TWAP
TRANSBOUNDARY WATERS ASSESSMENT PROGRAMME

Large Marine Ecosystems

A Global Comparative Assessment of Baseline Status and Future Trends

VOLUME 4: LARGE MARINE ECOSYSTEMS

UNEP

gef

United Nations
Educational, Scientific and
Cultural Organization

Intergovernmental
Oceanographic
Commission

Published by the United Nations Environment Programme (UNEP), January 2016

Copyright © UNEP 2016

ISBN: 978-92-807-3531-4
Job Number: DEW/1953/NA

This publication may be reproduced in whole or in part and in any form for educational or non-profit services without special permission from the copyright holder, provided acknowledgement of the source is made. UNEP would appreciate receiving a copy of any publication that uses this publication as a source.

No use of this publication may be made for resale or any other commercial purpose whatsoever without prior permission in writing from the United Nations Environment Programme. Applications for such permission, with a statement of the purpose and extent of the reproduction, should be addressed to the Director, DCPI, UNEP, P. O. Box 30552, Nairobi 00100, Kenya.

Disclaimers

Mention of a commercial company or product in this document does not imply endorsement by UNEP or the authors. The use of information from this document for publicity or advertising is not permitted. Trademark names and symbols are used in an editorial fashion with no intention on infringement of trademark or copyright laws. The views expressed in this publication are those of the authors and do not necessarily reflect the views of the United Nations Environment Programme. We regret any errors or omissions that may have been unwittingly made.

© Images and illustrations as specified.

Citation

This document may be cited as:

IOC-UNESCO and UNEP (2016). *Large Marine Ecosystems: Status and Trends*. United Nations Environment Programme (UNEP), Nairobi

UNEP promotes
environmentally sound practices
globally and in its own activities. This
report is printed on paper from sustainable
forests including recycled fibre. The paper is
chlorine free, and the inks vegetable-based.
Our distribution policy aims to reduce
UNEP's carbon footprint

VOLUME 4: LARGE MARINE ECOSYSTEMS

Large Marine Ecosystems

Status and trends

UNESCO
United Nations
Educational, Scientific and
Cultural Organization

Intergovernmental
Oceanographic
Commission

GESAMP
Joint Group of Experts on the
Scientific Aspects of Marine
Environmental Protection

NORWEGIAN MINISTRY
OF FOREIGN AFFAIRS

Center for Marine
Assessment and
Planning, UCSB

THE PEW
CHARITABLE TRUSTS

GLOBAL IGBP CHANGE
International
Geosphere-Biosphere
Programme

NOAA
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
U.S. DEPARTMENT OF COMMERCE

TAT
Tokyo University of Agriculture and Technology

DALHOUSIE
UNIVERSITY
Inspiring Minds

FORMIN.FINLAND.FI
MINISTRY FOR FOREIGN
AFFAIRS OF FINLAND

UNEP WCMC

CERMES

PlasticsEurope
Association of Plastics Manufacturers

Liberté • Égalité • Fraternité
RÉPUBLIQUE FRANÇAISE
DÉLÉGATION PERMANENTE
DE LA FRANCE
AUPRÈS DE L'UNESCO

UBC

SEA AROUND US

Acknowledgements

Lead Authors

Igor Belkin, Lucia Fanning, Michael Fogarty, Benjamin Halpern, Sherry Heileman, Miranda Jones, Peter Kershaw, Kristin Kleisner, Laurent Lebreton, Robin Mahon, Liana Talaue McManus, Chris McOwen, John O'Reilly, Daniel Pauly, Sybil Seitzinger, Hideshige Takada, Jan-Willem van Bochove

Contributing Authors

Courtney Arthur, Kimberly Baldwin, Julian Barbiere, Benjamin Best, Simon Blyth, Andrew Cooper, Mark Dickey-Collas, Selicia Douglas, Marcus Eriksen, Maria Estevanez, Lucia Fanning, Melanie Frazier, Elizabeth Fulton, Nicholas Gutiérrez, Benjamin Halpern, Kimberly Hyde, Peter Kershaw, Kristin Kleisner, Trond Kristiansen, Vicky Lam, Kara Lavender Law, Catherine Longo, Robin Mahon, Emilio Mayorga, Carolina Minte-Vera, Cóilín Minto, Iago Mosqueira, Giacomo Chato Osio, Daniel Ovando, Daniel Pauly, Jesus Gago Piñeiro, Andrew Rosenberg, Sybil Seitzinger, Elizabeth Selig, Kenneth Sherman, Damon Stanwell-Smith, Julie Stewart Lowndes, Emma Sullivan, James Thorson, Rei Yamashita, Yimin Ye

Reviewers

Name	Primary affiliation	Primary review responsibility
TWAP Scientific and Technical Advisory Committee (STAC)		
Andrew Rosenberg	Director, Center for Science and Democracy, Union of Concerned Scientists	Whole Report (interim and final draft)
Ashbindu Singh	Environmental Pulse Institute	Data Portal and Website
Pierre-Philippe Mathieu	European Space Agency (ESA), European Space Institute (ESRIN)	Data Portal and Website
Peer Review		
Paul Anderson	Environmental Monitoring Analyst, Secretariat of the Pacific Regional Environment Programme (SPREP), Samoa	Extent of mangroves and drivers of change
Thorsten Blenckner	Theme Leader, Regime shifts in social-ecological systems, Stockholm Resilience Centre, Stockholm Univ., Sweden	Cumulative human impacts in the world's large marine ecosystems
Cathy Dichmont	Senior Principal Research Scientist, CSIRO, QLD, Australia	The status of fisheries in LMEs, 1950-2010
FAO Experts	FAO, Rome	The status of fisheries in LMEs, 1950-2010
Rosalinda Gioia	Regulatory Environmental Fate Scientist, Centre for the Environment, Fisheries and Aquaculture (CEFAS), Lowestoft, UK	Pollution status of persistent organic pollutants
Patricia Glibert	Professor, Horn Point Laboratory, University of Maryland Center for Environmental Science, MD, USA	Nutrient inputs
Jakob Granit	Centre Director and STAC member for governance, Deputy Director, Stockholm Environment Institute, Sweden	Governance: Assessment of governance arrangements for transboundary LMEs
Angel Hsu	Assistant Professor, Yale School of Forestry and Environmental Studies	Identifying patterns of risk among large marine ecosystems using multiple indicators
Vainuupo Jungblut	RAMSAR Oceania Officer, SPREP, Samoa	Extent of mangroves and drivers of change
Richard Kenchington	Visiting Professorial Fellow, University of Wollongong, NSW, Australia	Change in protected area coverage within LMEs
Yi-Chin Kuo	Dept. Environmental Biology and Fisheries Science, National Taiwan ocean Univ., Taiwan	Sea surface temperature trends
Rebecca Martone	Assistant Director for Science and Research, Center for Ocean Solutions, Montery, CA, USA	Ocean Health Index for the world's large marine ecosystems
Patrick McConney	Senior Lecturer, Centre for Resource Management and Environmental Studies (CERMES) Univ. West Indies, Barbados	Examining socio-economic dimensions of risk and vulnerability among coastal inhabitants of large marine ecosystems

David Obura	CORDIO East Africa, Mombasa, Kenya	Reefs at Risk Index
Stephen Olsen	Coastal Resources Center, Univ. Rhode Island, RI, USA	Governance: Assessment of governance arrangements for transboundary LMEs
Candace Oviatt	Professor of Oceanography, Director, Marine Ecosystems Research lab, Graduate School of Oceanography, Univ. Rhode Island, RI, USA	Primary productivity patterns and trends
Daniel Pauly	Professor, Sea Around Us, Univ. British Columbia, BC, Canada	Examining socio-economic dimensions of risk and vulnerability among coastal inhabitants of large marine ecosystems
Kenneth Sherman	Director, NOAA Northeast Fisheries Science Center, Narragansett Laboratory, RI, USA	Sea surface temperature trends; Examining socio-economic dimensions of risk and vulnerability among coastal inhabitants of large marine ecosystems; Fishery production potential of LMEs: a prototype analysis
Ariana Spawn	Yale School of Forestry and Environmental Studies	Identifying patterns of risk among large marine ecosystems using multiple indicators
Femke Tonneijck	Project Manager, Mangrove Capital, Wetlands International, The Netherlands	Extent of mangroves and drivers of change
Nancy Wallace	Director, NOAA Marine Debris Program	Floating plastic debris
Dixon Wairunge	Nairobi Convention Secretariat, UNEP	Whole report
Mick Wilson	UNEP/DEWA	Whole report
Victor Tsang	UNEP	Whole report

Feedback was gratefully received from a number of colleagues and institutions during the following workshops and meetings:

- 17th Global Meeting of the Regional Seas Conventions and Action Plans, 20-22 October 2015, Istanbul, Turkey
- 17th Annual Large Marine Ecosystems Consultative Committee Meeting, 29 September-2 October 2015, Paris, France
- 2nd International Ocean Research Conference, 17-21 November 2014, Barcelona, Spain
- 16th Global Meeting of the Regional Seas Conventions and Action Plans, 29 September-1 October 2014, Athens, Greece
- 16th Annual Consultative Committee Meeting on Large Marine Ecosystems and Coastal Partners, 8-11 July 2014, Paris, France
- Technical Workshop on Selecting Indicators for the State of Regional Seas, 30 June-02 July 2014, Geneva, Switzerland
- TWAP Working Group Meetings; Open Ocean, Large Marine Ecosystems, and Joint, 7-11 April 2014, Paris, France
- TWAP Large Marine Ecosystems/ Open Ocean Inception Meeting, 20-22 March 2013, Paris, France

LMEs component manager: Julian Barbiere (IOC-UNESCO)

LMEs component coordinator: Sherry Heileman (Consultant, IOC-UNESCO)

Scientific editors: Sherry Heileman (Consultant, IOC-UNESCO) and Kenneth Sherman (NOAA)

Science communication expert: Joan Eamer, Eamer Science and Policy, Gabriola Island, BC, Canada

Maps and graphics designer: Kelly Badger, Eamer Science and Policy, Gabriola Island, BC, Canada

Copy editor: Peter Saunders

UNEP Secretariat: Liana Talaue McManus (Project Manager), Joana Akrofi, Kaisa Uusimaa (UNEP/DEWA) and Isabelle van der Beck (Task Manager)

Design and Layout: Audrey Ringler (UNEP) and Jennifer Odallo (UNON)

IOC-UNESCO support: Isabel Chavez, Bruno Combal, Fabiola Gaucher, Alejandro Iglesias-Campos, Laetitia Langlois

Administrative Boundaries: Source of administrative boundaries throughout the assessment: The Global Administrative Unit Layers (GAUL) dataset, implemented by FAO within the CountrySTAT and Agricultural Market Information System (AMIS) projects.

Photo © S. Heileman

Preface

The Global Environment Facility (GEF) approved a Full Size Project (FSP), "A Transboundary Waters Assessment Programme: Aquifers, Lake/Reservoir Basins, River Basins, Large Marine Ecosystems, and Open Ocean to catalyze sound environmental management", in December 2012, following the completion of the Medium Size Project (MSP) "Development of the Methodology and Arrangements for the GEF Transboundary Waters Assessment Programme" in 2011. The TWAP FSP started in 2013, focusing on two major objectives: (1) to carry out the first global-scale assessment of transboundary water systems that will assist the GEF and other international organizations to improve the setting of priorities for funding; and (2) to formalise the partnership with key institutions to ensure that transboundary considerations are incorporated in regular assessment programmes to provide continuing insights on the status and trends of transboundary water systems.

The TWAP FSP was implemented by UNEP as Implementing Agency, UNEP's Division of Early Warning and Assessment (DEWA) as Executing Agency, and the following lead agencies for each of the water system categories: the International Hydrological Programme (IHP) of the United Nations Educational, Scientific and Cultural Organization (UNESCO) for transboundary aquifers including groundwater systems in small island developing states (SIDS); the International Lake Environment Committee Foundation (ILEC) for lake and reservoir basins; the UNEP-DHI Partnership – Centre on Water and Environment (UNEP-DHI) for river basins; and the Intergovernmental Oceanographic Commission (IOC) of UNESCO for large marine ecosystems (LMEs) and the open ocean.

The five water-category specific assessments cover 199 transboundary aquifers and groundwater systems in 43 small island developing states, 206 transboundary lakes and reservoirs, 286 transboundary river basins; 66 large marine ecosystems; and the open ocean, a total of 758 international water systems. The assessment results are organized into five technical reports and a sixth volume that provides a cross-category analysis of status and trends:

Volume 1 – ***Transboundary Aquifers and Groundwater Systems of Small Island Developing States: Status and Trends***
Volume 2 – ***Transboundary Lakes and Reservoirs: Status and Trends***
Volume 3 – ***Transboundary River Basins: Status and Trends***
Volume 4 – ***Large Marine Ecosystems: Status and Trends***
Volume 5 – ***The Open Ocean: Status and Trends***
Volume 6 – ***Transboundary Water Systems: Crosscutting Status and Trends***

A Summary for Policy Makers accompanies each volume.

Volume 4 presents the results of the first global indicator-based, comparative assessment of large marine ecosystems, prepared in partnership with IOC-UNESCO (lead), the US National Oceanic and Atmospheric Administration (NOAA), the University of West Indies (Cave Hill) Centre for Resource Management and Environmental Studies (CERMES), the Center for Marine Assessment and Planning (CMAP) University of California Santa Barbara, Dalhousie University, the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP), the International Geosphere-Biosphere Programme (IGBP), the Tokyo University of Agriculture and Technology (TUAT), the University of British Columbia Sea Around Us (UBC SAU), the UNEP World Conservation Monitoring Centre (UNEP WCMC), and a number of independent experts. An assessment of the Western Pacific Warm Pool, based on a sub-set of the indicators, is included.

Acronyms

BOB	Bay of Bengal
CBD	Convention on Biological Diversity
CCAMLR	Commission for the Conservation of Antarctic Marine Living Resources
CHI	Cumulative Human Impacts (Index)
CIESIN	Center for International Earth Science Information Network
CO_2	carbon dioxide
DBEM	Dynamic Bioclimate Envelope Model
DDT	dichlorodiphenyltrichloroethane
EBM	ecosystem-based management
EEZ	exclusive economic zone
FAO	Food and Agriculture Organization of the United Nations
FiB	Fishing in Balance (Index)
GDEM	Global Digital Elevation Model
GDP	Gross Domestic Product
GEF	Global Environment Facility
GIS	geographical information system
GIWA	Global International Waters Assessment
GIZ	Gesellschaft für Internationale Zusammenarbeit
GNI	gross national income
HCH	hexachlorocyclohexane
HDI	Human Development Index
ICEP	Index of Coastal Eutrophication Potential
IOC-UNESCO	Intergovernmental Oceanographic Commission – United Nations Educational, Scientific and Cultural Organization
IPCC	Intergovernmental Panel on Climate Change
IPW	International Pellet Watch (programme)
LME	Large Marine Ecosystem
MPA	Marine Protected Area
MTI	Marine Trophic Index

NASA	National Aeronautics and Space Administration (US)
NEWS	Nutrient Export from WaterSheds (model)
NLDI	Night Light Development Index
NOAA	National Oceanic and Atmospheric Administration (US)
Norad	Norwegian Agency for Development Cooperation
OECD	Organisation for Economic Cooperation and Development
OHI	Ocean Health Index
PC	principal component
PCA	principal components analysis
PCB	polychlorinated biphenyl
POPs	persistent organic pollutants
PP	primary production
PPR	primary production required
RCP	Representative Concentration Pathway
SAP	Strategic Action Programme
SRES	Special Report Emission Scenario
SSP	Shared Socio-economic Pathway
SST	sea surface temperature
STAC	Scientific and Technical Advisory Committee
TDA	Transboundary diagnostic analysis
TWAP	Transboundary Waters Assessment Programme
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
WPWP	Western Pacific Warm Pool
WTTC	World Travel and Tourism Council

Contents

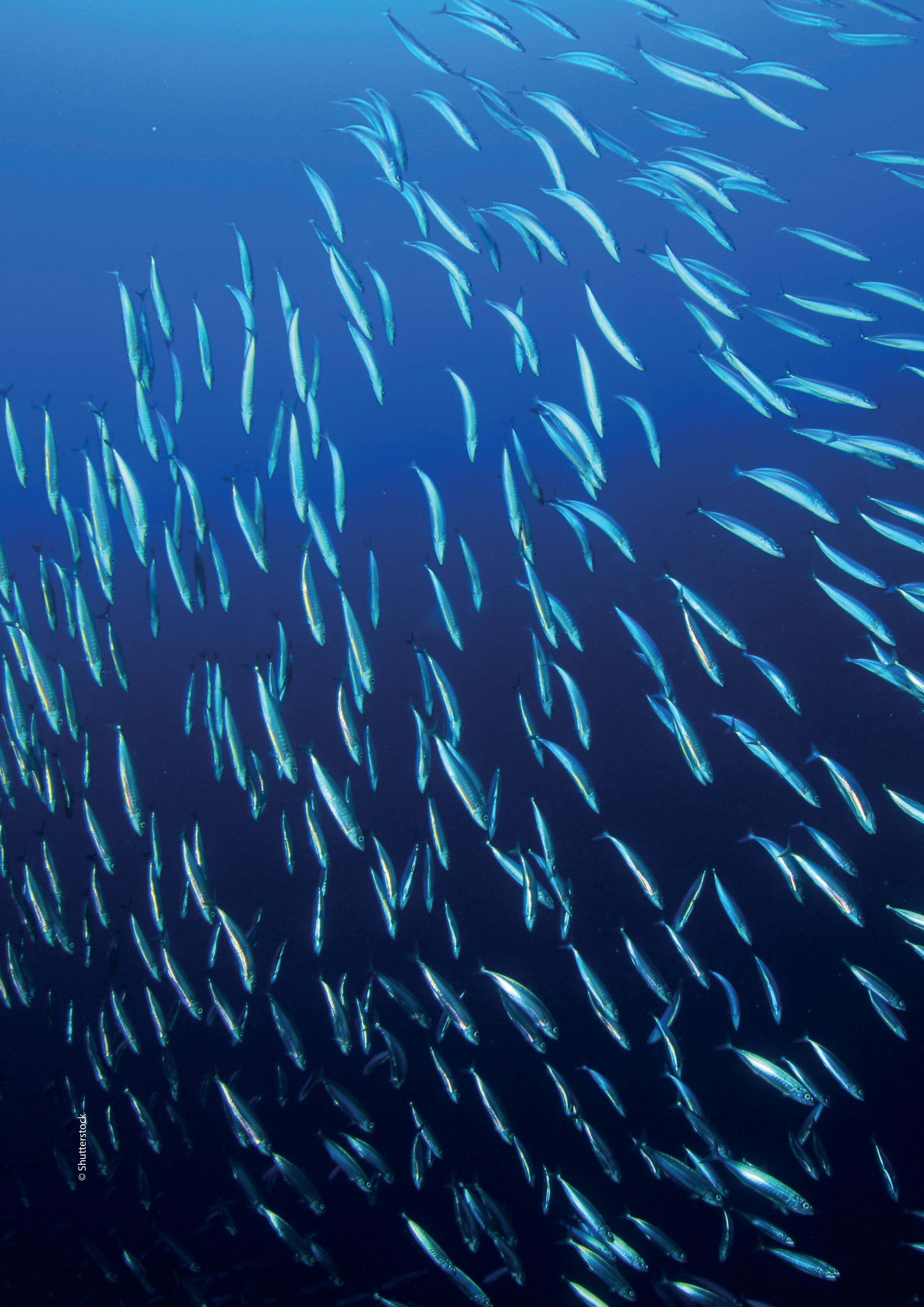
Figures

Annex Figures

Tables

Annex Tables

Boxes



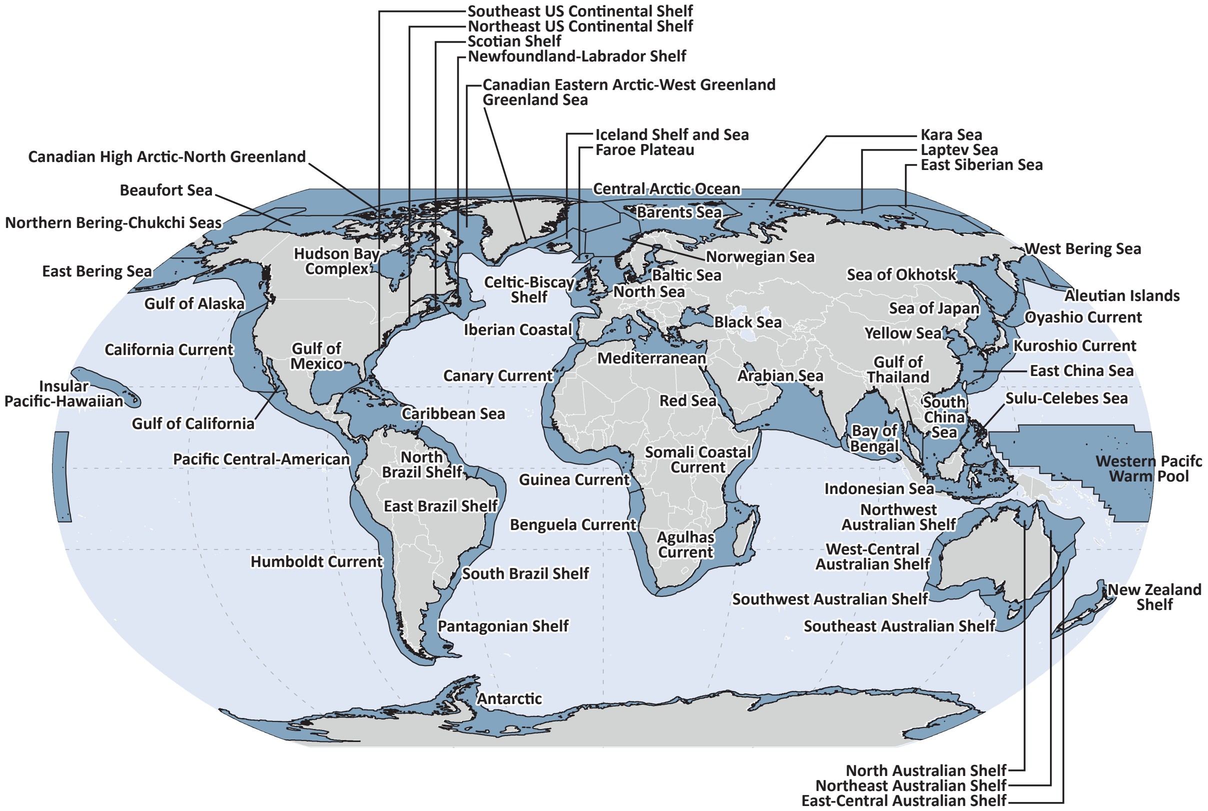
© Shutterstock

Technical Summary

Introduction

Large marine ecosystems (LMEs), 66 of which are defined globally, are relatively large areas of coastal waters of 200 000 km^2 or greater, encompassing coastal areas from river basins and estuaries to the seaward boundaries of continental shelves and outer margins of major coastal currents or enclosed or semi-enclosed seas (Summary Figure 1). These water systems, many of which are transboundary, contribute an estimated US$28 trillion annually to the global economy through the provision of ecosystem goods and services essential for human well-being and socio-economic development of the bordering countries. Undeniable trends, however, indicate that a growing human population and its activities, as well as a changing climate, are modifying the state of LMEs at an increasing rate, threatening their sustainability and the services they provide.

