstance? I think not. We have had benefit of 30 years of LME experience when science and management are practised within the same ecological unit. The simplified and highly transparent modular approach to LME assessment and management has proved useful to scientists and ministerial representatives alike. In this regard, a paper authored by a coalition of 12 ministers in support of the Benguella Current LME Commission carries the concept of country-driven LME projects as an example of LME Project best practices (Volume 17, *Environmental Development* journal, due out in early 2016).

It is, indeed, a rare privilege to have played a part in assisting developing countries on their forward movement towards sustainable development of LMEs. I am pleased to share a final lesson learned from my career experience. It is through individual participatory effort and commitment to the Common good that science practice can lead to lasting solutions to human and environmental global challenges.

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