Summary Figure 1 Large marine ecosystems and the Western Pacific Warm Pool



Since the mid-1990s the Global Environment Facility (GEF) and other donors have provided over US$3 billion to LME projects in more than 100 developing countries for ecosystem-based management (EBM) of LMEs. Recognizing the value of LMEs and other transboundary water systems (open ocean, groundwater aquifers, lakes and reservoirs, and river basins), their continued degradation, the fragmented approach to their management, and the need for better prioritization of interventions, the GEF embarked on the Transboundary Waters Assessment Programme (TWAP). Under TWAP, two projects were conducted between 2009 and 2015, the first to develop the assessment methodology and the second to conduct the assessment. The latter had two main objectives:

1. To undertake the first global assessment of transboundary waterbodies, through a formalized consortium of partners that will assist GEF and other international organizations to improve the setting of priorities for funding allocations;
2. To formalize the partnership with key institutions aimed at incorporating transboundary considerations into regular assessment programmes, resulting in periodic assessments of transboundary water systems.

The key TWAP partners were the United Nations Environment Programme (UNEP), the implementing agency, and four executing agencies, each of which was responsible for one of the five transboundary waters systems components: the Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational, Scientific and Cultural Organization (UNESCO) (LMEs and open ocean); the International Hydrological Programme of UNESCO (groundwater aquifers); UNEP-DHI (river basins); and the International Lake Environment Committee (lakes and reservoirs). The LMEs assessment was conducted by a working group of institutional partners and experts (see the acknowledgements section) under the leadership of the IOC/UNESCO. At the request of the GEF, an assessment of the Western Pacific Warm Pool (WPWP; Summary Figure 1) was also undertaken.

While the GEF Secretariat is the main target audience of this assessment, there are other major potential beneficiaries including GEF LME projects (specifically for the Transboundary Diagnostic Analysis and Strategic Action Programme processes), and LME commissions or similar regional bodies. This baseline assessment, as well as the assessment methodology, can make a significant contribution to other marine assessment processes such as the UN World Ocean Assessment and the Regional Seas state of the coast reporting. LMEs assessments can also support relevant reporting mechanisms of the UN Sustainable Development Goal (SDG) #14 that calls for nations to "*conserve and sustainably use the oceans, seas and marine resources for sustainable development*." A number of the key targets of SDG 14 are well-aligned with those of LMEs, including the need to reduce marine pollution of all kinds (including nutrients), to sustainably manage and protect marine and coastal ecosystems, and to support the sustainable development of fisheries.

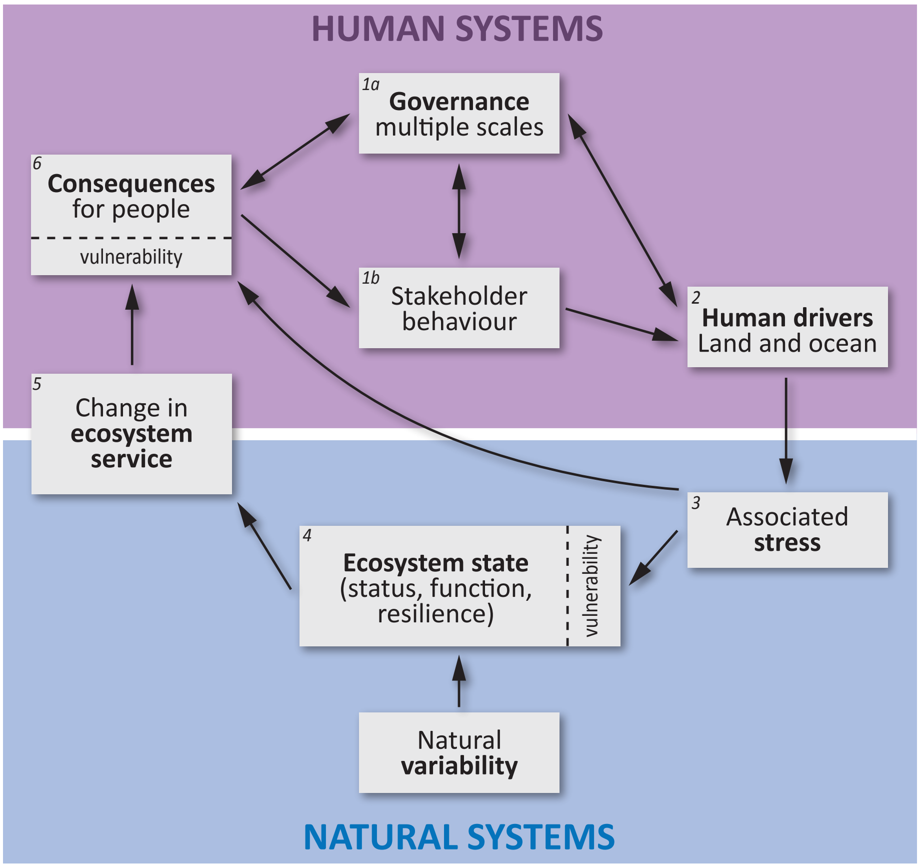
Assessment methodology

An indicator-based methodology for assessment of LMEs was developed during the first TWAP project conducted from 2009 to 2010 (www.geftwap.org/publications). The approach to the assessment and management of LMEs is based on five modules (Socio-economics, Governance, Productivity, Fish and Fisheries, and Pollution and Ecosystem Health), each with sets of indicators. Central, linked themes of TWAP are the vulnerability of ecosystems and human communities to natural and anthropogenic stressors, impairment of ecosystem goods and services, and consequences for humans. These links are captured in a conceptual framework that builds on the five LME modules (Summary Figure 2).

The present LMEs assessment consists of a Level 1 global baseline comparative assessment covering a range of environmental issues and a limited Level 2 (sub-LME-scale) assessment in the Bay of Bengal LME, focusing on nutrients. The Level 1 assessment is based on averages at the scale of the entire LME, and does not reflect the situation at smaller scales such as a country's exclusive economic zone (EEZ).

This assessment sought answers to key questions to help identify LMEs where human dependence on ecosystem services and vulnerability to LME degradation and climate-related extreme events are greatest, and LMEs where the risk of degradation is highest (Summary Box 1). Risk is defined broadly as the probability of adverse consequences for humans and the environment in relation to the changing states of the LME.

Summary Figure 2 Conceptual framework for TWAP large marine ecosystems assessment



Summary Box 1 Questions that the LMEs comparative assessment sought to answer

- Which LMEs are most heavily impacted for each issue?
- What are the current trends and main drivers in LMEs?
- Which ecosystem services are most at risk?
- Where is human dependence on LME ecosystem services the highest?
- Where are humans most vulnerable to changes in LME condition?
- What is the status of the governance architecture or arrangements in transboundary LMEs?

Since the TWAP is a global comparative assessment, the selection of indicators was constrained by the availability of global data sets. The indicators and indices used in this assessment are listed in Summary Table 1.

Summary Table 1 Indicators and indices by LME module
Note that indices often include indicators from several modules.

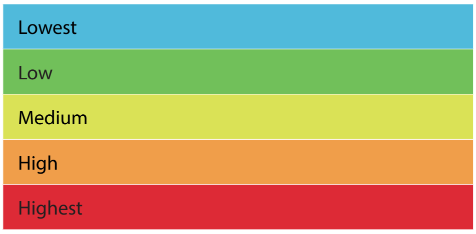
Module	Indicators
Socio-economics	• Coastal population and area of country segment within 100 km coastal zone • Coastal population by elevation up to 10 m and by distance from shore up to 50 km • Coastal poor • Fisheries revenues • Fish contribution to animal protein consumption • Tourism revenues • Tourism contribution to GDP • Night Light Development Index • Human Development Index • Projected Human Development Index 2100 • Present-day Climate-related Extreme Events Index • Sea-level Rise Threat Index 2100 • Contemporary Threat Index (includes measures of ecosystem state, socio-economic dependence, climate event risk, and capacity to adapt)
Governance	Governance arrangements or architecture related to fisheries, pollution, and biodiversity (including habitat destruction): • Completeness of the structure of arrangements to address a given issue or issues • Integration of institutions involved in addressing identified transboundary issues • Engagement of countries participating in arrangements
Productivity	• Average annual primary productivity, 1998– 2013 • Chlorophyll *a* concentrations and trends, 2003–2013 • Sea surface temperature trends, 1957– 2012
Fish and Fisheries	• Ratio of capacity-enhancing subsidies to value of landed catch • Primary production required (ecological footprint of fisheries) • Marine Trophic Index • Fishing-in-Balance Index • Stock status by number of stocks and catch biomass of exploited stocks • Catch from bottom-impacting gear types • Fishing effort • Change in catch potential under global climate change (2050s)[1,2] • Fishery production potential
Pollution and Ecosystem Health	• Relative abundance of floating micro- and macro-plastics[1] • Concentrations of three types of persistent organic pollutants (POPs) in plastic resin pellets washed up on shore • Indicator of coastal eutrophication based on two sub-indicators: nitrogen input from rivers and nutrient ratios[1,2] • Extent of mangroves • Reefs at Risk Index[2] • Extent of warm-water coral reefs • Changes in the areas protected in LMEs between 1983 and 2014 • Cumulative Human Impacts Index – CHI (incorporating data layers for ocean acidification and sea-level rise, commercial and artisanal fishing, land-based pollution, oil rigs, light pollution, invasive species, commercial shipping, and direct human impact on sensitive ecosystems) • Ocean Health Index (measuring progress on ten widely-agreed public goals for healthy oceans, including food provision, carbon storage, coastal livelihoods and economies, and biodiversity)

[1] *Where empirical time series data were unavailable, modelling approaches were used.*
[2] *Projections to 2030 and 2050 were carried out.*

The majority of the data sets used to assess the indicators are global, gridded data that can be scaled to other geographical units such as Regional Seas, countries' EEZs, or smaller. These 'raw' data sets are available from the respective TWAP LME partners.

To facilitate a comparative assessment of LMEs a consistent indicator scoring system was developed to identify LMEs at different levels of potential risk. This consists of five colour-coded categories of relative risk (Summary Figure 3).

Summary Figure 3 Risk categories



This approach is not suitable for indicators such as primary productivity and sea temperature that have no clear directionality in terms of what could be considered ‘good’ or ‘bad’. The risk categories do not reflect the actual level of environmental degradation in the LME and are only a means to facilitate the comparative assessment. Each expert decided on the cut-off points for the five categories for their respective indicator(s) either using scientifically defined reference points or thresholds for levels of ‘good’/’bad’ or high/low risk, based on the literature and expert judgement, or, where no such thresholds have been defined, on statistical approaches using ranks. LMEs were placed into the five risk categories based on individual indicators and indices. In addition, a sub-set of the indicators, including some from the CHI, were integrated to determine patterns of risk among LMEs using a multivariate analysis. Other types of indices can be created from the indicators based on stakeholder priorities and user-defined weightings.

Because this was a global comparative assessment across all LMEs, it was not possible to examine cause and effect, which will probably vary among and within LMEs. Detailed assessments, including at the sub-LME scale, are needed to link cause and effect for specific issues. More conclusive results can be obtained with improved data, including data at the sub-LME scale and ground-truthing to validate remotely sensed data. As indicated in the individual chapters, confidence levels in the assessment are dependent on the quality of the data underpinning the indicators or models.

Results

Results of the global comparative assessment (TWAP objective 1) are summarized below for individual indicators and indices under each of the five LME modules, followed by results of multivariate analyses using multiple indicators. The results for individual LMEs and the WPWP, as well as the data, are available on the TWAP LMEs website (onesharedocean.org).

HUMAN SYSTEM

Socio-economics

The assessment of socio-economics of LMEs aimed to identify where human dependence on LMEs goods and services is greatest and to describe the patterns of current vulnerability or risk to coastal communities from a combination of ecological degradation and climate-related extreme events. Risk levels in 2100 were projected, factoring in socio-economic scenarios and sea-level rise. A number of indicators were developed and subsets were used to construct three threat indices to examine vulnerability of coastal populations. Because few of these data sets are available at the LME scale, geo-referenced population or other regional data were used as weighting factors to downscale national data before they were aggregated for each LME.

Human dependence

Coastal population, fish protein in diet, and contribution of LME tourism to coastal country economies were combined as a metric of dependence on LME goods and services. The Indonesian Sea LME has the highest dependence, followed by the Gulf of Thailand and the Bay of Bengal LMEs.

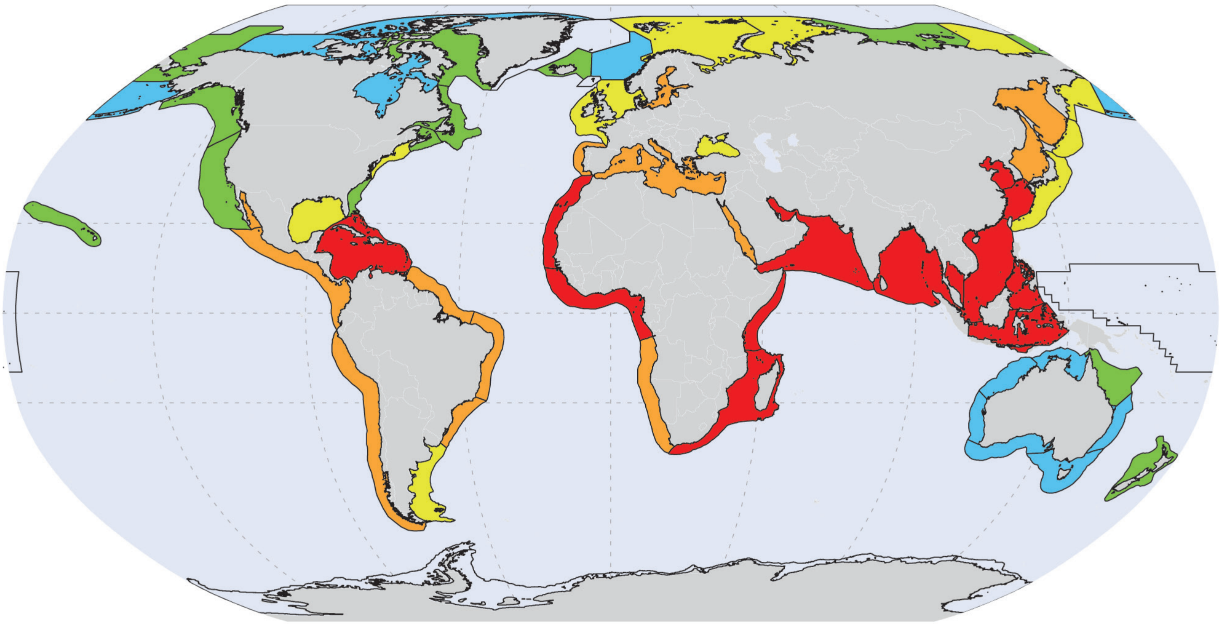
Present-day Climate-related Extreme Events Threat Index

This index includes hazard measures (annual rates of deaths and property loss from climate-related events for the period 1994 to 2013), the 2010 population in the 100 km coastal zone as a coarse proxy for exposure; and the Human Development Index (HDI) Gap (calculated as 1-HDI, averaged for the period 2009 to 2013) as a vulnerability metric that reflects the lower coping ability of poorer countries. LMEs most at risk from extreme climate events (in order of decreasing risk) are the Bay of Bengal, Arabian Sea, South China Sea, East China Sea, Caribbean Sea, Yellow Sea, Sulu-Celebes Sea, Canary Current, Pacific Central-American, Somali Coastal Current, Gulf of Thailand, Mediterranean, and Agulhas Current.

Sea-level Rise Threat Index under two contrasting Shared Socio-Economic Pathways (SSPs)

The Sea-level Rise Threat Index for 2100 integrates maximum sea-level rise, population living within a 10-km strip along the coast and at elevations of no more than 10 m above sea level, and projected HDI Gap. The regionalized maximum sea-level rise estimates at LME scale are based on the Representative Concentration Pathway 8.5 (with global warming reaching 8.5 watts per m^2 in 2100). Most coastal areas will experience sea-level rise while some locations near ice sheets will experience land uplift caused by melting ice sheets. Estimates of future population exposure in the 10 m by 10 km coastal zone are very different for the two SSPs (plausible alternative pathways for society and natural systems over the 21st century), with a global total of 308 million inhabitants for the sustainable world pathway and 507 million for the fragmented world pathway. Sea-level rise threat is amplified by the size of population exposure and the degree of HDI-based vulnerability.

Summary Figure 4 Contemporary Threat Index: threat levels for 64 populated LMEs



Contemporary Threat Index categories

🟦 Lowest risk 🟩 Low risk 🟨 Medium risk 🟧 High risk 🟥 Highest risk

Contemporary Threat Index

The Contemporary Threat Index is calculated as the geometric mean of measures of human dependence (as defined above), lack of adaptive capacity (the HDI Gap), environmental risk (risk of losses and deaths from climate-related extreme events, and risk scores for selected indicators from the Fish and Fisheries and the Pollution and Ecosystem Health modules). The Index for the Barents Sea and Norwegian Sea LMEs excludes the fisheries indicators. The LMEs most at risk based on this Index are in highly populated tropical LMEs (Summary Figure 4). Those in the 'highest' risk category (in order of decreasing risk) are Bay of Bengal, Canary Current, Gulf of Thailand, South China Sea, Sulu-Celebes Sea, Somali Coastal Current, Indonesian Sea, Guinea Current, Arabian Sea, Caribbean Sea, East China Sea, Yellow Sea, and the Agulhas Current.

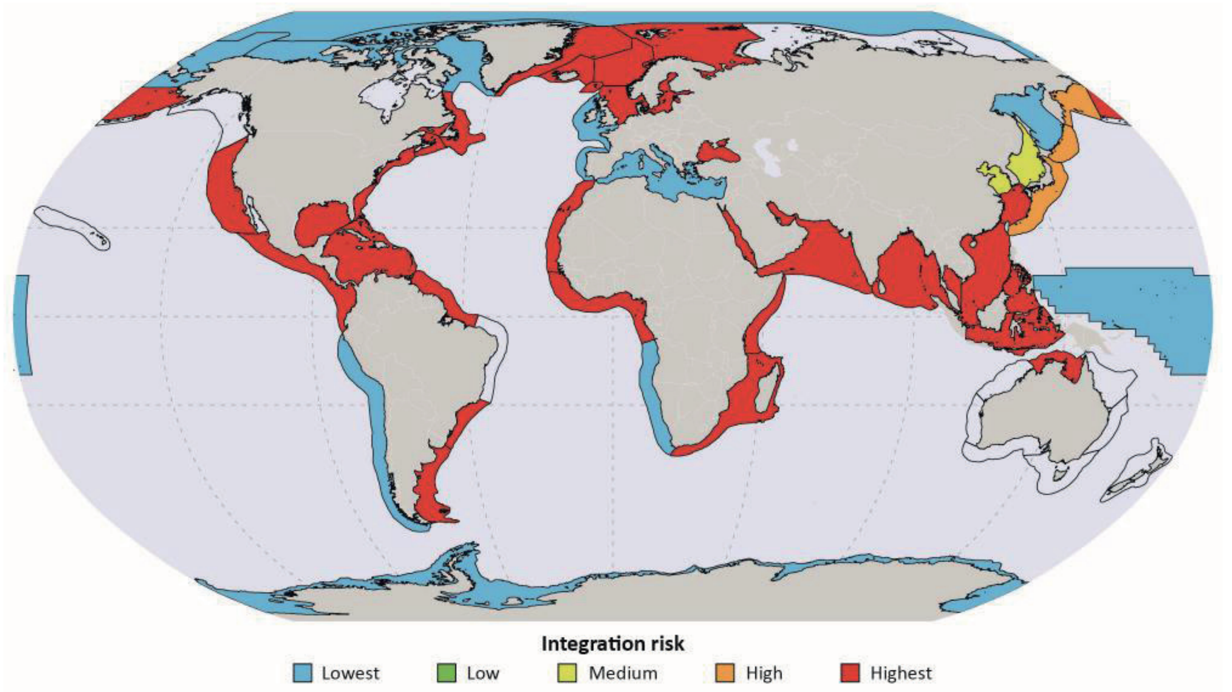
Key messages

1. **High levels of human well-being and ecosystem health are indicative and mutually reinforcing outcomes of sustainable ecosystems.** To achieve these, reducing risk and vulnerability of coastal populations must be addressed without sacrificing ecosystem health, and vice-versa. Universal safety nets that guarantee opportunities for human development are integral to smart ecosystem management that aims to achieve sustainable LMEs.
2. **Coastal populations in highly populated tropical regions are the most at risk, taking into account the combined effects of environmental threats, dependence on LME resources, and shortfalls in capacity to adapt.** Environmental threats include loss or degradation of fish stocks and ecosystem health, and damage from climate-related extreme events. Dependence includes coastal population size and reliance on fish for food and on tourism for income. The LMEs at highest risk are: Bay of Bengal, Canary Current, Gulf of Thailand, South China Sea, Sulu-Celebes Sea, Somali Coastal Current, Indonesian Sea, Guinea Current, Arabian Sea, Caribbean Sea, East China Sea, Yellow Sea, and Agulhas Current.
3. **Risks associated with future deterioration of ecosystem health and with climate change are additional burdens that exacerbate an already precarious state for coastal populations of some LMEs – but measures can be taken to mitigate these risks.** Sea-level rise threat is amplified by the size of population exposure and the degree of socio-economic vulnerability. LMEs most at risk from sea-level rise include many of those currently at highest risk, especially those of the southern coastal regions of Africa. Assessing vulnerability to sea-level rise in 2100 using contrasting future socio-economic scenarios indicates that development pathways that strengthen opportunities for better education, health, and livelihood, and reduce population growth, at national scale and in the coastal areas of LMEs, should decrease future risk levels.
4. **Regional assessments may prove essential for designing appropriately-scaled programmes to reduce vulnerability and risk.** Such assessments would substantiate this baseline global assessment and highlight sub-national features. While the indicators used in assessments are evidence-based, choices made about what indicators to combine into an index affect the outcomes of the assessment. The set of results presented here is influenced by these choices. Future assessments should validate the results using a suite of indicators based on finer-scale spatial data, including geo-referenced data on LME resource utilization, poverty distribution, urbanization, and economic activity.

Governance

The assessment evaluates formally-established transboundary governance arrangements relevant to fisheries, pollution, and biodiversity (including habitat destruction) in 49 transboundary LMEs (those shared by two or more coastal countries) and the WPWP. Only transboundary governance arrangements and their associated architecture, defined as the set of commonly-shared principles, institutions, and practices that affect decision making, were examined. The assessment does not evaluate the performance of the governance arrangements. Three indicators for monitoring progress towards 'good' governance in LMEs were evaluated: **completeness** of the structure of arrangements to address a given issue or issues, **integration** of institutions involved in addressing the suite of identified transboundary issues within a given LME, and **engagement** of countries participating in arrangements that address the identified transboundary issues within the LME.

Summary Figure 5 Levels of integration and perceived risk for 49 transboundary LMEs and the WPWP



A global comparison of the completeness indicator shows that five LMEs have a 'high' level of relative risk (South Brazil Shelf, Yellow Sea, Sea of Japan, Sea of Okhotsk, and Oyashio Current). None of the LMEs are in the 'highest' risk category. Over 50 per cent of LMEs are in the 'highest' risk category for integration (Summary Figure 5). No LME is at the 'high' or 'highest' risk level for engagement. The Mediterranean LME shows the lowest level of risk across the three indicators, mainly due to the presence and nature of an overarching integrating mechanism to address transboundary issues.

Key messages

1. **An average 'medium' risk level for completeness of arrangements across all stages of the policy cycle indicates that there is considerable room for improvement in the design of transboundary governance for LMEs.** Improvements in completeness can be achieved by ensuring that current and new agreements have policy-cycle mechanisms in place that include a wide array of data and information providers, that provide a strong, knowledge-based policy interface, and that hold decision-makers and those responsible for implementation accountable; and ensure that monitoring and evaluation mechanisms are implemented, thereby facilitating adaptive management. Some highlights of the analysis of completeness by issue and policy stage are:
    - Fisheries arrangements tend to have high completeness levels but need improvement in levels of institutional collaboration on implementation;
    - Pollution arrangements are low in accountability: few arrangements have repercussions for lack of compliance;
    - Biodiversity arrangements, which are mainly recommendations or decisions that can be opted out of, tend to have the lowest levels of completeness. Accountability is limited for most, and lack of data and information provisions is a serious shortcoming at the LME level.

2. **Levels of institutional integration for arrangements that are in place to address transboundary issues are generally low.** Over 60 per cent of LMEs have very low scores and consequently 'highest' risk levels for this indicator. This points to a need to ensure better collaboration on transboundary governance arrangements if ecosystem-based management is to be effectively implemented in LMEs. The low scores for integration are due mainly to the significant disconnection between organizations involved with fisheries issues in many LMEs and those involved with pollution and biodiversity issues. This finding points to the need to focus efforts on collaboration between these organizations, and/or the creation of overarching integrating mechanisms.
3. **Engagement levels in transboundary arrangements are generally high, reflecting the high level of commitment that countries in LMEs have towards participation in agreements addressing transboundary issues.** This is positive, but does not guarantee follow-through actions on the part of the countries, especially if there are few or no repercussions for failing to comply with the terms of an agreement. This is of concern since the nature of the agreements, binding or non-binding, influences the level of commitment by countries.

BIOPHYSICAL MODULES

The indicators assessed cover drivers of change in LME condition, anthropogenic stress (or pressure) on the ecosystem, and environmental state. In addition, three composite indicators or indices were assessed: Reefs at Risk Index, Cumulative Human Impacts (CHI), and Ocean Health Index (OHI). Spatial variability of primary productivity (PP), chlorophyll *a* (CHL), and sea surface temperature (SST) are representative of natural LME variability. Most indicators were assessed at current condition. Projections to 2030 and 2050 were also made for nutrient inputs from watersheds, Reefs at Risk, and fish catch potential under global warming.

Productivity

The indicators are PP, CHL, and SST, which are manifested at a large (LME-wide) scale, are highly influenced by global processes such as climate change, and usually cannot be managed on a decadal timeframe. They have cross-modular effects that are very important for overall ecosystem productivity. However, as productivity and SST trends are not linked consistently to environmental risks, these indicators give no clear indication of 'good' or 'bad' ecosystem state. Changes can be beneficial or detrimental, depending on the context.

Primary productivity

A 16-year (1998 to 2013) time-series of satellite ocean colour data from NASA Goddard Space Flight Centre was used to examine spatial trends in average levels of PP and CHL in LMEs and the WPWP. PP supports marine food webs and can be related to the carrying capacity of marine ecosystems for supporting biodiversity and fisheries resources. High primary productivity is generally regarded as beneficial except when stimulated by excessive nutrient loads, resulting in phytoplankton blooms and subsequent low oxygen levels when these blooms decompose, resulting in problems such as toxic algal blooms and fish kills. CHL data were also analysed for time trends over the past decade.

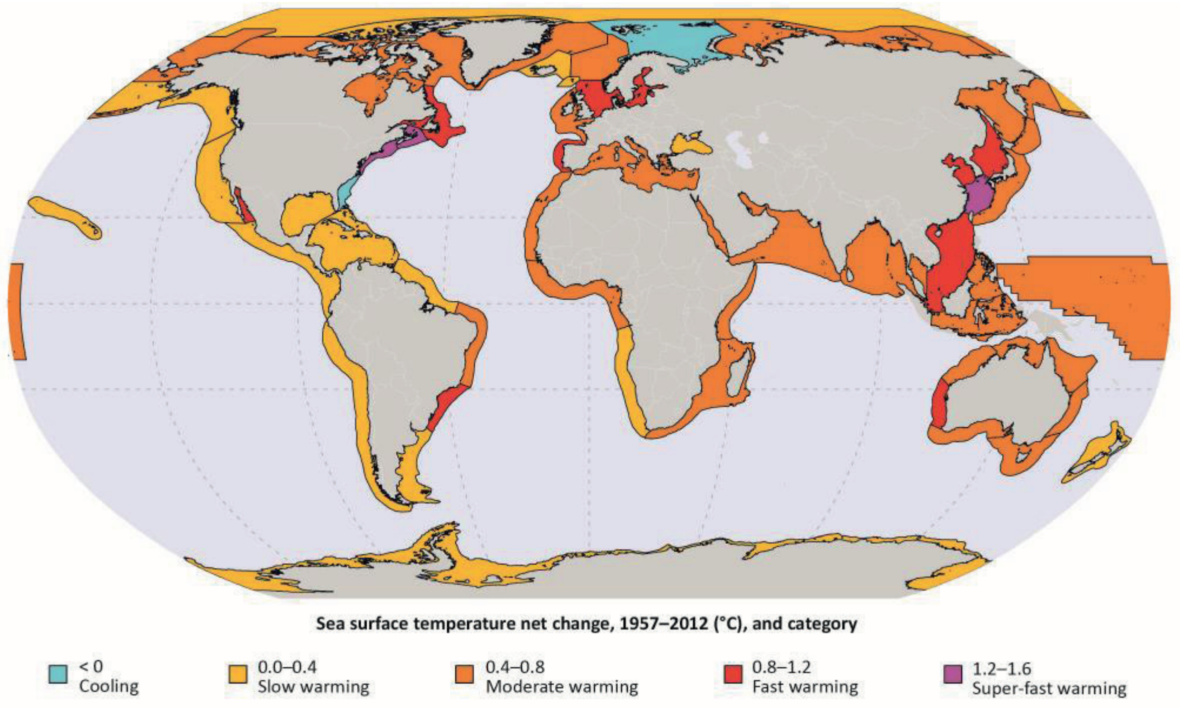
Key messages

1. **Most relatively high values of primary productivity in the global ocean are in coastal waters, within LME boundaries.** Across the entire global ocean, average annual primary productivity ranges over three orders of magnitude, while it varies by one order of magnitude in the 66 LMEs and the WPWP (from 74 to 755 grams of carbon per m^2 per year). Average chlorophyll concentrations show the same global distribution pattern.
2. **No large-scale, consistent pattern of either increase or decrease in chlorophyll was observed (2003 to 2013).** There are 36 LMEs with increasing trends in chlorophyll (measured as chlorophyll *a*) and 31 with decreasing trends. Trends are weakly correlated with latitude, and most are not statistically significant ($P<0.05$).
    - LMEs with significant increasing chlorophyll trends: Scotian Shelf, Patagonian Shelf, Labrador Newfoundland, and Southeast Australian Shelf LMEs.
    - LMEs with significant decreasing chlorophyll trends: Indonesian Sea, Oyashio Current, and Celtic-Biscay Shelf.

Sea surface temperature (SST)

The Earth's climate has become substantially warmer since the 19th century, which has already had major effects on marine ecosystems. Long-term consequences of global warming will be LME-specific, with the ongoing warming beneficial for some LMEs, but detrimental for others. The United Kingdom Met Office Hadley Centre global climatology data were used to construct long-term SST time series (1957 to 2012) in the 66 LMEs and WPWP. All but two LMEs warmed between 1957 and 2012 (Summary Figure 6). Temperature change varied widely among different regions and even between adjacent LMEs. The long-term warming between 1957 and 2012 was not steady in the majority of LMEs. Instead, their thermal history consisted of alternating cooling and warming epochs, separated by regime shifts.

Summary Figure 6 Long-term sea surface temperature trends (net changes) in 66 LMEs, 1957–2012



Calculated from linear regressions of annual SSTs for each LME.

Key messages

1. **Between 1957 and 2012, SST in all but two LMEs increased.** SST change varied widely between regions, from -0.28°C to +1.57°C in the 55 years.
    - LMEs with highest rates of warming: East China Sea, Scotian Shelf, and Northeast US Continental Shelf;
    - LMEs that cooled over this period: Barents Sea and Southeast US Continental Shelf.
2. **The LMEs with the largest increases in SST are mainly in three regions: Northwest Atlantic, eastern North Atlantic, and the Western Pacific.** LMEs with high rates of seawater warming:
    - Northwest Atlantic: US Continental Shelf, Scotian Shelf, and Faroe Plateau LMEs;
    - Eastern North Atlantic: Celtic-Biscay Shelf, North Sea, and Baltic Sea LMEs;
    - Western Pacific: South China Sea, East China Sea, Yellow Sea, and Sea of Japan LMEs.

Fish and Fisheries

The status of fisheries

LMEs contribute the major proportion of global marine fisheries landings, about 75 per cent in recent times. Global marine fisheries landings data for the period 1950 to 2010 (mainly from the Food and Agriculture Organization of the United Nations, FAO) were regrouped to produce the annual catches by fish taxa for LMEs and the WPWP. The resulting data were then used to evaluate a number of indicators, which are presented for each LME except the Barents Sea and Norwegian Sea. Of these indicators, three are drivers or pressures: ratio of capacity-enhancing subsidies to the value of landed catch (a measure of potential overfishing), fishing effort, and catch from bottom-impacting gear (a measure of potential habitat destruction). Five indicators relate to ecosystem state: ecological footprint (measured as the ratio of primary production required to sustain fisheries landings reported by countries fishing within the LME to the total primary production), Marine Trophic Index (MTI), Fishing-in-Balance (FiB) Index, and number and catch biomass of exploited stocks. Projected change in catch potential by 2030 and 2050 under global warming was also assessed.

While the LMEs rank very differently on different indicators, some of the indicators have relatively high values in many LMEs as well as in the WPWP (‘high’ and ‘highest’ risk categories), as shown in Summary Table 2.

Summary Table 2 Subset of LMEs (with GEF-eligible countries) showing colour-coded risk categories for the indicators

LME name	Subsidy to landed value	Ecological footprint (PPR/PP)	Marine Trophic Index	Fishing in Balance Index	Stock status (biomass) in percentage	Per cent catch from bottom-impacting gear	Rate of change of effective fishing effort (kW days per year)	Per cent change in catch potential in the 2050s
Gulf of California	0.14	0.04	-0.05	1.93	6.95	10.38	803,921	-8.34
Gulf of Mexico	0.11	0.06	0.06	0.67	44.21	27.46	9,651,794	-5.09
Pacific Central-American Coastal	0.09	0.05	-0.14	2.46	34.03	6.45	5,609,491	-3.57
Caribbean Sea	0.09	0.03	-0.37	0.38	25.27	19.56	8,419,253	-1.45
Humboldt Current	0.03	0.19	-0.58	1.87	9.67	1.79	8,218,267	-6.44
Patagonian Shelf	0.25	0.20	0.28	3.40	21.99	62.25	6,315,226	-5.63
South Brazil Shelf	0.29	0.05	0.24	1.80	31.89	47.60	3,782,796	-4.55
East Brazil Shelf	0.31	0.06	0.19	1.40	18.17	19.99	2,414,615	3.58
North Brazil Shelf	0.24	0.04	-0.02	1.48	14.39	43.12	4,244,746	-10.67
Mediterranean	0.14	0.14	-0.04	0.68	10.89	18.20	33,725,342	-14.53
Canary Current	0.17	0.18	-0.02	2.41	18.23	9.15	6,033,983	-4.30
Guinea Current	0.10	0.06	-0.03	1.72	17.98	15.63	15,474,117	-4.38
Benguela Current	0.19	0.13	0.43	1.81	60.05	11.00	-1,557,565	-0.01
Agulhas Current	0.11	0.06	0.58	1.81	15.01	13.24	10,971,939	11.64
Somali Coastal Current	0.08	0.01	0.07	0.92	22.94	4.13	3,756,822	14.60
Arabian Sea	0.31	0.17	0.03	1.78	10.50	17.11	24,329,676	-4.99
Red Sea	0.20	0.11	0.26	2.29	17.67	22.80	3,982,575	-7.65
Bay of Bengal	0.14	0.25	-0.03	2.13	7.04	11.63	128,945,675	2.43
Gulf of Thailand	0.17	0.46	0.41	2.55	7.68	25.51	7,759,858	-12.72
South China Sea	0.22	0.69	-0.02	1.65	9.04	22.22	10,415,054	-12.09
Sulu-Celebes Sea	0.31	0.44	-0.12	1.90	4.21	17.09	61,822,343	-6.11
Indonesian Sea	0.18	0.23	0.03	2.10	5.81	17.97	49,883,233	-26.75
East China Sea	0.31	1.24	-0.08	0.86	15.26	33.51	5,848,689	-15.90
Yellow Sea	0.26	0.95	-0.14	0.89	8.43	32.18	2,005,531	2.97
Kuroshio Current	0.48	0.23	-0.12	-0.20	60.35	24.03	9,498,713	2.32
Black Sea	0.12	0.06	-0.14	0.17	36.27	11.37	17,186,030	-0.10

Most of the LMEs with 'highest' risk scores for both driver/pressure and state indicators are in Asia. LMEs with the highest average scores across all the fisheries indicators (except change in catch potential) are the Bay of Bengal with the highest score, followed by the Sulu-Celebes Sea and Indonesian Sea. In developed regions, LMEs with the highest average scores include the Celtic-Biscay Shelf, Mediterranean, and Northeast US Continental Shelf. LMEs with lowest scores include those with limited commercial fishing activity (Beaufort Sea, East Siberian Sea, and Laptev Sea) and the East Central Australian Shelf and Benguela Current. The WPWP shows similar trends to the average LME trends for some indicators, but has experienced greater increases in certain indicators, including fishing effort. The catch potential for the WPWP is projected to drop by 7 per cent by the 2050s. Catch data accounting for small-scale fisheries (artisanal, subsistence, and recreational) at the national level are needed to improve the quality of the indicators.

Key messages

1. **Sources of pressure and degree of risk to ecosystems from fisheries vary among LMEs, with implications for management.** Management approaches need to be tailored to the dominant sources of pressure. All but two LMEs (the Laptev and Northern Bering-Chukchi Seas LMEs in the Arctic) and the WPWP have high-scoring indicators, and nearly 80 per cent of LMEs have three or more of the nine indicators in the 'medium', 'high' and 'highest' risk categories. There were, however, no consistent patterns in the distribution or combinations of indicators with high risk scores.
2. **Although the number of collapsed stocks in LMEs is increasing, the number of rebuilding stocks is also increasing, an encouraging sign.** Overall, 50 per cent of global stocks within LMEs are deemed overexploited or collapsed, and only 30 per cent fully exploited. However, the fully exploited stocks still provide 50 per cent of the globally reported landings, with the remainder produced by overexploited, collapsed, developing and rebuilding stocks. This appears to confirm the common observation that fisheries tend to affect biodiversity (as reflected in the taxonomic composition of catches) even more strongly than they affect biomass (as reflected in the landed quantities).
3. **The parts of LMEs that are under national jurisdiction should do better, as both domestic and foreign fishing within Exclusive Economic Zones can be regulated by the coastal countries concerned.** The parts of LMEs that are beyond the EEZs of coastal states are subjected to a management regime that is essentially open-access. A few countries are fully using the governance tools available to them to rebuild overfished stocks and mitigate the impact of fishing and competition between local and foreign fleets in their EEZs, and hence in the LMEs that they belong to.
4. **The projected change in the productivity of marine living resources under climate change may have significant implications for the fishing industries, economies, and livelihoods of many countries.** This is because climate change affects marine ecosystems and is expected to affect fisheries and a range of other ecosystem services. The East Siberian Sea and Indonesian Sea LMEs are projected to be the most affected by warming, with the largest decrease in fish catch potential by the 2050s. The projected substantial decrease in the catch potential of certain LMEs due to global warming would cause these regions to become more vulnerable as a result of other synergistic factors such as increasing fishing and socio-economic pressures.
5. **Fisheries and other statistics for LMEs are always uncertain composites and the indicators derived here may not represent any specific country or policy.** This is partly because countries do not report fisheries data at the LME scale. In addition, countries bordering a specific LME may be rebuilding their exploited stocks and have different fisheries policies that affect trends for the LME.
6. **Accurate catch data needed for fisheries assessments are not available because the fisheries statistics supplied by member countries to the FAO usually fail to account for small-scale fisheries.** Catch reconstruction data accounting for small-scale fisheries (artisanal, subsistence, and recreational) at the national level are needed to improve the accuracy of LME catch time-series and hence the quality of the indicators.

Fishery production potential of LMEs: A prototype analysis

Updated estimates of global fishery production potential from marine fisheries are provided to place the prospects for meeting increasing human needs for protein and essential micronutrients into context. Estimates of fishery production potential for LMEs were determined using a prototype model of energy flow in fishery systems and satellite-based estimates of primary productivity. The overall potential annual yield is approximately 140 to 180 million tonnes for the benthivore, planktivore, and piscivore functional groups, and approximately 50 million tonnes of benthic organisms if up to 10 per cent of the benthic production is suitable for harvest. Fisheries exploitation rates should not exceed 25 per cent of available production in order to be sustainable. This prototype analysis is illustrative and further work is needed to refine these figures.

Key messages

1. **As a rule of thumb based on our preliminary analysis and the literature, fisheries exploitation rates should not exceed 25 per cent of available production in order to be sustainable, and in some systems even lower rates are warranted.** The determination of a harvest reference level is critical for estimating fishery production potential. In the past, assumptions that 50 to 70 per cent of production at a defined mean trophic level could be extracted led to risk-prone decisions. Standard reference points have not been fully established to guide overall policies for marine ecosystems.
2. **Ecosystem exploitation rates vary among functional groups and are highest for fish at high trophic levels.** Exploitation rates for benthos (bottom-dwelling organisms) are uniformly low. This reflects the generally low level of landings reported for benthos relative to other ecosystem components. Species that prey on benthos and those that eat plankton exhibit generally low to moderate exploitation rates, typically less than 20 per cent of estimated production. Relatively high exploitation rates were observed for species that prey on fish, in some cases exceeding the estimated level of available production.

Pollution and Ecosystem Health

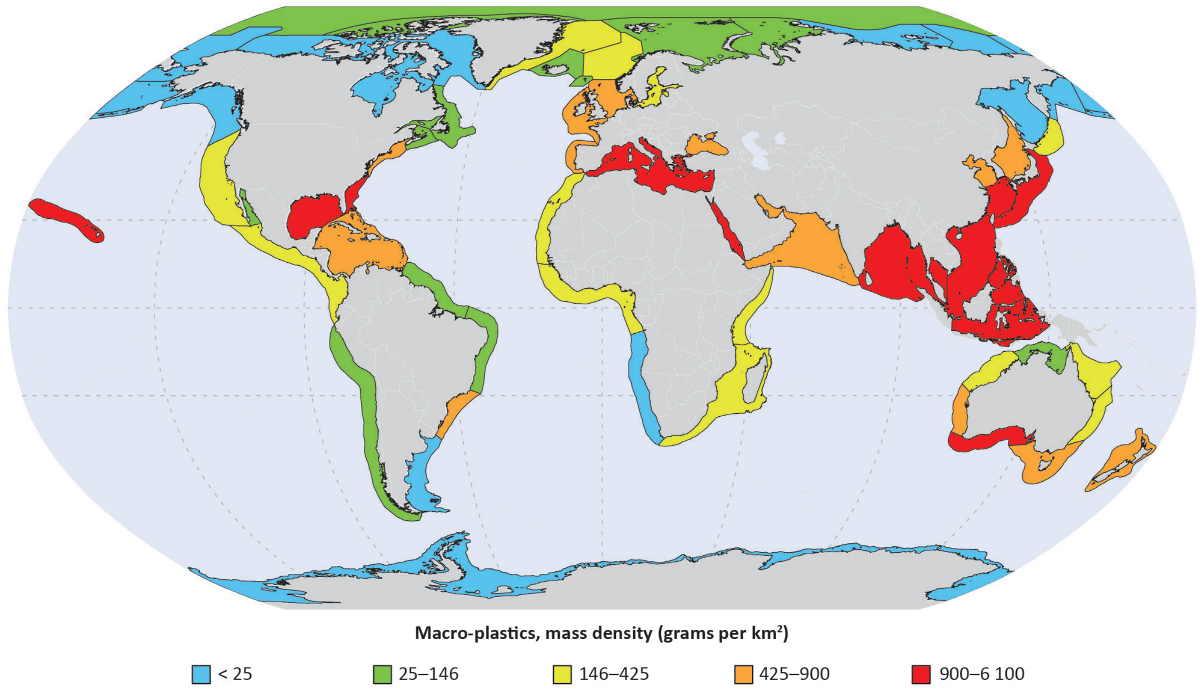
Pollution

Indicators assessed are floating micro- and macro-plastic debris, concentration of persistent organic pollutants (POPs) in beached plastic resin pellets, and nutrient input to coastal areas from watersheds. Land-based, and, to some extent, sea-based human activities accompanied by irresponsible human behaviour and weak governance are among the major drivers for these issues. Increase in the use of plastics, use of persistent chemicals including pesticides, and application of agricultural fertilizers and release of untreated sewage, among others, have resulted in high levels of these substances in some LMEs, especially those with high coastal human populations. These substances can affect the ecological status of marine ecosystems, impairing their health and that of living marine resources, and in some cases can result in harmful consequences for humans.

Floating plastic debris

Since the 1950s there has been an almost exponential increase in the use of plastics. A proportion of the plastic entering one LME is likely to be transported by wind and currents into an adjoining LME or the open ocean, making plastic pollution a classical transboundary issue. The relative abundances of floating micro-plastics (less than 4.75 mm in diameter) and macro-plastics (more than 4.75 mm in diameter) in each LME were estimated through a model that uses coastal population density, shipping density, and the level of urbanization within major watersheds, to develop proxy sources of plastics. The modelled estimates of floating plastics, which are in broad agreement with observational data from shipboard measurements and shoreline surveys, vary by more than four orders of magnitude between the lowest value (Antarctic LME) and the highest (Gulf of Thailand LME). Slightly over half of the LMEs with the 'highest' abundances of floating plastics are in east-southeast Asia (Summary Figure 7).

Summary Figure 7 Spatial distribution of the relative abundance of floating macro-plastics in 66 LMEs, based on model estimates



LMEs were separated into five categories of relative abundance, based on model estimates using proxy sources; based on Eriksen *et al.* (2014) and Lebreton *et al.* (2012).

Key messages

1. **Many of the LMEs with high to highest relative abundances of floating plastics are located in east-southeast Asia, with the Gulf of Thailand LME having the highest abundance of both micro- and macro-plastics.** Other LMEs with highest abundances of both size categories of floating plastics are the Southeast US Continental Shelf, Mediterranean Sea, Red Sea, Bay of Bengal, South China Sea, Sulu-Celebes Sea, Indonesian Sea, Southwest Australian Shelf, East China Sea, and Kuroshio Current LMEs.
2. **Plastics enter the marine environment from a wide variety of land-based and sea-based activities, and there are few reliable or accurate estimates of the nature and quantities of material involved.** This poses difficulties in designing and implementing cost-effective measures to reduce inputs to LMEs. In most cases, solutions will need to be multi-agency, multi-sector, and trans-national to be effective.
3. **While the estimates of plastic concentrations derived from modelling are imperfect, they provide information for focusing efforts to improve predictive capacity, assess potential socio-economic consequences, and target mitigation measures.** Further improvement to these model estimates should be made if data become available on key sources of plastics (such as fishing, aquaculture, and coastal tourism, which are not accounted for in the current model) and on actual quantities of plastics entering the ocean and how this may be influenced by the level of economic development in different countries.

Pollution status of persistent organic pollutants in coastal waters

Three classes of POPs – polychlorinated biphenyls (PCBs), dichlorodiphenyltrichloroethane and its metabolites (DDTs), and hexachlorocyclohexane isomers (HCHs) – were assessed, based on their concentrations in plastic resin pellets from 193 locations in 37 LMEs. Pellets were collected by volunteers through the International Pellet Watch (IPW) Programme between 2005 and 2014 and analysed for POPs. POPs were detected in all the samples, including those from remote islands. Background levels of each class of POPs were established using pellets collected from remote islands and were used as cut-off concentrations for the lowest risk category. POPs levels are highly variable within each LME. Several LMEs show relatively high contamination levels for multiple POPS ('medium' risk and above), and a number of hotspots were found ('high' and 'highest' risk). 'Highest' concentrations of PCBs and 'high' levels of DDTs were found in the South Brazil Shelf LME. Other LMEs with 'highest' or 'high' levels of these two POPs classes are the California Current, Mediterranean, and Kuroshio Current. 'High' levels of HCHs were observed in the Southeast Australian Shelf and Benguela Current LMEs. In some areas, such as in Mozambique and South Africa (Agulhas Current LME), and Ghana (Guinea Current LME), significant decreases in HCH concentration were observed, which may indicate the effective regulation of HCHs by the Stockholm Convention on POPs.

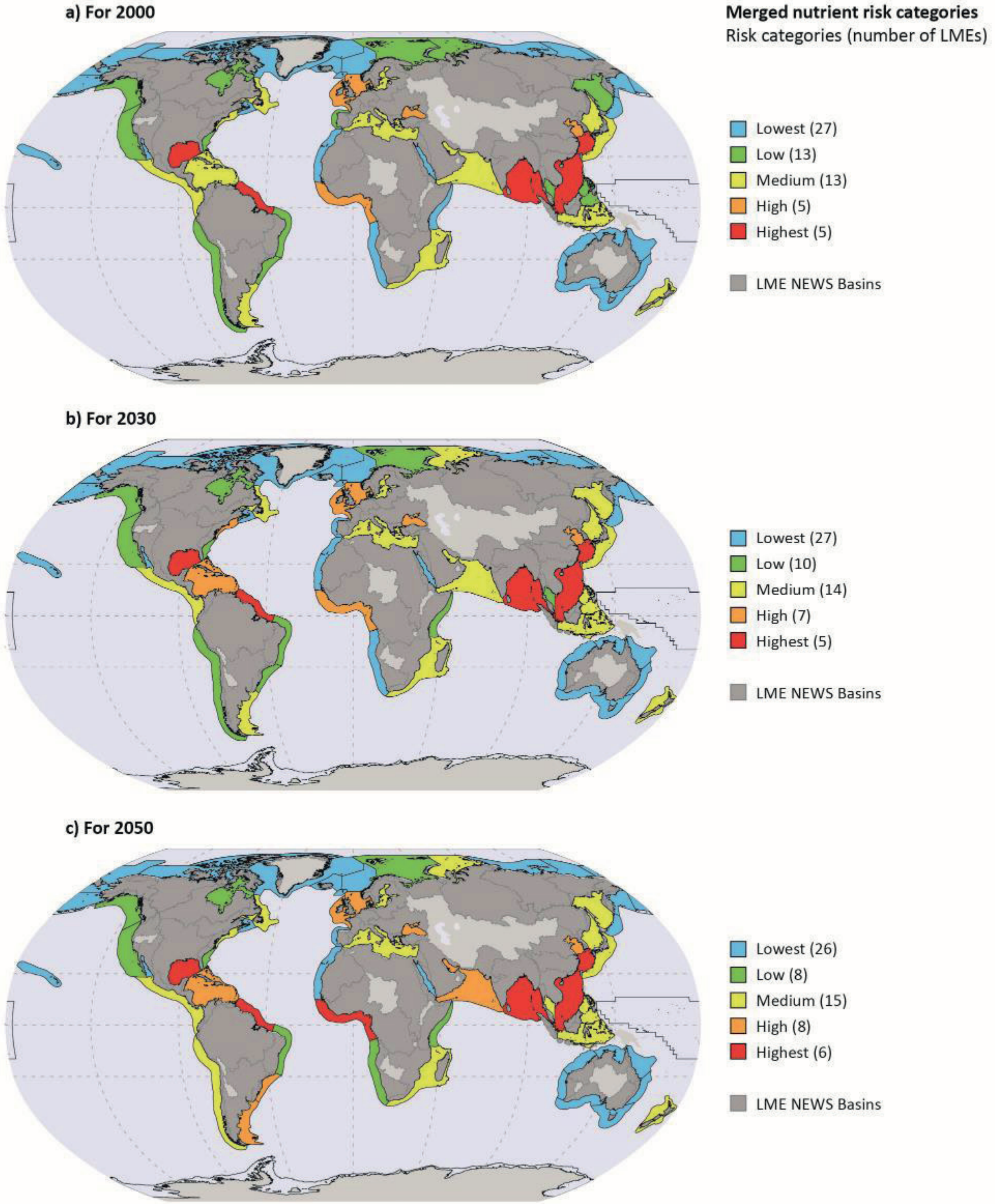
Key messages

1. **Several POPs hotspots were identified, indicating a need for follow-up action.** For example, remedial action such as dredging and/or capping of bottom sediment should be considered where hotspots of PCBs and DDTs have been identified and attributed to contamination of the water column through release of POPs from contaminated bottom sediments.
    - PCB hotspots: In five LMEs of Western Europe, two along US coasts, and one along the coast of Japan. While these may be legacies of past PCB use, increasing levels were also observed in LMEs along the coasts of more recently industrialized countries, including Brazil, Chile, and South Africa.
    - DDT hotspots: In the California Current LME, Durres (Albania) in the Mediterranean LME, and Ghana in the Guinea Current LME. Moderate to high levels of DDTs are found in 20 widely distributed LMEs, probably due to widespread application of DDT before it was banned in the 1980s.
2. **Results from some LMEs indicate current or recent use or release of banned POPs.** This is indicated by levels of:
    - PCBs in some developing countries (Ghana in the Guinea Current LME and the Philippines in the Sulu-Celebes Sea LME). These findings point to a need for better source control, such as improved management and regulation of electronic waste;
    - DDTs in the South China Sea, Brazil, Ghana, Athens and Sydney. DDT use in malaria control may account for the elevated levels in some tropical and subtropical regions, whereas illegal application of DDT pesticides and antifouling agents may be the cause in other regions;
    - HCHs, with further analyses of the isomers present indicating that illegal use of lindane, a pesticide that is banned for agricultural use, may be responsible for elevated HCHs in pellets from some Southern Hemisphere sample sites, including in Mozambique and South Africa (Agulhas Current LME) and in the New Zealand Shelf LME, as well as along the French coast in the Celtic-Biscay Shelf LME.
3. **The International Pellet Watch programme serves as a sentinel to assess the status of POPs in coastal waters and identify pollution hotspots – but other POPs monitoring is also needed.** The IPW data set would be improved by additional spatial coverage, as data are sparse for some LMEs and missing for others. Time-series sampling of POPs in LMEs is needed to detect trends, evaluate the effectiveness of regulation, and identify emerging pollution sources. Conventional monitoring of POPs in sediments, water, and biota should be conducted in hotspots to confirm the pollution levels and identify the types and sources of pollution so that mitigation actions can be undertaken.

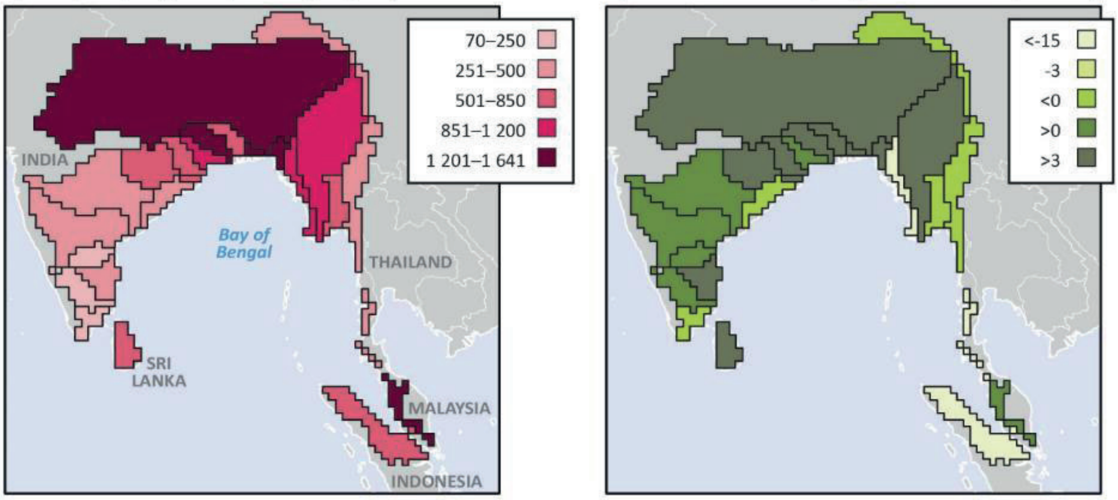
Nutrient inputs from rivers to LMEs

Among the major anthropogenic sources of river nutrient loading are runoff from fertilizer use and livestock production, sewage, and atmospheric nitrogen deposition. Excess nutrients – nitrogen (N), phosphorus (P), silica (Si) – entering coastal waters (eutrophication) can result in algal blooms, leading to reduced oxygen conditions, increased turbidity, and changes in community composition, and threats to human health, among other effects. A combined indicator of coastal eutrophication, based on two sub-indicators (N loading rate, which is the amount of nitrogen carried by rivers as they enter the LME, and ratio of dissolved Si to N or P), was developed for 63 LMEs for contemporary (approximately 2000) conditions and for one future scenario for 2030 and 2050 using the Global NEWS (Nutrient Export from Watersheds) model results (Summary Figure 8). Although the majority of the LMEs are in the 'lowest' or 'low' risk categories for coastal eutrophication, a number are at 'high' or 'highest' risk, including the Gulf of Mexico and several LMEs in Western Europe and southern and eastern Asia. Furthermore, the risk for coastal eutrophication will increase in many LMEs by 2050 based on current trends. There can be considerable variation within an LME in the nutrient yields, coastal eutrophication potential, and N sources, as shown by the sub-LME-scale assessment for the Bay of Bengal (Summary Figure 9).

Summary Figure 8 Merged nutrient risk categories for LMEs for a) 2000, b) 2030, and c) 2050 LME NEWS Basins shown on the maps are the watersheds used for modelling nutrient inputs with the Nutrient Export from Watersheds (NEWS) model.

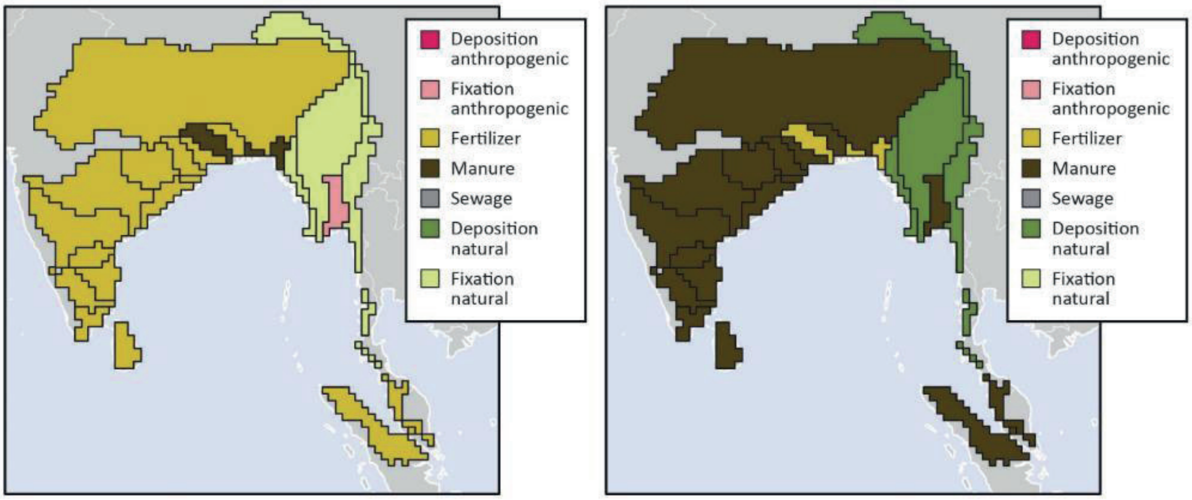


Summary Figure 9 Dissolved inorganic nitrogen (DIN) yield, Index of Coastal Eutrophication Potential (ICEP), and sources of DIN in river basins draining to the Bay of Bengal LME. A detailed analysis of the watersheds draining to the Bay of Bengal LME illustrates the spatial variation in nutrient loads, ratios, and sources of nutrients. The dominance of fertilizer and manure in many of these basins as sources of dissolved inorganic nitrogen is evident.



a) DIN yield (kilograms per km² per year)

b) ICEP sub-indicator (kilograms of carbon per km² per day)



c) Primary DIN sources

d) Secondary DIN sources

Source: Seitzinger *et al.* (2014)

Key messages based on the combined nutrient indicator

1. **Coastal eutrophication is associated with large urban populations and intense agricultural production that has high fertilizer use and/or large numbers of livestock.** Of the 63 LMEs assessed, 16 per cent are in the 'high' or 'highest' risk categories for coastal eutrophication. They are mainly in Western Europe and southern and eastern Asia, and the Gulf of Mexico. Most LMEs, however, are in the 'lowest' or 'low' risk category.
2. **In many watersheds around the world, nutrient loads in rivers are projected to increase as a result of increasing human activities.** Based on current trends, the risk of coastal eutrophication will increase in 21 per cent of LMEs by 2050. Most of the projected increase is in LMEs in southern and eastern Asia, but also in some in South America and Africa. Only two LMEs (Iberian Coastal and Northeast US Continental Shelf) are projected to lower their coastal eutrophication risk by 2050.
3. **To reduce current and future risks, reductions in nutrient inputs to specific watersheds are required.** This can include increased nutrient-use efficiency in crop production, reduction in livestock and better management of manure, and increased treatment level of human sewage.
4. **Analysis at the sub-LME scale is needed to identify sources and spatial variations of nutrients in order to develop effective nutrient reduction strategies.** Nutrient yields, eutrophication potential, and sources of nitrogen can vary considerably within an LME, as shown by a study of the Bay of Bengal LME.

Ecosystem Health

Marine ecosystems in general, and coastal ecosystems in particular, experience a wide range of stressors associated with human activities as well as natural variability. Under the Ecosystem Health sub-module, the assessment examined the extent and drivers of change in mangroves, extent of and risks to coral reefs, cumulative human impacts in LMEs, and the Ocean Health Index (OHI). A widely-implemented response to protect these valuable habitats is the establishment of marine protected areas (MPAs). Increase in MPAs since the 1980s was assessed.

Extent of mangroves and drivers of change

Thirty-three LMEs and the WPWP contain mangroves, which, over the past century, have experienced extensive loss and degradation from pressures that are both local and global. Results of Delphi-type (iterative) surveys with regional experts highlight the relative importance of key drivers of mangrove loss in different regions worldwide, as well as likely future trends. While overexploitation for timber, fuel wood, and charcoal has the greatest impact on mangrove loss, the most widespread driver of mangrove loss is coastal development, and its impact is projected to increase in almost all regions. The relative impact of the different drivers is highest and increasing in Southeast Asia. A first global baseline of mangrove extent in LMEs and the WPWP, based on the US Geological Survey's Global Distribution of Mangroves data set, is also presented. The Bay of Bengal LME has the largest area of mangroves (more than 19 000 km^2) while only 0.003 per cent (410 km^2) of the WPWP, whose area is almost 3.5 times greater than any of the LMEs, is covered by mangroves.

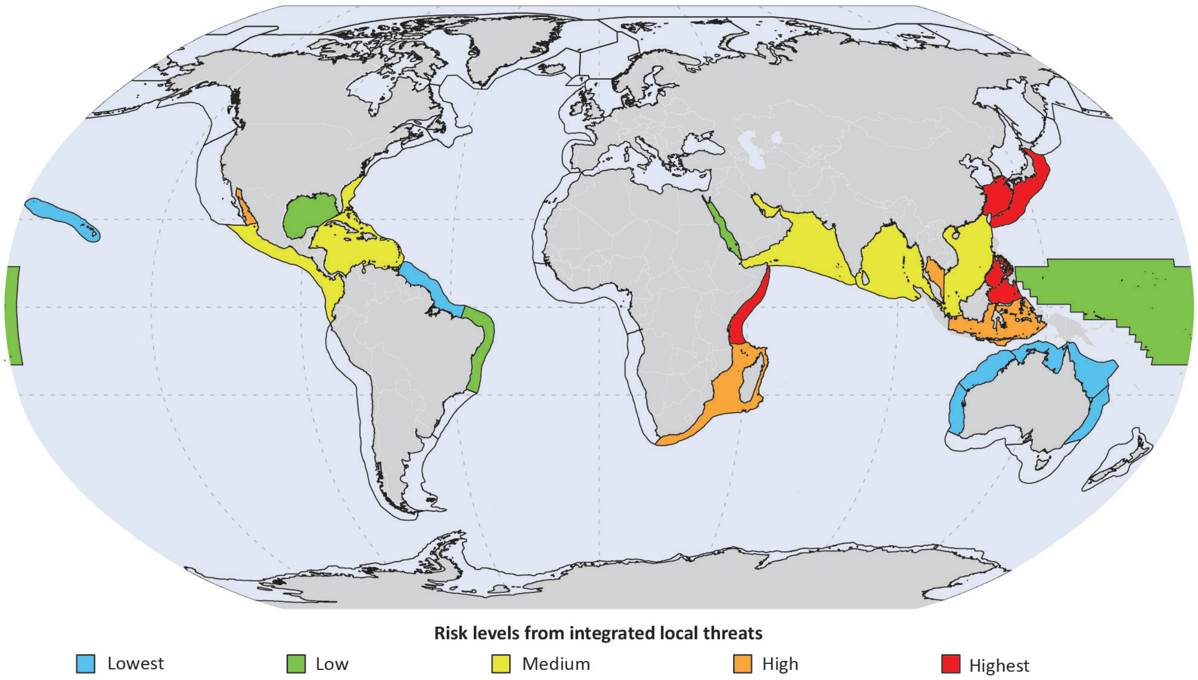
Key messages

1. **About 20 per cent of total global mangrove area was lost between 1980 and 2005 due to human activities including coastal development, aquaculture expansion, and timber extraction.** The impact of coastal development has widespread, and increasing, importance. The impact of climate change on mangroves is largely unknown, but is projected to increase.
2. **Mangrove habitat continues to decline at an estimated 1 per cent per year; actual rates and key drivers of loss vary between regions.** Overexploitation for timber, fuel wood, and charcoal is the main driver of mangrove loss, in particular in Africa and South and Southeast Asia, although the future impacts of this driver are largely unknown.
3. **Due to the high rates of mangrove deforestation in many areas, current calculations probably overestimate the extent of mangrove cover.** Future mangrove assessments in LMEs can be improved by using more recent data on mangrove coverage as a baseline and by more frequent ground-truthing, which will also allow change in coverage to be estimated. Assessments of the impacts of key drivers of mangrove loss would benefit from the incorporation of surveys from a larger number of experts and at the LME scale.

Coral reefs at risk

Twenty-four LMEs and the WPWP contain coral reefs, which are one of the most endangered habitats on the planet as a result of pressures that include warming seawater, ocean acidification, pollution, overfishing, and extraction. This first assessment of the threats faced by coral reefs within LMEs and the WPWP used the Global Distribution of Coral Reefs 2010 and the Reefs at Risk Revisited data sets. Coral reefs were assessed using an integrated threat score, incorporating local threats (from overfishing and destructive fishing, coastal development, pollution, and damage) and a global threat score (incorporating warming sea temperatures and ocean acidification projected to 2030 and 2050). Several LMEs were found to have reefs facing high levels of integrated local threats (Summary Figure 10). The

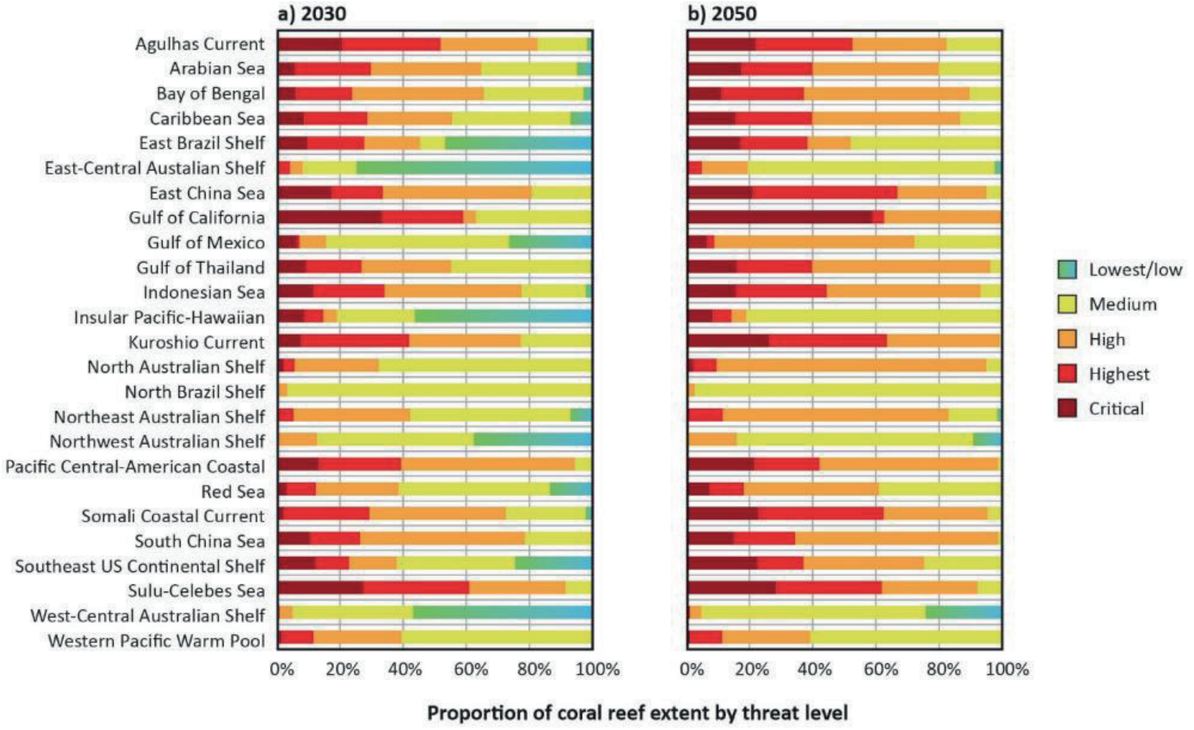
Summary Figure 10 Risk from integrated local threats for LMEs containing coral reefs and the WPWP



Source: UNEP-WCMC

percentage coral cover estimated as facing 'high' or 'highest' risk from integrated threats increases substantially if past thermal stress is included. Ocean warming and acidification will further increase threat to coral reefs in the future (Summary Figure 11). The Northeast Australian Shelf LME (which includes the Great Barrier Reef) has the largest extent of coral reef (2.83 per cent of its area), followed by the Indonesian Sea LME (2.66 per cent).

Summary Figure 11 Projected proportion of LMEs and WPWP coral reef area by threat level for global threats (warming and acidification) by a) 2030 and b) 2050



Key messages

1. **One quarter of LMEs have more than 50 per cent of their coral reef area under 'high' to 'highest' threat from local, present-day threats.** Overfishing and destructive fishing practices are of greater threat to coral reefs than coastal development and marine pollution.
    - LMEs with high local, present-day threats: Somali Coastal Current, Kuroshio Current, Sulu-Celebes Sea, East China Sea, and others.
    - LME with lowest level of local threats to coral reefs: North Brazil Shelf.
2. **Ocean warming and acidification is projected to increase the threats faced by coral reefs.** By 2030, over 50 per cent of coral reefs are projected to be at 'high' to 'critical' risk, increasing to almost 80 per cent by 2050. By 2050, only four LMEs are projected to have any reef area left at 'low' threat.
    - Conditions may be particularly severe in the Gulf of California and Kuroshio Current LMEs.
3. **Implementing measures such as marine protected areas may enhance ecosystem resilience in the face of increasing global threats.** The extent of the negative impact on coral reefs will depend on their resilience, as well as on measures to manage and protect them and their associated biodiversity. Multiple local threats are likely reduce the ability of coral reefs to respond and adapt to ocean warming and acidification.
4. **Monitoring coral reef health is important for assessing the impacts on this threatened ecosystem from both local and global threats.** The Reefs at Risk indicator is not a direct measure of coral reef condition. Monitoring coral reef health by tracking, for example, species diversity, algal cover, and live coral cover, provides information needed to understand the extent and nature of impacts from the identified threats.

Change in extent of marine protected areas (MPAs)

Aichi Target 11 of the Convention on Biological Biodiversity aims to effectively conserve 10 per cent of the world's coastal and marine areas by 2020. The first estimate of the change in area of the world's MPAs in LMEs and the WPWP was developed using the latest version of the World Database on Protected Areas. In 1983 five LMEs did not contain MPAs (Gulf of California, Northwest Australian Shelf, West Central Australian Shelf, Faroe Plateau, and Central Arctic). This decreased to two LMEs with no MPAs by 2014 (Faroe Plateau and Central Arctic).

Key messages

1. **The continuing designation of MPAs in recent decades has led to a 15-fold increase in global MPA extent between 1983 and 2014.** The total extent of protected areas with marine components increased from about one-third of a million km^2 in 1982 to more than 5 million km^2 in 2014. The increase in global MPA extent indicates progress towards the CBD's target to conserve 10 per cent of the world's coastal and marine areas by 2020 – it is currently about 2.3 per cent.
    - LMEs with the highest percentage change in area of MPAs include three Australian Shelf LMEs, Gulf of California and Red Sea;
    - LMEs with the lowest percentage change include the Arctic LMEs: Beaufort Sea, Canadian High Arctic-North Greenland, and Northern Bering-Chukchi Seas.
2. **Monitoring the effectiveness of designated MPAs and analysing how increasing coverage relates to the conservation of ocean biodiversity and productivity remain of high importance.** This type of analysis cannot be based only on the distribution of MPAs because countries vary in their interpretation and classification of MPA types, and also in the degree of implementation and enforcement of protection measures. Distribution of MPA coverage does, however, indicate areas where potential threats to marine biodiversity may be reduced by the creation of new MPAs.

Cumulative human impacts (CHI)

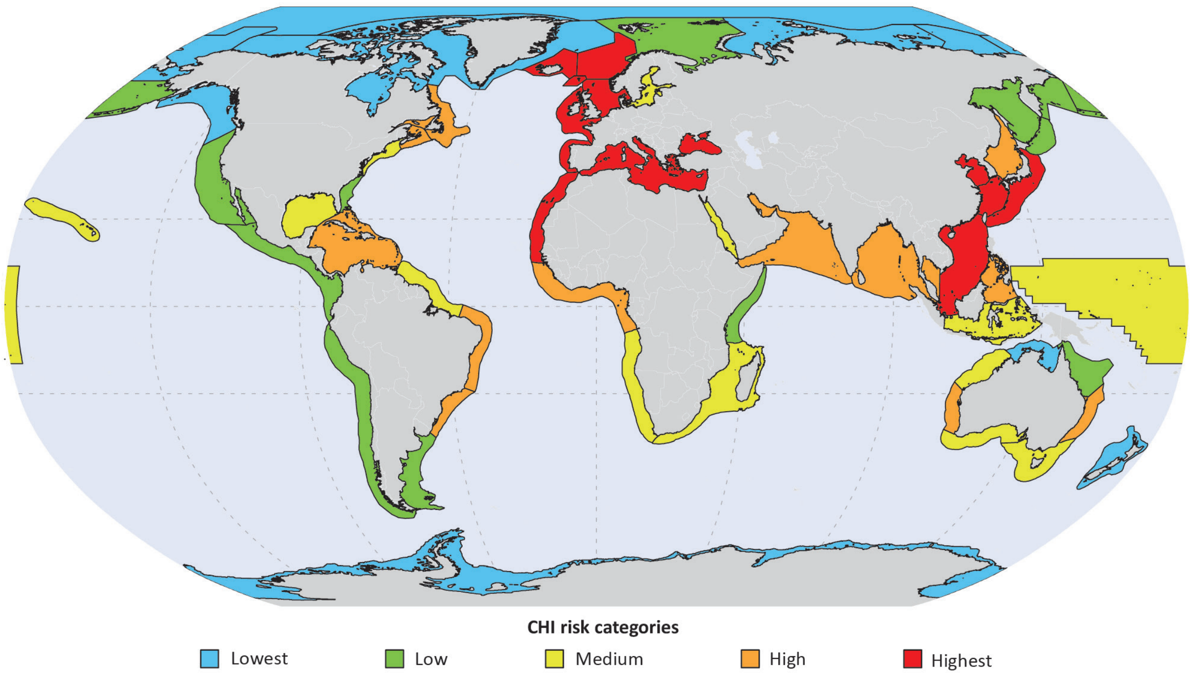
Marine ecosystems in general, and coastal systems in particular, experience multiple stressors associated with human activities, which impact systems cumulatively and with a combined impact that is always greater than that of the individual stressors. These stressors fall into four main categories: climate change, commercial fishing, land-based pollution, and commercial activity (such as shipping). Assessing and mapping the cumulative impact of human activities on marine ecosystems provides a unique perspective and understanding of the condition of marine regions and of the relative contributions of different human stressors. This assessment draws on data from a variety of sources that provide globally consistent outputs for 19 stressors and 20 marine habitats. Scores for individual stressors and for CHI were calculated by averaging the per-habitat scores for each 1 km^2 pixel within the area of each LME and the WPWP. In general, LMEs adjacent to heavily populated coastlines, particularly in developed countries that encompass large watersheds, have the highest impact scores (highest risk levels), while polar regions have the lowest scores (Summary Figure 12). The average CHI score of the WPWP places it at the medium risk level.

Key messages

1. **Stressors associated with climate change, most notably ocean acidification and increasing frequency of anomalously high sea-surface temperatures, are the top stressors for nearly every LME.** However, this result emerges partly from the scale of the assessment. At smaller scales, particularly along coastlines, many other stressors, such as land-based pollution and fishing, play a dominant role.
2. **Commercial shipping and demersal commercial fishing are the other two main stressors at the scale of LMEs.** Stressors associated with these activities tend to affect different parts of the ecosystem, so that where they overlap, cumulative impacts are likely to directly affect the entire food web.

3. **In general, LMEs adjacent to heavily populated coastlines, particularly in developed countries that encompass large watersheds, have the highest impact scores.**
    - The most heavily impacted LMEs are adjacent to China and Europe. The most impacted regions also contain most of the highest cumulative impact scores based on assessments at scales smaller than LMEs, indicating a need to improve ecosystem conditions in these regions.
    - The least impacted LMEs are in polar and subarctic regions. However, this assessment does not include projected impacts. Climate change and other human stressors are projected to lead to a rapid increase in polar LME impact scores in the near future.
4. **Efforts to manage marine ecosystems at the scale of LMEs will require coordination not only among countries bordering the LME but also among sectors.** Coordination at the sector scale is critical to successful management because the key stressors are global in nature, and are therefore beyond the scope of what can be identified and addressed through single-sector management. Cumulative human impact assessments provide a tool for transparently and quantitatively informing such policy processes and decisions.

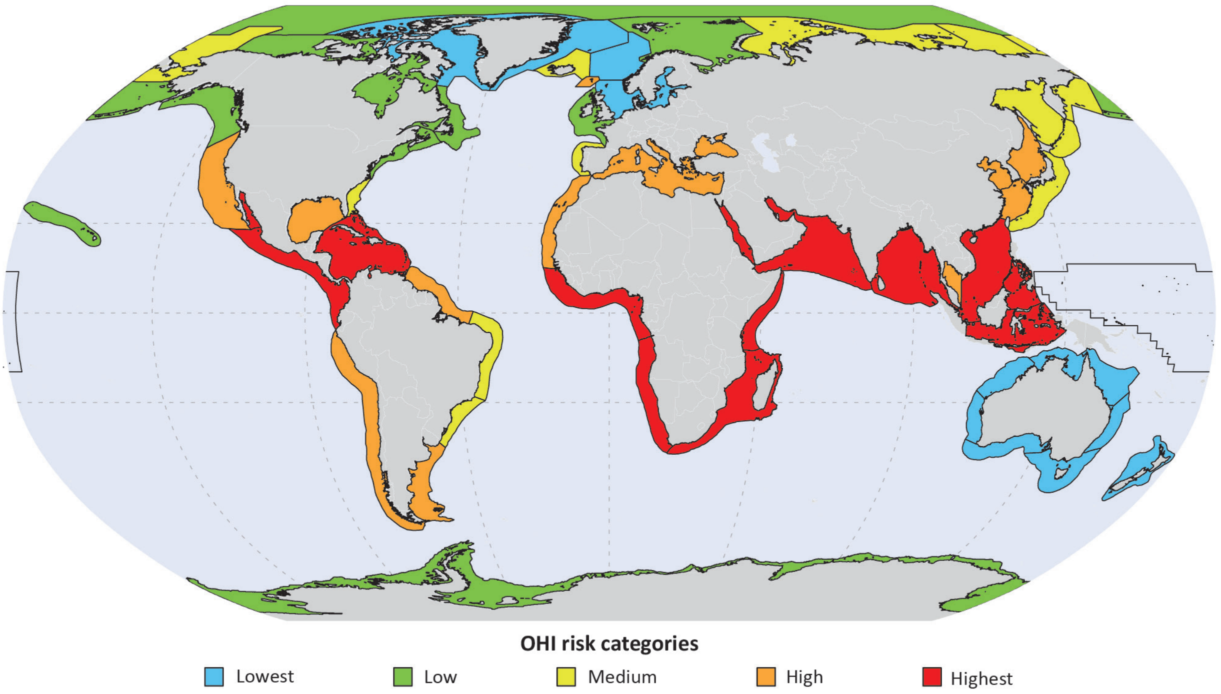
Summary Figure 12 Cumulative human impact risk categories of LMEs and the WPWP



Ocean Health Index

The Ocean Health Index (OHI) measures the performance of ten widely-agreed public goals for healthy oceans, including food provision, carbon storage, coastal livelihoods and economies, and biodiversity. The OHI highlights the relative performance of different human values and goals for the ocean, and can help elucidate where and why trade-offs among goals may occur under different management actions. Each goal is assessed against an ideal state, defined as the optimal and sustainable level that can be achieved for the goal. Nearly 80 different global data sets spanning ecological, social, economic, and governance measures were used for the OHI assessment. OHI scores for the 66 LMEs ranged from 57 to 82 out of 100, with two-thirds of all LMEs scoring between 65 and 75 (average 70.6). The lowest-scoring LMEs were along the equator, in particular in western Africa, while the highest scores were around Australia and in the sub-polar North Atlantic (Summary Figure 13). The OHI was compared for the years 2012 to 2014. For nearly three-quarters of all LMEs the scores remained unchanged or improved since the previous year, although several others had significant declines in overall index scores.

Summary Figure 13 Ocean Health Index risk category by LME



Key messages

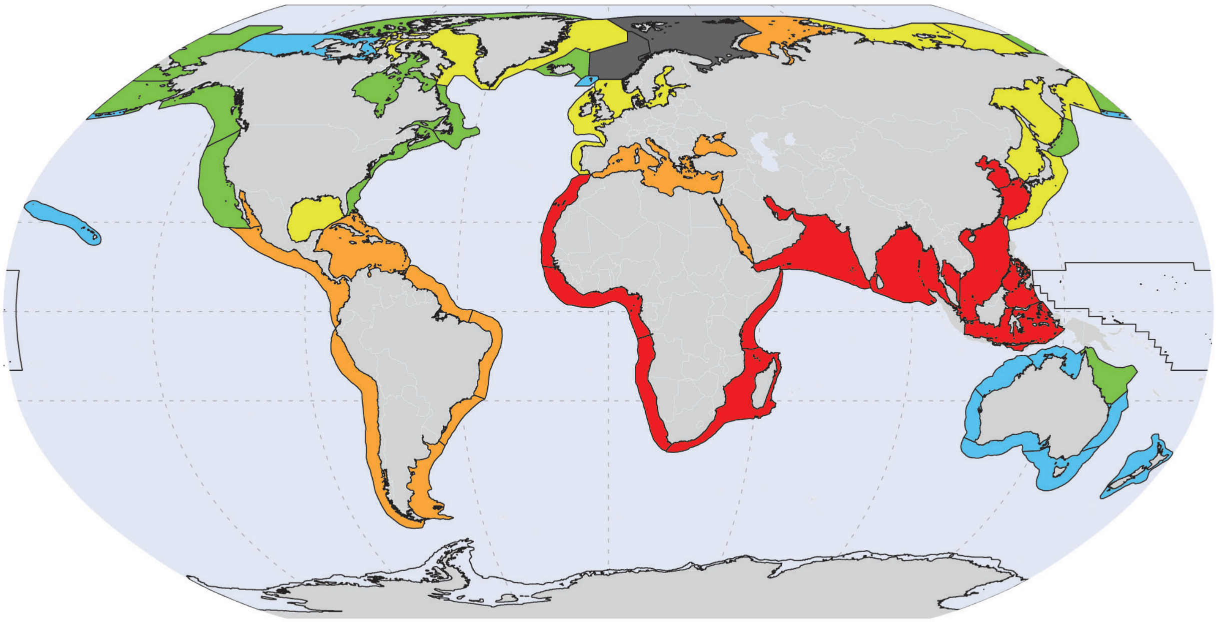
1. **Nearly all the LMEs that lie along the equator have low OHI scores and are thus in the 'highest' risk category.** This indicates that priority should be given to improving the health of the ocean in these regions.
    - LMEs in the 'highest' risk category: Agulhas Current; Gulf of California; South China Sea; Sulu-Celebes Sea; Pacific Central-American Coastal; Arabian Sea; Benguela Current; Bay of Bengal; Caribbean Sea; Red Sea; Somali Coastal Current.
2. **Tracking how scores for the ten goals contribute to the OHI score for each LME provides insights into which goals drive overall ocean health and which parameters are in most need of improvement.** Examples:
    - For nearly all LMEs, food provision could be improved by increasing the sustainable harvest of fish and the sustainable production of seafood through mariculture. Achieving these outcomes would have important benefits for food security and local economies.
    - Overall ocean health tends to score lower where coastal habitats are degraded or destroyed. Habitat restoration and protection offers a key way to improve ocean health. Coastal habitats play a key role in protecting coastal communities, storing carbon to help mitigate climate change, and supporting biodiversity.
3. **The use of the OHI together with measures of cumulative human impacts provides added insights on conditions in LMEs and can inform management of transboundary issues.** Examples:
    - High cumulative human impacts and low OHI scores (China and Southeast Asia) indicate heavy human use leading to degraded ocean health; managing to reduce human impacts should improve overall ocean health.
    - High cumulative human impacts and high OHI scores (North and Norwegian Seas) indicate high impact translating into sustainable delivery of ocean health benefits; managing to reduce human impacts would improve ecological conditions but not necessarily overall ocean health.
4. **Improving data-reporting standards for all UN member states would improve assessments of ocean health and improve decision making based on those assessments.** In addition, many aspects of ocean health remain poorly monitored, hindering the tracking of ocean health across space and through time.

Identifying patterns of risk among LMEs using multiple indicators

Single indicators or indices provide valuable information on LME condition and drivers of change. However, triggers of risk are usually multiple factors, which may be some combination of biophysical, socio-economic, or governance-related. Groups of LMEs were identified based on their similarities across a suite of eleven multivariate indicators (from the Fish and Fisheries, Pollution and Ecosystem Health, and Socio-economics modules) assessed in other chapters of this report. Only indicators that could clearly distinguish between 'poor' status and 'good' status are used, thereby eliminating the indicators in the Productivity module from this multivariate analysis. The LMEs were grouped into six clusters based on the selected indicators using clustering and ordination techniques. Shipping pressure and coastal rural populations were most important in separating the LMEs, followed by demersal non-destructive low bycatch fishing and catch from bottom-impacting gear types, then by pressures due to capacity-enhancing fisheries subsidies and floating plastic debris.

Because the statistical techniques used only group LMEs and do not rank them in any order, a separate risk analysis (Summary Figure 14) was computed, based on average normalized values of the selected indicators from the Fish and Fisheries and Pollution and Ecosystem Health modules. The Human Development Index (HDI) was used as a weighting factor in determining an overall TWAP risk score for each LME, based on the assumption that LMEs with lower socio-economic development levels (low HDI) will be at higher risk for the same levels of environmental status as those with higher human development levels, and vice versa. LMEs with developing economies in Africa and Asia show highest risks in terms of coastal eutrophication and plastic litter density, and high risks from collapsed and overexploited fish stocks. LMEs such as the Somali Coastal Current, the Bay of Bengal, and the Sulu-Celebes Sea are at 'highest' risk, while the Caribbean Sea and Mediterranean LMEs are in the 'high' risk category. LMEs along the coast of developed nations are impacted by risks from high shipping frequencies, high capacity-enhancing fisheries subsidies, and from the high levels of use of bottom-impacting fishing gear and pelagic and demersal low-bycatch gear. LMEs with mainly rural coastal areas in developed countries, such as the East Siberian Sea, or LMEs surrounded by developed countries with the most-frequented shipping routes, make up the 'medium' risk category. The coastal

Summary Figure 14 TWAP risk scores by LME. Scores are the averaged normalized indicator values for the Fish and Fisheries module (for all LMEs except the Barents Sea and Norwegian Sea) and the Pollution and Ecosystem Health module (all LMEs), weighted by the Human Development Index.



Risk categories based on TWAP risk scores

🟦 Lowest 🟩 Low 🟨 Medium 🟧 High 🟥 Highest waters of the US and Canadian LMEs are rated 'low' risk, and the Australian and New Zealand Shelf LMEs are assessed as 'lowest' risk. All LMEs, except those around the coast of Australia, the Red Sea, and the Gulf of California, are at risk because of low proportion of MPAs. Results relate to the scale of the entire LME and do not reflect on any individual country's management of its coastal waters. Patterns may change as more spatial data specific to the LMEs become available and depending on the weighting factors used.

Key messages

1. **Socio-economic development has a strong influence on the ranking of LMEs by overall risk.** Based on the 11 indicators used in this analysis:
    - LMEs with developing economies show highest risks from coastal eutrophication and plastic litter density, and moderate to high risks from collapsed and overexploited fish stocks;
    - LMEs along the coasts of developed nations have lower overall risk scores but may be at risk from a combination of high shipping frequencies, high capacity-enhancing fisheries subsidies, high use of bottom-impacting fishing gear, and from pelagic and demersal low-bycatch fishing pressure.
2. **Grouping the LMEs by similarities in multiple indicator values and ranking the LMEs by overall risk scores provides insight into patterns of risk.** Some patterns identified:
    - The clustering of LMEs by similarities in the 11 indicator values does not broadly correspond with the LME risk ranks. The exception is the Australian shelf LMEs, which are all in cluster 3 and all ranked in the 'lowest' risk category;
    - LMEs bordered by developing countries in Africa and Asia (in clusters 1 and 4), are rated as 'highest' risk;
    - LMEs in developed countries with either mainly rural coastal populations or the most-frequented shipping routes (found in clusters 1 and 6) make up the 'medium' risk category;
    - The coastal waters of the US and Canadian LMEs (in clusters 1, 5, and 6) are rated 'low' risk, and the Australian and New Zealand Shelf LMEs are assessed as 'lowest' risk.
3. **Weak points and gaps in the assessment are identified and recommendations provided for improving assessment of transboundary water systems.** The multivariate and risk-scoring techniques used provide complementary approaches to delineating LMEs at risk, through the simultaneous use of multiple indicators that measure biophysical, socio-economic, and governance pressures and states. These analyses constitute a Level 1 assessment for which the use of data sets with global spatial coverage is a priority. A Level 2 assessment, which focuses on transboundary environmental issues, would make use of more finely resolved indicators and evaluations, which could include:
    - spatially explicit and time-varying indicators that address gaps in the conceptual frameworks used in this report and provide an indication of trends in status;
    - metrics that address changes in ecosystem services due to climate and societal pressures and their impact on livelihoods and ecosystems;
    - improvements in the scale and quality of reporting of fisheries data, and improvement of the techniques for evaluating the status and trends of global fisheries biomass;
    - incorporation of economic considerations into metrics for pollution and ecosystem health;
    - assessment of how changes in land use and land cover influence material flows from land to sea, and how they may cause modifications in the structure and functioning of marine food webs;
    - tools and indicators such as poverty maps for coastal and inland areas, and regionalized input-output models that track the response of marine industries to changes in climate and governance;
    - finer-scale alternatives to the use of the HDI (a national metric);
    - evaluation of governance performance to complement the current indicators of government architecture.

Conclusion

The patterns of risk among LMEs based on single indicators and on analyses of multiple indicators from both the human and natural systems highlight which LMEs are at highest potential risk of degradation, what the contributing factors are, and where human dependence on LME goods and services and vulnerability to LME degradation and natural phenomena are greatest. Results show that in general LMEs in developing regions are at highest potential risk. However, LMEs are impacted to different degrees by each issue assessed, and the factors accounting for high risk vary across LMEs. These factors are mainly localized, but global threats (warming seas and acidification) are projected to play an increasing role in LME condition. Furthermore, under a business-as-usual scenario, risks levels in a number of LMEs are projected to rise due to factors such as increasing nutrient inputs from watersheds and increasing coastal human populations. While the assessment focuses attention on LMEs at relatively high risk, those at low and moderate risk levels should not be ignored, since appropriate actions are necessary to ensure that the risk levels in these LMEs do not increase.

Future TWAP LMEs assessments

The second objective of the current TWAP project was to formalize a partnership with key institutions, aimed at incorporating transboundary considerations into regular assessment programmes and leading to periodic assessments of transboundary water bodies. The current Working Group of institutional partners and experts is the foundation for a formal partnership for future LMEs assessments, and other partners will be identified for future assessments. The potential mechanisms for sustaining the TWAP LMEs assessment are described in the TWAP LMEs Sustaining Mechanisms document (onesharedocean.org). Future assessments will require improvements in data and in maintaining and sustaining the current data portal as new data and information become available.

In order to develop appropriate management strategies for an LME, information at the sub-LME scale may be needed, depending on the issue to be addressed. Future TWAP LMEs assessments should therefore incorporate Level 2 assessments and include more in-depth analysis to identify cause and effect. Additional indicators can also be assessed, depending on the priority issues in specific LMEs and data availability. Future assessments should also include an evaluation of the performance of governance arrangements for transboundary issues.

TWAP LMEs assessment will greatly benefit from strengthening the capacity at national and regional levels for conducting assessments and for applying the results in developing management strategies for addressing transboundary issues in LMEs. Mechanisms to facilitate capacity strengthening include the GEF LME-Learn project and the LME community of practitioners. In addition, closer engagement with relevant regional stakeholders will be an important exercise to ensure that the assessment meets their needs for information to manage their respective LMEs and to promote the acceptance and uptake of the assessment results.

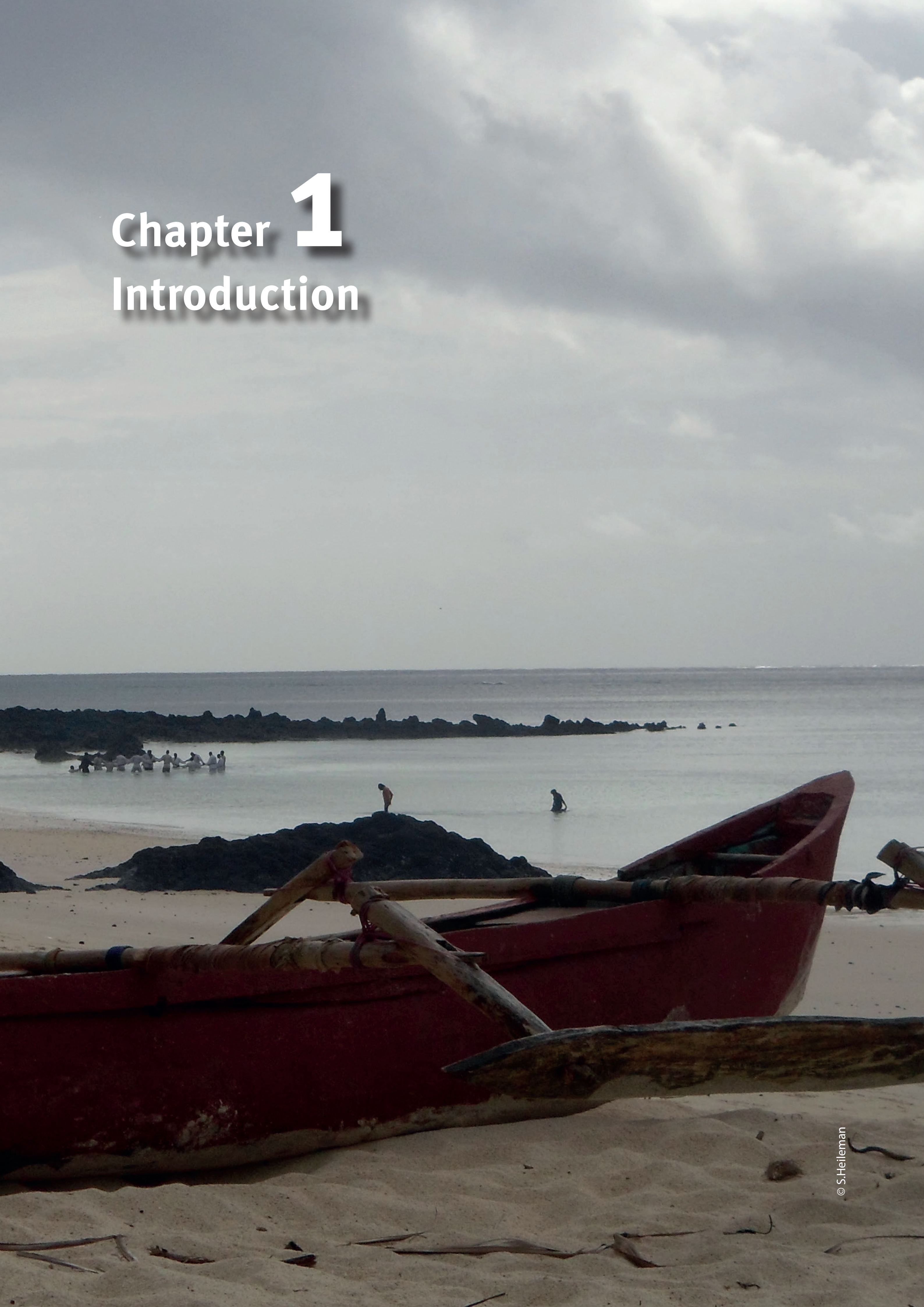
The sustainability of TWAP LMEs assessments will depend to a large extent on the availability of adequate financial resources. Potential mechanisms for financing future assessments are discussed in the Sustainability Mechanisms document, available at onesharedocean.org.

More information is available online at onesharedocean.org.


© S.Heileman

Chapter 1

Introduction



© S.Heileman

Lead Author

Sherry Heileman (Consultant, Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization).

Contributing Authors

Julian Barbiere (Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization), Kenneth Sherman (US National Oceanic and Atmospheric Administration, Northeast Fisheries Science Center).

Chapter Citation

Heileman, S., Barbiere, J., Sherman, K. (2016). Chapter 1: Introduction. In IOC-UNESCO and UNEP (2016). *Large Marine Ecosystems: Status and Trends*. United Nations Environment Programme, Nairobi, pp 1-7

1 Introduction

1.1 Background

Most of the Earth's surface is covered by water systems that are transboundary (extending across or beyond national boundaries). These include the open ocean, 49 (out of a total of 66) large marine ecosystems (LMEs), more than 1 600 lakes and reservoirs, and 286 river basins. About 455 groundwater aquifers are also transboundary.

The well-being and socio-economic development of a significant portion of the world's population depend on the ecosystem services provided by these water systems, including fresh water for domestic, industrial, and agricultural use, and fisheries, tourism, transportation, water purification and climate regulation. Clear trends, however, show that growing human populations and expanding human activities, as well as a changing climate, are modifying these systems at an increasing rate, threatening their sustainability and the services they provide.

Recognizing the value of transboundary water systems, their continued degradation, the fragmented approach to their management, and the need for better prioritization when allocating limited financial resources, the Global Environment Facility (GEF), in collaboration with a number of institutional partners, launched the Transboundary Waters Assessment Programme (TWAP) under its International Waters Portfolio. The partners included the United Nations Environment Programme (UNEP) – the implementing agency – and four executive agencies, each of which assumed responsibility for one or more of the components of the five transboundary water systems:

1. Open ocean – IOC-UNESCO;
2. LMEs – IOC-UNESCO;
3. Groundwater aquifers – International Hydrological Programme of UNESCO;
4. River basins – UNEP-DHI;
5. Lakes and reservoirs – International Lake Environment Committee.

The first TWAP project (2009–2010) focused on the development of scientifically robust indicator-based methodologies and institutional arrangements for assessing changes from human and natural causes in the five types of transboundary water systems, and the consequences of these changes for human populations dependent on them. Subsequently, between 2013 and 2015, five independent indicator-based assessments of transboundary water systems were conducted, each led by one of TWAP's executive agencies, listed above. With the exception of the open ocean component, these are comparative assessments that identify groups of water bodies that are most affected by human and natural stressors. The assessments will assist GEF, policy-makers, and the international community in general in setting priorities for the conservation of transboundary waters. In addition, they provide a baseline for monitoring future changes and evaluating the effectiveness of interventions in these systems.

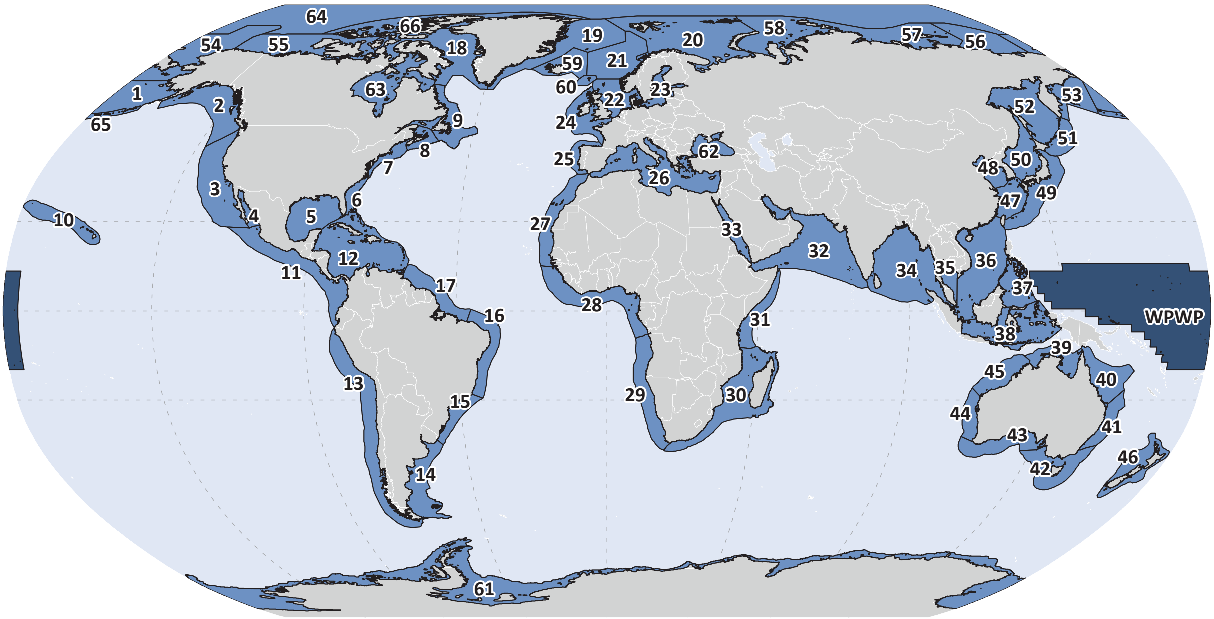
This report presents the results of the comparative assessment of LMEs, which was conducted by a working group of institutional partners and experts under the leadership of the IOC-UNESCO. It includes an assessment of the Western Pacific Warm Pool (WPWP), using a sub-set of the indicators used in the LME assessment.

1.2 Large marine ecosystems

LMEs are relatively large areas (200 000 km^2 or more) of water. They encompass coastal areas extending from river basins and estuaries to the seaward boundaries of continental shelves and to the outer margins of major coastal currents or enclosed/semi-enclosed seas. Sixty-six LMEs have been defined globally (Figure 1.1), of which 49 are transboundary. A list of LMEs with the bordering countries is presented in the Annex to this chapter.

LMEs are defined by four ecological criteria: bathymetry, hydrography, productivity, and trophically-linked populations (Sherman 1994 and 1991; Sherman and Alexander 1994). LMEs provide a diverse range of ecosystem services that are of immense socio-economic value to bordering countries. On a global scale, LMEs produce 80 per cent of the

Figure 1.1 Map of the 66 Large marine ecosystems of the world, plus location of the Western Pacific Warm Pool. LMEs are relatively large areas (200 000 km^2 or more) encompassing coastal areas extending from river basins and estuaries to the seaward boundaries of continental shelves and to the outer margins of major coastal currents or enclosed/semi-enclosed seas.



1. East Bering Sea
2. Gulf of Alaska
3. California Current
4. Gulf of California
5. Gulf of Mexico
6. Southeast US Continental Shelf
7. Northeast US Continental Shelf
8. Scotian Shelf
9. Newfoundland-Labrador Shelf
10. Insular Pacific-Hawaiian
11. Pacific Central-American
12. Caribbean Sea
13. Humboldt Current
14. Patagonian Shelf
15. South Brazil Shelf
16. East Brazil Shelf
17. North Brazil Shelf
18. Canadian Eastern Arctic-West Greenland
19. Greenland Sea
20. Barents Sea
21. Norwegian Sea
22. North Sea
23. Baltic Sea
24. Celtic-Biscay Shelf
25. Iberian Coastal
26. Mediterranean
27. Canary Current
28. Guinea Current
29. Benguela Current
30. Agulhas Current
31. Somali Coastal Current
32. Arabian Sea
33. Red Sea
34. Bay of Bengal
35. Gulf of Thailand
36. South China Sea
37. Sulu-Celebes Sea
38. Indonesian Sea
39. North Australian Shelf
40. Northeast Australian Shelf
41. East-Central Australian Shelf
42. Southeast Australian Shelf
43. Southwest Australian Shelf
44. West-Central Australian Shelf
45. Northwest Australian Shelf
46. New Zealand Shelf
47. East China Sea
48. Yellow Sea
49. Kuroshio Current
50. Sea of Japan
51. Oyashio Current
52. Sea of Okhotsk
53. West Bering Sea
54. Northern Bering-Chukchi Seas
55. Beaufort Sea
56. East Siberian Sea
57. Laptev Sea
58. Kara Sea
59. Iceland Shelf and Sea
60. Faroe Plateau
61. Antarctic
62. Black Sea
63. Hudson Bay Complex
64. Central Arctic Ocean
65. Aleutian Islands
66. Canadian High Arctic-North Greenland

WPWP - Western Pacific Warm Pool

Source: NOAA

world's annual marine fish catch (Pauly *et al.* 2008) and their coastal waters contribute an estimated US$28 trillion annually to the global economy through ecosystem services (Costanza *et al.* 2014). However, most of the effects of coastal ocean stressors occur within the boundaries of LMEs, which continue to be degraded by multiple and complex anthropogenic and natural stressors.

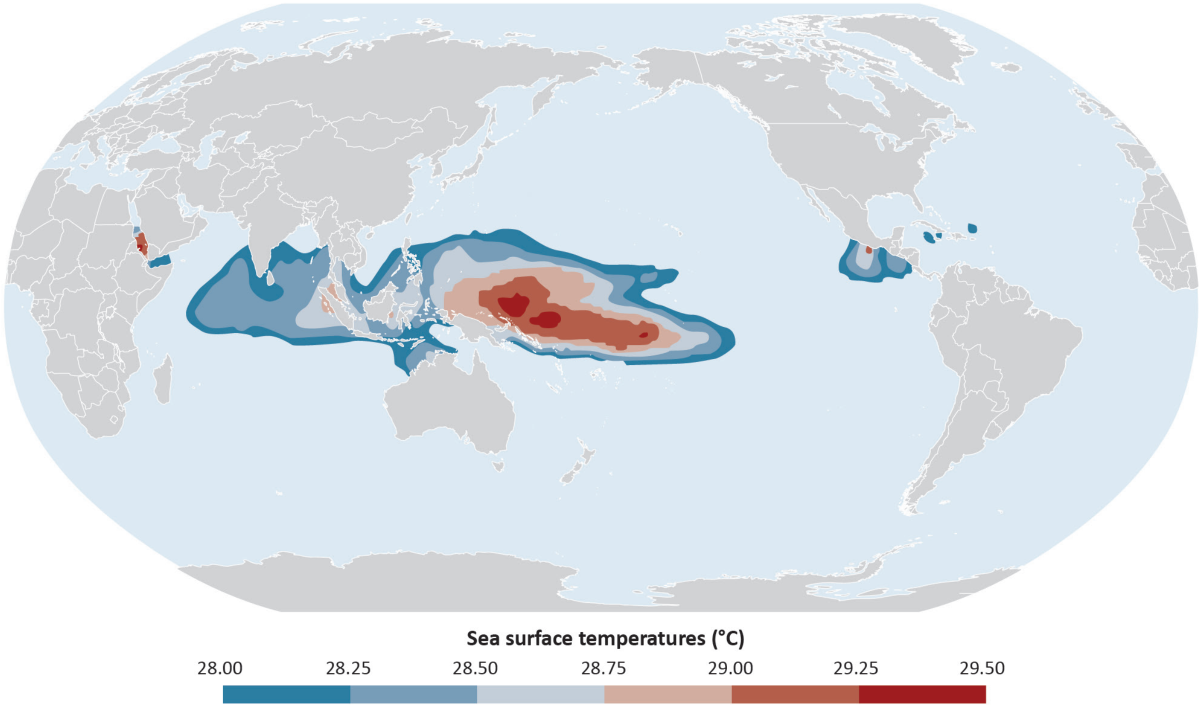
As a result, the world's LMEs have become centres of a global movement to develop ecosystem-based management (EBM) approaches to recover and sustain depleted marine fisheries; control coastal pollution, nutrient over-enrichment, and acidification; restore habitats; conserve biodiversity; and adapt to climate change (Sherman 2014; Sherman *et al.* 2005; Duda and Sherman 2002). Since the mid-1990s, 110 developing countries, in Africa, Asia, Latin America and the Caribbean, the Pacific, the Arctic, and eastern Europe, have received about US$3 150 million in financial support for this purpose, mainly from the GEF, but also from other financial institutions, including the World Bank, and from donor nations. Initiatives were undertaken in partnership with five UN agencies (UN Development Programme, UNEP, UN Industrial Development Organization, Food and Agriculture Organization, and IOC-UNESCO) and several countries (including the United States through NOAA (the National Oceanic and Atmospheric Administration), Norway through Norad (Norwegian Agency for Development Cooperation), and Germany through GIZ (Gesellschaft für Internationale Zusammenarbeit)).

This is the first indicator-based global comparative assessment of LMEs. The previous global assessment of LMEs (Sherman and Hempel 2008) was based on a combination of quantitative and qualitative information and did not use a comparative approach. Prior to the 2008 LME report, an assessment of a number of LME areas was included in the Global International Waters Assessment (GIWA), which was supported by the GEF and implemented by UNEP between 1999 and 2005. GIWA was an integrated global assessment of international waters in 66 regions around the world (UNEP 2006). Each GIWA region comprised one or more international river basins, and many included an adjacent LME. The objective of GIWA was to produce a comprehensive and integrated global assessment of international waters, encompassing the ecological conditions and problems of transboundary freshwater basins and their associated coastal and ocean systems. The GIWA methodology, however, was not entirely indicator-based. GIWA results related to LMEs were included in the report by Sherman and Hempel (2008).

1.3 The Western Pacific Warm Pool

The Western Pacific Warm Pool (WPWP) is an immense area of open-ocean warm water in the western Pacific Ocean (Figure 1.2) and does not include coastal waters at the margins of the continents. It lies north of Papua New Guinea, and its size fluctuates as it expands and contracts each year. Because its open-ocean geographic location and physical characteristics differ from the criteria that define LMEs (Sherman and Alexander 1986), the WPWP is not considered as an LME (Honey and Sherman 2013). Figure 1.1 depicts the boundary of the WPWP for the purposes of the TWAP assessment and as originally described by Longhurst in 1998 (Honey and Sherman 2013; Longhurst 1998). Although the WPWP is not an LME, lessons learned and insights from the LME modular approach for assessment and management of LMEs can aid scientists, policy experts, and resource managers in the assessment and management of WPWP ecosystem services.

Figure 1.2 Warm-water areas of the global ocean, highlighting the Western Pacific Warm Pool. The Western Pacific Warm Pool is an immense area of open-ocean warm water in the western Pacific Ocean; its size fluctuates as it expands and contracts each year.



The warm tones depict a 28.75–29.25°C sea surface temperature range.

Source: CRCES 2013

References

Costanza, R., de Groot, R., Sutton, P., van der Ploeg, S. and others (2014). Changes in the global value of ecosystem services. *Global Environmental Change* 26, 152–158

CRCES (2013): http://www.crces.org/presentations/dmv_ipwp/

Duda, A. M. and Sherman, K. (2002*).* A new imperative for improving management of large marine ecosystems*. Ocean and Coastal Management* 45, 797-833

Honey, K. and Sherman, K. (2013). *The Western Pacific Warm Pool Assessment Approach for the Transboundary Waters Assessment. Background Brief*. NOAA Large Marine Ecosystem Program, Narragansett, RI, USA

Longhurst, A. (1998). *Ecological Geography of the Sea*. Academic Press, San Diego, California, 560 pages

Pauly, D., Alder, J., Booth, S. and others (2008). Fisheries in large marine ecosystems: Descriptions and diagnoses. In *The UNEP Large Marine Ecosystem Report: A perspective on changing conditions in LMEs of the world's Regional Seas*. UNEP Regional Seas Report and Studies 182. United Nations Environment Programme, Nairobi, Kenya, 852 pages

Sherman, K. (1991). The large marine ecosystem concept: A research and management strategy for living marine resources. *Ecological Applications* 1, 349-360

Sherman, K. (1994). Sustainability, biomass yields and health of coastal ecosystems: An ecological perspective. *Marine Ecology Progress Series* 112, 277-301

Sherman, K. (2014). Toward ecosystem-based management (EBM) of the world's large marine ecosystems during climate change. *Environmental Development* 11, 43-66

Sherman, K. and Alexander, L.M. (1994). *Management of large marine ecosystems*. Encyclopaedia of Environmental Biology (ed. Nierenberg, W.A.). San Diego

Sherman, K. and Alexander, L.M. (eds.) (1986). *Variability and management of Large Marine Ecosystems Boulder*. CO, AAAS Symposium 99, Westview Press, 319 pages

Sherman, K. and Hempel, G. (eds.) (2008). *The UNEP Large Marine Ecosystem Report: A perspective on changing conditions in LMEs of the world's Regional Seas*. UNEP Regional Seas Report and Studies 182. United Nations Environment Programme, Nairobi, Kenya, 852 pages

Sherman, K., Sissenwine, M., Christensen, V. and others (2005). A global movement toward an ecosystem approach to marine resources management. *Marine Ecology Progress Series* 300, 275-279

UNEP (2006). *Challenges to international waters – regional assessments in a global perspective*. United Nations Environment Programme, Nairobi, Kenya, 122 pages

Annex

Annex Table 1-A LMEs and Western Pacific Warm Pool and bordering countries

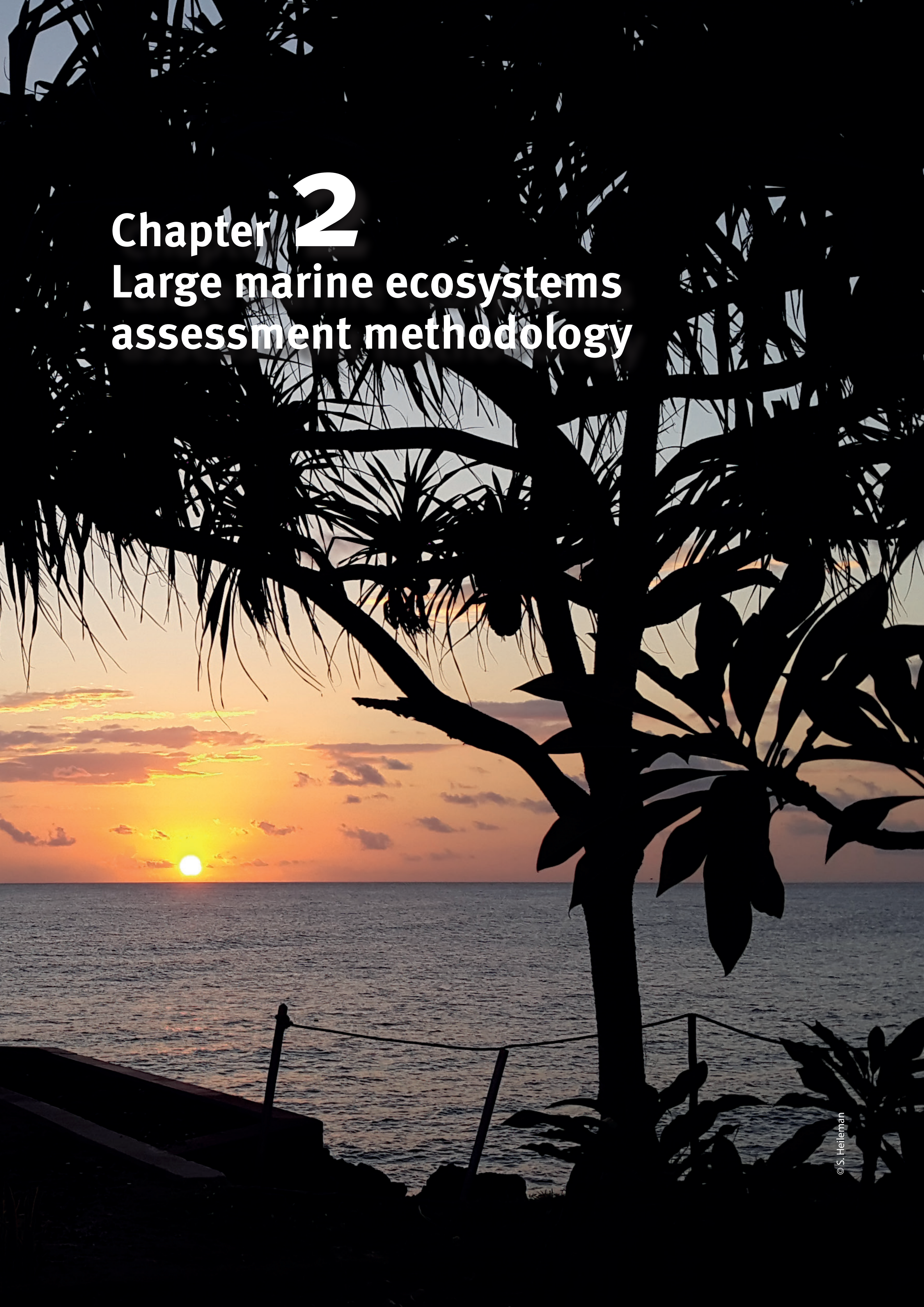
LME number	LME name	Bordering countries
1	East Bering Sea	Russian Federation, United States of America
2	Gulf of Alaska	Canada, United States of America
3	California Current	Mexico, United States of America
4	Gulf of California	Mexico
5	Gulf of Mexico	Cuba, Mexico, United States of America
6	Southeast US Continental Shelf	Bahamas, United States of America
7	Northeast US Continental Shelf	Canada, United States of America
8	Scotian Shelf	Canada
9	Newfoundland-Labrador Shelf	Canada, Saint Pierre et Miquelon (France)
10	Insular Pacific-Hawaiian	United States of America
11	Pacific Central-American	Colombia, Costa Rica, Ecuador, El Salvador, Guatemala, Honduras, Mexico, Nicaragua, Panama, Peru
12	Caribbean Sea	Antigua and Barbuda, Aruba (The Netherlands), Bahamas, Barbados, Belize, Bonaire (The Netherlands), Cayman Islands, Colombia, Costa Rica, Cuba, Curacao (The Netherlands), Dominica, Dominican Republic, Grenada, Guadeloupe (France), Guatemala, Haiti, Honduras, Jamaica, Martinique (France), Mexico, Montserrat, Nicaragua, Panama, Puerto Rico, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Trinidad and Tobago, Turks and Caicos Islands, United States Virgin Islands (United States of America), Venezuela
13	Humboldt Current	Argentina, Chile, Peru
14	Patagonian Shelf	Argentina, Uruguay
15	South Brazil Shelf	Brazil, Uruguay
16	East Brazil Shelf	Brazil
17	North Brazil Shelf	Barbados, Brazil, French Guiana (France), Guyana, Suriname, Trinidad and Tobago, Venezuela
18	Canadian Eastern Arctic-West Greenland	Canada, Greenland (Denmark)
19	Greenland Sea	Greenland (Denmark), Norway
20	Barents Sea	Norway, Russian Federation
21	Norwegian Sea	Norway, Faroe Islands (Denmark), Iceland, U.K. of Great Britain and Northern Ireland
22	North Sea	Belgium, Denmark, Faroe Islands (Denmark), France, Germany, The Netherlands, Norway, Sweden, U.K. of Great Britain and Northern Ireland
23	Baltic Sea	Denmark, Estonia, Finland, Germany, Latvia, Lithuania, Norway, Poland, Russian Federation
24	Celtic-Biscay Shelf	France, Guernsey (United Kingdom), Ireland, Isle of Man (United Kingdom), Jersey (United Kingdom), U.K. of Great Britain and Northern Ireland
25	Iberian Coastal	France, Portugal, Spain
26	Mediterranean	Albania, Algeria, Bosnia and Herzegovina, Croatia, Cyprus, Egypt, France, Palestine, Greece, Israel, Italy, Lebanon, Libya, Malta, Monaco, Montenegro, Morocco, Slovenia, Spain, Syrian Arab Republic, Tunisia, Turkey
27	Canary Current	Cabo Verde, Gambia, Guinea-Bissau, Mauritania, Morocco, Senegal, Spain, Western Sahara
28	Guinea Current	Angola, Benin, Cameroon, Congo, Côte d'Ivoire, Democratic Republic of Congo, Equatorial Guinea, Gabon, Ghana, Guinea, Guinea-Bissau, Liberia, Nigeria, Sao Tome and Principe, Sierra Leone, Togo
29	Benguela Current	Angola, Namibia, South Africa
30	Agulhas Current	Comoros, Madagascar, Mayotte (France), Mozambique, South Africa
31	Somali Coastal Current	Comoros, Kenya, Somalia, Seychelles, United Republic of Tanzania

LME number	LME name	Bordering countries
32	Arabian Sea	Bahrain, Djibouti, India, Iran (Islamic Republic of), Iraq, Kuwait, Maldives, Oman, Pakistan, Qatar, Saudi Arabia, Somalia, United Arab Emirates, Yemen
33	Red Sea	Djibouti, Egypt, Eritrea, Israel, Jordan, Saudi Arabia, Sudan, Yemen
34	Bay of Bengal	Bangladesh, India, Indonesia, Malaysia, Myanmar, Sri Lanka, Thailand
35	Gulf of Thailand	Cambodia, Malaysia, Thailand, Viet Nam
36	South China Sea	Brunei Darussalam, China, Hong Kong (China), Indonesia, Macau (China), Malaysia, Philippines, Singapore, Taiwan, Viet Nam
37	Sulu-Celebes Sea	Indonesia, Malaysia, Philippines
38	Indonesian Sea	Indonesia, Timor-Leste
39	North Australian Shelf	Australia
40	Northeast Australian Shelf	Australia, Papua New Guinea
41	East-Central Australian Shelf	Australia
42	Southeast Australian Shelf	Australia
43	Southwest Australian Shelf	Australia
44	West-Central Australian Shelf	Australia
45	Northwest Australian Shelf	Australia
46	New Zealand Shelf	New Zealand
47	East China Sea	China, Japan, Republic of Korea, Taiwan
48	Yellow Sea	China, Democratic People’s Rep of Korea, Republic of Korea
49	Kuroshio Current	Japan, Philippines, Taiwan
50	Sea of Japan	Dem. People’s Rep. of Korea, Japan, Republic of Korea, Russian Federation
51	Oyashio Current	Japan, Russian Federation
52	Sea of Okhotsk	Japan, Russian Federation
53	West Bering Sea	Russian Federation, United States of America
54	Northern Bering-Chukchi Seas	Russian Federation, United States of America
55	Beaufort Sea	Canada, United States of America
56	East Siberian Sea	Russian Federation
57	Laptev Sea	Russian Federation
58	Kara Sea	Russian Federation
59	Iceland Shelf and Sea	Faroe Islands (Denmark), Greenland (Denmark), Iceland, Norway
60	Faroe Plateau	Faroe Islands (Denmark)
61	Antarctica	Antarctica
62	Black Sea	Bulgaria, Georgia, Romania, Russian Federation, Turkey, Ukraine
63	Hudson Bay Complex	Canada
64	Central Arctic	Canada, Greenland (Denmark), Norway, Russian Federation
65	Aleutian Islands	United States of America
66	Canadian High Arctic-North Greenland	Canada, Greenland (Denmark)
WPWP	Western Pacific Warm Pool	American Samoa (United States of America), Cook Islands, Fiji, French Polynesia (France), Guam (United States of America), Micronesia (Federated States of), Nauru, New Caledonia (France), Northern Mariana Islands (United States of America), Palau, Pitcairn (United Kingdom), Samoa, Solomon Islands, Tokelau, Tonga, Tuvalu, Marshall Islands, Vanuatu, Wake Island (United States of America), Wallis and Futuna (France)


© S. Heileman

Chapter 2

Large marine ecosystems assessment methodology



©S. Heileman

Lead Author

Sherry Heileman (Consultant, Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization).

Contributing Authors

Kenneth Sherman (US National Oceanic and Atmospheric Administration, Northeast Fisheries Science Center), Julian Barbiere (Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization).

Chapter Citation

Heileman, S., Barbiere, J., Sherman, K. (2016). Chapter 2: Methodology. In IOC-UNESCO and UNEP (2016). *Large Marine Ecosystems: Status and Trends*. United Nations Environment Programme, Nairobi, pp 11-17.

Large marine ecosystems assessment methodology

2.1 Approach to assessment and management of LMEs: LME modules

A detailed description of the Transboundary Waters Assessment Programme (TWAP) Large marine ecosystems assessment methodology (IOC-UNESCO 2011) is available online at http://www.geftwap.org/publications/methodologies-for-the-gef-transboundary-assessment-programme-1/volume-5). The approach to LME assessment and management is based on five linked modules – Productivity, Fish and Fisheries, Pollution and Ecosystem Health, Socio-economics, and Governance (Sherman 2005), with corresponding sets of indicators for monitoring and assessing changing conditions in LMEs. The first three modules focus on natural systems, the other two deal with human interactions with these systems. The natural system modules have so far received the most attention, but increasing consideration is being given to the human dimension of LMEs, for example in ecosystem-based management approaches. The TWAP LME assessment methodology is built on these five modules.

Socio-economics module

The socio-economic module emphasizes the explicit integration of social and economic indicators and analyses with scientific assessments, to ensure that management measures accurately reflect the value of LMEs and the costs of impairment of the ecosystem services they provide. Socio-economic considerations must be closely integrated with science-based assessments to provide the information needed to adapt to changing ecological conditions (Tallis *et al.* 2008). The estimated annual contribution from coastal waters to the global economy of around US$28 trillion (Costanza *et al.* 2014) highlights the critical importance of LMEs. At the same time, socio-economic factors, such as those related to human populations and activities, are often the source of threats to the sustainability of LMEs. Lower sustainability of LMEs, in turn, has potentially severe consequences for human communities dependent on them. Indicators and indices assessed under this module include coastal human population, the Human Development Index (HDI), climate threat index, sea-level rise threat indices, contribution of fish protein in diets, and fisheries and tourism revenues.

Governance module

There are three key general mechanisms of governance (Juda and Hennessy 2001): the marketplace, the government, and non-governmental institutions and arrangements. These mechanisms interact through a changing pattern of dynamic relationships. Governance mechanisms influence one another across scales (global, regional, national, and local), including down to the scale of personal behaviour. These mechanisms and their interactions determine who benefits from the delivery of ecosystem services (equity), and what kinds of activities people engage in (for example choices that are influenced by regulations and social norms).

Observations supporting the need for improvements in the governance of LMEs include incompatible human uses of LME space and resources that result in mutual interference, and human uses of the LME environment that interfere with natural processes and limit the potential for future use of that environment (Juda and Hennessey 2001). Through GEF LME projects, countries are moving towards joint governance arrangements to address priority transboundary issues identified in the LMEs they share. The current assessment evaluates formally established transboundary governance arrangements relevant to fisheries, pollution, and biodiversity and habitat destruction in the 49 transboundary LMEs.

Productivity module

Primary productivity drives the flow of energy through the food webs of LMEs and can be related to the carrying capacity of these ecosystems for supporting fish resources (Rosenberg *et al.* 2014; Christensen *et al.* 2009; Pauly and Christensen 1995). Measurements of ecosystem primary productivity are also useful indicators of the growing problem of eutrophication (pollution from excessive nutrients), which is leading to an increase in the frequency and extent of dead zones in coastal waters around the globe (Diaz and Rosenberg 2008). Ocean primary productivity is closely coupled to climate variability (Behrenfeld *et al*. 2006), as it is affected by increases in sea surface temperature and changes in ocean stratification. For TWAP, indicators assessed under this module are primary productivity, chlorophyll *a*, and change in sea surface temperature (SST).

Fish and Fisheries module

Fish populations are important for the trophic transfer of energy within LMEs, and for providing an important ecosystem service in the form of fish catch. LMEs produce 80 per cent of the world's annual marine fish catch (Pauly *et al*. 2008), providing a significant source of food, livelihoods, and foreign exchange to bordering countries. Nevertheless, overexploitation is widespread and is more severe within LMEs than in the rest of the ocean. Changes in biodiversity and species dominance within fish communities have resulted from pressures such as excessive exploitation, naturally occurring environmental shifts caused by climate change, and coastal pollution. This module focuses on monitoring and assessing changes in the condition of capture fisheries and mariculture, in impacts of environmental variability (including climate change), and in predator-prey dynamics within the fish community, from benthic components and plankton at the base of the food web to apex predators (Rosenberg *et al.* 2014; Fu *et al.* 2012; Link *et al.* 2012; Chassot *et al.* 2007; Frank *et al.* 2005; Daskalov 2003). The current assessment includes time-series of a number of fisheries indicators, and fishery production potential as a function of primary production.

Pollution and Ecosystem Health module

Marine- and land-based pollution and degradation of marine habitats are of major concern in many LMEs. Pollution is often transboundary, since hydrological links between river basins, marine ecosystems, and the atmosphere often result in effects far from the sources of the pollutants. The risk of transboundary impacts tends to be highest for persistent organic pollutants (POPs), particularly substances that readily migrate between air and water (such as DDT). In many coastal areas, pollution and eutrophication have been important driving forces of change in biomass yields. For this module, floating plastic debris, POPs in plastic resin pellets, and nutrient inputs from watersheds to coastal areas were assessed.

Ecosystem health is an emerging concept of wide interest, but is difficult to capture in a single, precise scientific definition (Tett *et al.* 2013; Borja and Rodríguez 2010). Indicators and indices assessed under this module include the extent of mangroves and coral reefs, reefs at risk index, marine protected areas, cumulative human impacts on marine ecosystems, and the Ocean Health Index.

Conceptual framework

Central, linked themes of TWAP are the vulnerability of ecosystems and human communities to natural and anthropogenic stressors, impairment of ecosystem services, and consequences for humans. Many coastal human communities around the world are vulnerable to changes in ecosystem services because of their heavy dependence on them for their survival and well-being. This is of particular concern in poor communities that have few alternatives for food security and livelihoods in the face of declining living marine resources. Further, human communities are increasingly being exposed to the impacts of global climate change through increases in the frequency and intensity of extreme weather events such as storms and droughts. In coastal areas, this vulnerability increases when the protective function of coastal habitats, including coral reefs and mangroves, is lost. Assessing social well-being and vulnerabilities, in addition to economic well-being, provides a more complete picture of human–environment interactions.

A conceptual framework (Figure 2.1) was developed during the first phase of TWAP and adopted by both the LME and open ocean components. This framework builds on the five LME modules and illustrates the links between human vulnerability, natural and anthropogenic stressors, ecosystem services, and consequences for humans, with governance as an overarching concept. The framework focuses on the idea of 'causal chains', which is consistent with causal chain analysis conducted in GEF LME projects, and accommodates ecosystem services, so that they can be taken into account in decision making. A detailed description of the conceptual framework is presented in the LME assessment methodology document (IOC-UNESCO 2011).

Figure 2.1 LME assessment conceptual framework illustrating the interactions between the human and natural systems. This framework illustrates the links between human vulnerability, natural and anthropogenic stressors, ecosystem services, and consequences for humans, with governance as an overarching concept.

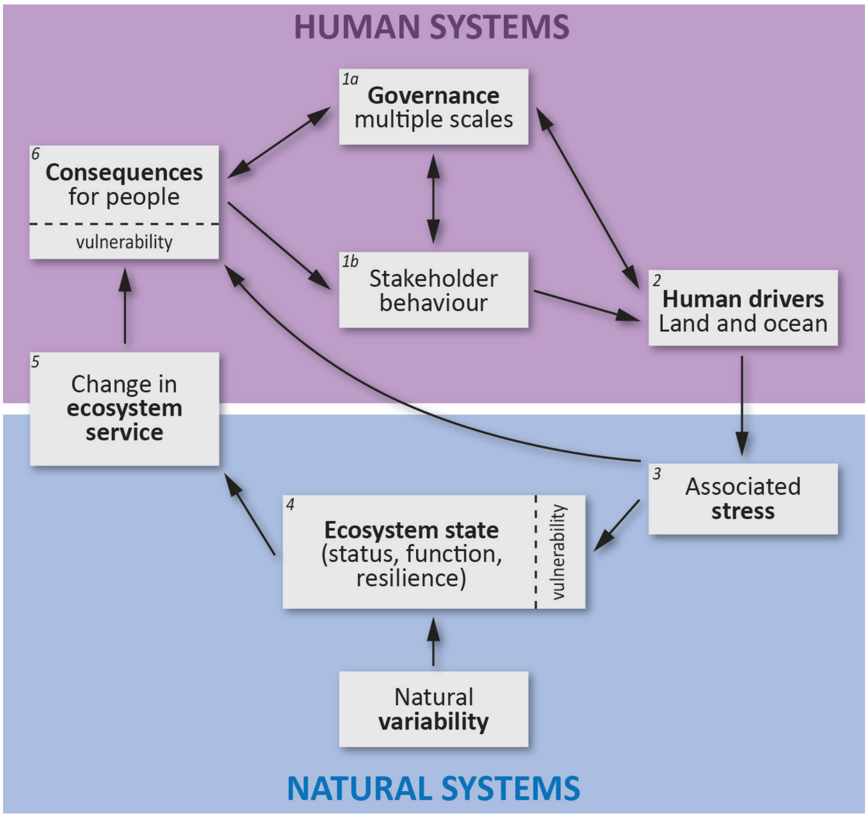


Figure 2.1 shows that governance factors (Box 1a) influence each other across scales, including through to personal behaviour (Box 1b), and determine, for example, who benefits from the delivery of ecosystem services and what kinds of activities people engage in. Moving clockwise from Box 1a, the framework shows that human drivers on land and sea (Box 2) have associated stressors (Box 3) that can impact the state of the natural system (Box 4), affecting the delivery (and value) of ecosystem services (Box 5), with potential consequences for people (Box 6). While this conceptual framework identifies the protection of ecosystem services as the main pathway for mitigating consequences for people, under some other internationally recognized value systems for management (such as protection of biodiversity, endangered species, and natural heritage sites), the goal of management is focused not on sustaining ecosystem services but on directly conserving ecosystem state. Indicators for all elements of human and natural systems cannot be developed in the context of this assessment – the systems and their interrelationships across varying scales of time and space are too complex – but the framework allows some clarity about priorities for data to be assessed or captured as an indicator or descriptor, and about what assumptions are inherent in linking indicators with their consequences. In the context of a future GEF intervention, the full framework may be useful for deciding what main points of intervention in the human system would help manage a positive outcome through the natural system.

2.3 Scale and scope of the assessment

The current assessment covers all 66 LMEs and, at GEF's request, the Western Pacific Warm Pool (WPWP). The original LME assessment methodology makes provisions for two levels of assessment:

> Level 1: an indicator-based global baseline comparative assessment of the current state of all LMEs (except for assessment of fisheries indicators for the Barents Sea and Norwegian Sea LMEs), plus projections to 2030 and 2050 where possible, using a set of core indicators (of stress, status, socio-economic conditions, and governance) for which data are available globally, under each of the five LME modules;
>
> Level 2: more detailed assessments at the sub-LME scale where data are available.

Because of funding constraints, the current assessment consisted mainly of Level 1, with a pilot Level 2 assessment of nutrients in the Bay of Bengal (BOB) LME, in collaboration with the GEF BOB LME project.

Since the TWAP LME assessment is global, the selection of indicators was partly constrained by the availability of comparable global data sets. A detailed description of each indicator used in the current assessment is available on the LME website (onesharedocean.org). Key questions that the comparative assessment sought to answer using the selected indicators were:

- Which LMEs are most heavily impacted for each issue?
- What are the current trends and main drivers in LMEs for each thematic area?
- Which ecosystem services are most at risk?
- What are the implications for humans?
- Where is human dependency on LME ecosystem services the highest?
- Where are humans most vulnerable to changes in LME condition?
- What is the status of the governance architecture or arrangements in transboundary LMEs?

2.4 Approach to the comparative assessment

Identifying LMEs for priority intervention by the GEF requires a consistent indicator scoring system that can facilitate a comparative assessment. The system needs to have enough categories to identify LMEs at different levels of risk or degradation for specific indicators or environmental issues. In November 2013 the TWAP Steering Committee agreed to use a five-category scoring system to categorize the relative levels of risk or degradation for transboundary water systems. These risk categories are 'lowest', 'low', 'medium', 'high', and 'highest'. This approach, however, is not suitable for indicators without clear directionality in terms of what can be considered 'good' or 'bad' (such as primary productivity and sea surface temperature). The interpretation of such indicators is context-specific.

2.4.1 Comparative assessment – individual indicators

Two overall approaches for assigning LMEs to each of the five risk/degradation categories were adopted for individual indicators:

1. based on literature and science-based expert judgement, where some scientifically defined reference points or thresholds of 'good' and 'bad' or low/high risk existed. The remaining thresholds were defined to give a relatively equal distribution of the results between the remaining categories;

2. a statistically-based approach for indicators where no scientifically defined thresholds exist. If the LME groups were statistically determined, some statistically-derived parameter (for example, ranking or normalization from zero to one) was applied.

Each expert decided on the cut-off points for the five categories for their respective indicator(s).

2.4.2 Comparative assessment – multiple indicators

Multivariate statistical analyses were carried out to identify patterns of risk among LMEs. Objective and simultaneous analysis of a suite of indicators with clear directionality allowed placement of the LMEs in the five risk groups. These analyses helped to identify indicators that were most influential in defining the groups. The results could then be used to guide the setting of priorities.

Details of the methodological approaches used are presented in the individual chapters in this report, which focuses on the comparative assessment. Results for individual LMEs are presented on the LME website (onesharedocean.org) together with the underlying data.

2.5 Assessment process

A working group of institutional partners and experts was convened by the IOC to conduct the LME assessment over the period April 2013 to March 2015. The working group members are listed in Annex 2.1. Each partner or expert was responsible for one or more indicators. A smaller working group, which included some members of the main working group, developed the methodology and carried out the computations for the multivariate comparative assessment.

Because of time and budgetary constraints, it was not possible to consult or solicit inputs from regional experts. Information on the LME assessment and preliminary results were, however, presented at a number of international forums, including several annual meetings of the IOC/IUCN/NOAA LME Consultative Committee and Global Meetings of the Regional Seas Conventions and Action Plans (2010, 2013, 2014, and 2015).

During the course of the project, two meetings of the main working group were held at the IOC in Paris, and one of the smaller working group in Florida. There were also extensive interactions between the working groups electronically (via email, skype, and telephone). Partners and experts prepared draft chapters on their respective themes, which were peer reviewed by external experts from around the world. The revised chapters were then reviewed by the TWAP Scientific and Technical Advisory Committee (STAC), an independent, high-level body established by the Project Steering Committee. The STAC consisted of one internationally recognized expert for each of the transboundary water body types, one member from the GEF Scientific and Technical Advisory Panel, and additional experts. Following the STAC review, the chapters were reviewed by two scientific editors (designated by the IOC) and then finalized by the authors with the assistance of a science communication expert, graphics designer, and copy editor.

2.6 Organization of this report

The rest of this report is organized in sections corresponding to the five LME modules (Socio-economics, Governance, Productivity, Fish and Fisheries, and Pollution and Ecosystem Health). Each section presents the assessment results in thematic chapters, based on individual indicators or indices. The final thematic chapter presents the results of analyses identifying patterns of risk among LMEs using multiple indicators from all the LME modules except the Productivity module. This is followed by the conclusion chapter.

References

Behrenfeld, M., O'Malley, R., Siegel, D. and others (2006*). Climate-driven trends in contemporary ocean productivity. Nature* 444, 752-755

Borja, Á. and 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*. Marine Pollution Bulletin* 60, 1143-1146

Chassot, E., Mélin, F., Le Pape, O. and others (2007). Bottom-up control regulates fisheries production at the scale of eco-regions in European seas*. Marine Ecology Progress Series* 343, 45-55

Christensen, V., Walters, C.J., Ahrens, R. and others (2009). Database-driven models of the world's Large Marine Ecosystems. *Ecological Modelling* 220, 1984-1996

Costanza, R., de Groot, R., Sutton, P., van der Ploeg, S. and others (2014). Changes in the global value of ecosystem services. *Global Environmental Change* 26:152-158

Daskalov, G.M. (2003). Overfishing drives a trophic cascade in the Black Sea. In: *Large Marine Ecosystems of the World: Trends in Exploitation, Protection, and Research* (eds. Hempel, G. and Sherman, K.), The Netherlands, Elsevier Science, 171-191

Diaz, R.J. and Rosenberg, R. (2008). Spreading dead zones and consequences for marine ecosystems. *Science* 321, 926-929

Frank, K.T., Petrie, B., Choi, J.S. and others (2005*).* Trophic cascades in a formerly cod-dominated ecosystem*. Science* 308, 1621-1623

Fu, C., Gaichas, S., Link, J.S. and others (2012). Relative importance of fisheries, trophodynamic and environmental drivers in a series of marine ecosystems*. Marine Ecology Progress Series* 459, 169-184

IOC-UNESCO (2011). *Methodology for the GEF Transboundary Waters Assessment Programme. Volume 5. Methodology for the Assessment Large Marine Ecosystems*, viii + 115 pages. IOC-UNESCO, Paris

Juda, L. and Hennessey, T. (2001). Governance profiles and the management of the uses of Large Marine Ecosystems. *Ocean Development and International Law* 32, 41-67

Link, J.S., Gaichas, S., Miller, T.J. and others (2012). Synthesizing lessons learned from comparing fisheries production in 13 northern hemisphere ecosystems: emergent fundamental features*. Marine Ecology Progress Series* 459, 293-302

Pauly, D. and Christensen, V. (1995). Primary production required to sustain global fisheries. *Nature* 374, 255-257

Pauly, D., Alder, J., Booth, S. and others (2008). Fisheries in large marine ecosystems: Descriptions and diagnoses. In *The UNEP Large Marine Ecosystem Report: A perspective on changing conditions in LMEs of the world's Regional Seas*. UNEP Regional Seas Report and Studies 182. United Nations Environment Programme, Nairobi, Kenya, 852 pages

Rosenberg, A.A., Fogarty, M.J., Cooper, A.B. and others (2014). *Developing new approaches to global stock status assessment and fishery production potential of the seas.* FAO Fisheries and Aquaculture Circular 1086. Rome, FAO. 175 pages

Sherman, K. (2005). The large marine ecosystem approach for assessment and management of ocean coastal waters. *Sustaining Large Marine Ecosystems: The Human Dimension* (eds. Hennessey, T.A. and Sutinen, J.G.), Amsterdam: Elsevier B.V. p. 3-16

Tallis, H., Kareiva, P., Marvier, M. and others (2008). An ecosystem services framework to support both practical conservation and economic development. *Proceedings of the National Academy of Sciences of the United States of America* 105 (28), 9457-9464

Tett, P., Gowen, R.J., Painting, S.J. and others (2013). Framework for understanding marine ecosystem health. *Marine Ecology Progress Series* 494, 1-27

Annex

Annex Table 2-A TWAP LMEs assessment working group of institutional partners and experts. Other contributors are listed in the report chapters and the acknowledgements section.

Institutions and experts	Role/Thematic area
IOC-UNESCO (Julian Barbière, Manager, and Sherry Heileman, Coordinator)	Management and coordination, TWAP LMEs component
National Oceanic and Atmospheric Administration (NOAA), Rhode Island, US (Kenneth Sherman)	Scientific advice
Liana Talaue-McManus (individual expert, Florida, US)	Socio-economics
Robin Mahon (individual expert, Centre for Resource Management and Environmental Studies, University of the West Indies, Barbados) Lucia Fanning (individual expert, Dalhousie University, Nova Scotia, Canada)	Governance
John O'Reilly (individual expert, Rhode Island, US) Kenneth Sherman (NOAA, NE Fisheries Center, Rhode Island, US)	Primary productivity
University of Rhode Island, Rhode Island, US (Igor Belkin)	Sea surface temperature
University of British Columbia, BC, Canada (Daniel Pauly and Vicky W.Y. Lam)	Fisheries status (multiple indicators)
FAO-CI Fishery Production Potential Working Group – Michael J. Fogarty (NOAA, US), Andrew A. Rosenberg (Union of Concerned Scientists, US), and others	Fishery production potential
Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection – GESAMP, UK (Peter J. Kershaw)	Floating plastic debris
Laboratory of Organic Geochemistry, Tokyo University of Agriculture and Technology, Tokyo, Japan (Hideshige Takada)	Persistent organic pollutants in plastic resin pellets
International Geosphere Biosphere Programme, Sweden (Sybil Seitzinger)	Nutrient inputs from watersheds
UNEP – World Conservation Monitoring Centre, Cambridge, UK (Chris Mcowen)	Mangrove extent and threats; Reefs at Risk Index; change in MPA extent
University of California, Santa Barbara, US (Benjamin S. Halpern)	Cumulative human impacts on marine ecosystems
University of California, Santa Barbara, US (Benjamin S. Halpern)	Ocean Health Index
Kristin M. Kleisner (individual expert, Sea Around Us, BC, Canada) and Liana Talaue-McManus (individual expert, Florida, US)	Identifying patterns of risk among LMEs using multiple indicators

© Yosomono/flickr

Chapter 3
Socio-economics

© Yosomono/flickr

Lead Author

Liana Talaue-McManus (Independent consultant, Miami)

Contributing Author

Maria Estevanez (University of Miami Rosenstiel School of Marine and Atmospheric Science)

Chapter Citation

Talaue-McManus, L., Estevanez, M. (2016). Chapter 3: Socio-economics: Examining socio-economic dimensions of risk and vulnerability among coastal inhabitants of large marine ecosystems. In IOC-UNESCO and UNEP (2016). *Large Marine Ecosystems: Status and Trends*. United Nations Environment Programme, Nairobi, pp 21-61.

Socio-economics: Examining socio-economic dimensions of risk and vulnerability among coastal inhabitants of large marine ecosystems

SUMMARY

This study assesses large marine ecosystems (LMEs) to examine patterns of vulnerability among their coastal populations and the influence of this vulnerability on environmental and disaster risk. Vulnerability encompasses factors that affect people's capacity to cope and recover from impacts, not only of natural hazards, but also of marine ecosystem degradation. Risk is the chance of danger, loss, income reduction, or diminished or lost opportunity for an improved life for an individual, a household, or a community. Vulnerability and risk both result from the interactions of natural and anthropogenic factors. Threat and risk are used synonymously in this study.

To compare the vulnerability and risk of populated LMEs, we selected quantitative indicators that address these key concepts (as highlighted in the LME assessment conceptual framework) and that are supported by publicly available global databases. These indicators include measures of coastal demographics (population sizes and rural/urban fractions, and number of coastal poor); measures of resource use (fisheries and tourism revenues, fish protein in diet, and the contribution of LME tourism to national economies); measures of well-being (Human Development Index (HDI)); impact measures as hazard proxies of climate-related extreme events such as floods and storms (deaths and property losses from such events); projections of sea-level rise to 2100; and risk scores indicating the states of marine ecosystems. Because few of these data sets are available at the LME scale, geo-referenced population or other regional data are used as weighting values to downscale national data before they are aggregated for each LME. Where feasible, indicator values were projected, using two contrasting development scenarios for 2100, for example, for coastal populations and the HDI.

We constructed two risk indices to examine the vulnerability of coastal populations to relatively high-frequency climate-related extreme events (storms, flooding, and drought) and to projected sea-level rise. A third risk index – the Contemporary Threat Index – combines indicators of present-day LME states (provided by authors of this report) with current climate event-related risks, and integrates these measures of environmental risk with measures of dependence of coastal populations on LMEs and a measure of the capacity to adapt to change. These indicators and indices are used to categorize the 64 populated LMEs into five risk categories, from lowest to highest risk.

The global coastal population was slightly over 2.5 billion in 2010, nearly 40 per cent of the total global population. Almost 60 per cent of coastal residents live in rapidly urbanizing areas; more than 20 per cent are considered poor. Estimates of the worldwide coastal population in 2100 range from 2.9 to 4.7 billion based on contrasting development scenario-based population projections.

Key messages

1. **High levels of human well-being and ecosystem health are indicative and mutually reinforcing outcomes of sustainable ecosystems.** To achieve these, reducing risk and vulnerability of coastal populations must be addressed without sacrificing ecosystem health, and vice-versa. Universal safety nets that guarantee opportunities for human development are integral to smart ecosystem management that aims to achieve sustainable LMEs.
2. **Coastal populations in highly populated tropical regions are the most at risk, taking into account the combined effects of environmental threats, dependence on LME resources, and shortfalls in capacity to adapt.** Environmental threats include loss or degradation of fish stocks and ecosystem health, and damage from climate-related extreme events. Dependence includes coastal population size and reliance on fish for food and on tourism for income. The LMEs at highest risk are Bay of Bengal, Canary Current, Gulf of Thailand, South China Sea, Sulu-Celebes Sea, Somali Coastal Current, Indonesian Sea, Guinea Current, Arabian Sea, Caribbean Sea, East China Sea, Yellow Sea, and Agulhas Current.
3. **Risks associated with future deterioration of ecosystem health and with climate change are additional burdens that exacerbate an already precarious state for coastal populations of some LMEs – but measures can be taken to mitigate these risks.** Sea-level rise threat is amplified by the size of population exposure and the degree of socio-economic vulnerability. LMEs most at risk from sea-level rise include many of those currently at highest risk, especially those of the southern coastal regions of Africa. Assessing vulnerability to sea-level rise in 2100 using contrasting future socio-economic scenarios indicates that development pathways that strengthen opportunities for better education, health, and livelihood, and reduce population growth, at national scale and in the coastal areas of LMEs, should decrease future risk levels.
4. **Regional assessments may prove essential for designing appropriately scaled programmes to reduce vulnerability and risk.** Such assessments would substantiate this baseline global assessment and highlight sub-national features. While the indicators used in assessments are evidence-based, choices made about what indicators to combine into an index affect the outcomes of the assessment. The set of results presented here is influenced by these choices. Future assessments should validate the results using a suite of indicators based on finer-scale spatial data, including geo-referenced data on LME resource utilization, poverty distribution, urbanization, and economic activity. Impacts of changing climate and coastal ecosystems on disadvantaged groups such as women, children, and the elderly should be quantified and addressed by national and regional sustainable development goals.

3.1 Introduction

Sixty-six large marine ecosystems (LMEs), each at least 200 000 km^2 in area, encompass the majority of the world's coastal areas along continental margins. Human populations that live on or near the coast rely on the innumerable ecosystem services LMEs provide, such as fish for food and trade, cultural services for tourism, and waste processing (UNEP 2006). Spatial distribution of populations, the extent of their economic activities and reliance on LMEs for food and amenities, levels of well-being, and risks of current and projected climate-related changes – all superimposed on achievements in human development – significantly influence the social-ecological states of LMEs. In this chapter, 13 socio-economic indicators are used to assess these features at the LME scale with the aim of providing comparative baseline profiles of vulnerabilities and risks of climate-related disasters and environmental degradation across the 64 populated LMEs. This assessment references the LME assessment conceptual framework that highlights interactions between the human and natural systems in defining trajectories of change in LME states (IOC-UNESCO and NOAA, this report) and the patterns of risk these interactions generate. It thus complements the biophysical and governance assessments included in this report.

Central to the comparison of LME-scale coastal populations are the concepts of vulnerability and risk. Wisner *et al*. (2003) defines disaster vulnerability as *"characteristics of a person or group and their situation that influences their capacity to anticipate, cope with, resist, and recover from the impact of a natural hazard."* In the context of this study, vulnerability is expanded to include the socio-economic impacts not only of natural hazards but also of environmental degradation of LMEs, notwithstanding the inherent differences between hazards, and degraded ecosystem health and the interactions between these. The indicators used in assessing overall vulnerability include: coastal population size, reliance on fish for protein, dependence on LME tourism for GDPs of coastal states, and the level of human development (or the inadequacy of the human development level, referred to as the HDI Gap). These features have been downscaled to the 100 km coastal zone. For transboundary LMEs, an LME coastal area differs from an individual country's coastal area: it is an aggregate of all country coastal segments surrounding the LME.

In this study, risk is the *"chance of danger, damage, loss, injury, or any other undesirable consequences for a household (or an individual or a community)"* (Heltberg *et al*. 2009). Numerically, the Intergovernmental Panel on Climate Change (IPCC) equates disaster risk to the product of exposure and vulnerability, and the impacts when risk events do occur (Oppenheimer *et al*. 2014). Three threat indices are used to represent current and future climate threats: the extent of current risks to climate-related extreme events (flooding, storms, and extreme temperatures); projected risks from sea-level rise in 2100; and the Contemporary Threat Index, which combines risks of extreme climate events with those of ecosystem change as additional challenges to human development.

A number of key points need to be kept in mind when using the results of this assessment. First, analysing an LME coast is complex because it is made up of coastal-country segments, the unit of analysis for this study. In continental areas, this spatial unit is sub-national in character, which requires that data be spatially explicit (geographically referenced) or that national data be appropriately downscaled. Secondly, the aggregation of data from coastal-country segment to LME scale is accompanied by a loss of the heterogeneity of features observed at finer scales. This makes the derived LME-scale features homogenized and spatially coarse. Describing human populations at this coarse scale is necessary but insufficient for examining human-environment interactions at national and local scales. The sub-LME scale (for example, sub-national) is the scale at which patterns of risk may best be studied. It is prudent to retain the ability to scale down to the sub-national or national scales, where risks may be more amplified, and where targeted actions may be required. This would be possible in a more in-depth, regional (rather than global) assessment. For brevity and consistency, only the LME-scale patterns are presented in this chapter. We envision that this baseline global assessment will be followed by regional assessments that highlight sub-national features of risk and vulnerability. Regional mitigation plans may then complement global-scale programmes so that actions are mutually supportive to reduce risk.

3.2 Findings

Annex Table 3-A lists the indicators by sub-theme with their underlying metrics and data sources, and summarizes the methods used in assessing LMEs and the levels of confidence in the results. More details on methodology are presented in the last section of this chapter.

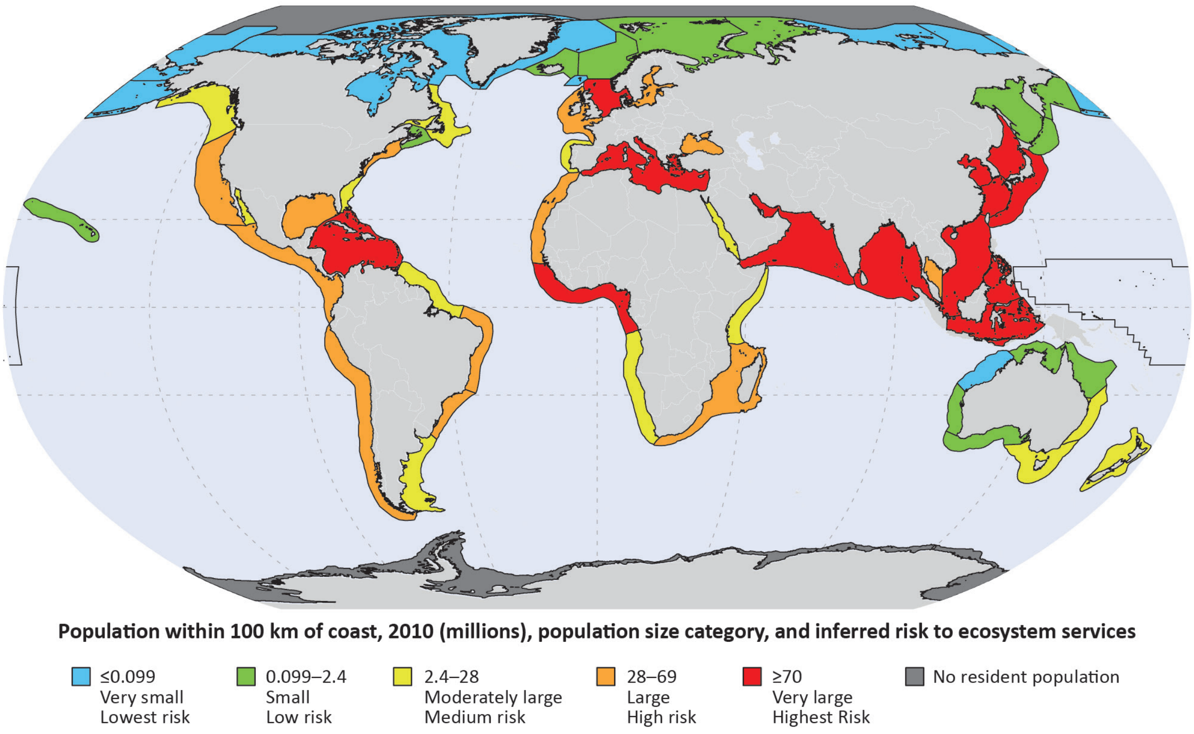
A general limitation of the study is the use of non-spatially-explicit data such as most of the national input data used in assessing well-being. Where sub-national data are available, as in the case of sub-national regional estimates of Gross Domestic Product, these are used to downscale national estimates of tourism and fishing revenues to coastal-country segments, prior to aggregating these to LME-scale values. In defining risk categories, the range of assessed values is divided into five groups with equal or nearly equal numbers of LMEs per group, or into unequal groups where there are natural breaks in index values. The boundaries between risk classes are arbitrary and less important than the overall range of values assessed for each indicator.

3.2.2 Coastal demographics

3.2.2.1 Coastal population in 100 km coastal zones

Coastal populations living around LMEs, at slightly more than 2.7 billion, made up 37 per cent of the global population in 2010. They live on 22 per cent of the Earth's total land area. Worldwide, around 58 per cent live on urban coasts, indicating that the global coast is urbanizing. The ten most populated LMEs are, in decreasing order: Bay of Bengal, South China Sea, Mediterranean, Arabian Sea, Indonesian Sea, Yellow Sea, East China Sea, Kuroshio Current, Caribbean Sea, and Sulu-Celebes Sea (Figure 3.1). Coastal inhabitants around these ten LMEs together account for half of the global coastal population. In the context of risk, a large population in the 100 km coastal area indicates a high risk of natural resource depletion and water quality degradation. The most populous LMEs are almost always the most threatened by extreme degradation of LMEs, although the relationship between population growth and environmental change is more complex, being influenced by consumption patterns and institution-defined resource rights (Bremner *et al.* 2010).

Figure 3.1 The size of coastal populations – a proxy measure of pressure on ecosystem services provided by LMEs. The most populated coastal areas include the Bay of Bengal (323 400 000), the South China Sea (271 700 000), the Mediterranean (236 700 000), the Arabian Sea (192 400 000), and the Indonesian Sea (172 300 000).

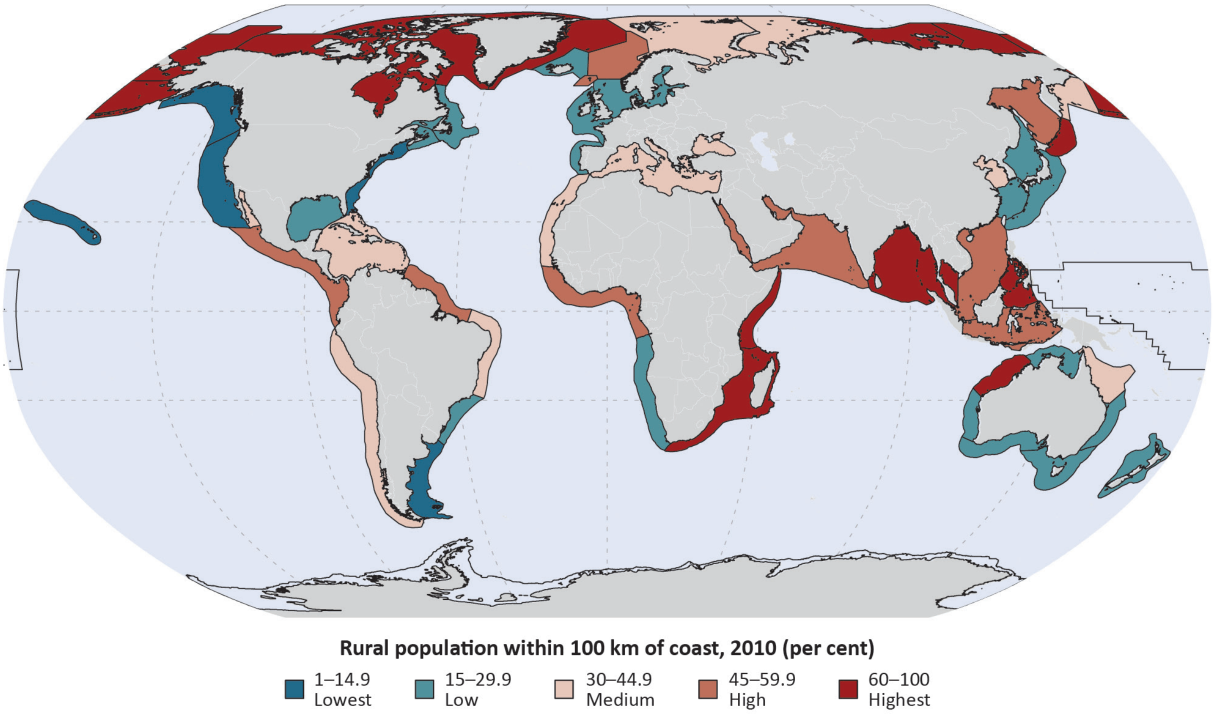


3.2.2.2 Rural populations

Coastal populations in rural areas (Figure 3.2) are of particular interest because natural resources very often support their livelihoods, including through fishing and agriculture. The small populations of the East Siberian Sea, Laptev Sea, Beaufort Sea, Hudson Bay Complex, and the Canadian Eastern Arctic-West Greenland LMEs (243 000 in total), are 80 to 100 per cent rural – 'few' and 'rural' may not connote high pressure on marine living resources. In these high-latitude LMEs, fishing supplements other subsistence activities, including hunting and reindeer herding, and cash economies rely on mining, oil and gas and government employment (Glomsrød and Aslaksen 2006). Rural populations are proxy measures that indicate significant pressure on fishery resources when large in size, as in the cases of the Sulu-Celebes Sea, Agulhas Current, Somali Coastal Current, Bay of Bengal, and Oyashio Current

LMEs. Large rural coastal populations indicate higher dependence on marine living resources with fishing as a major livelihood, thus placing an LME at higher risk of overexploitation. For fisheries, the harvest rates of coastal states (in addition to those of the distant-water fishing countries) need to be accounted for to have a more complete picture of fishing pressure.

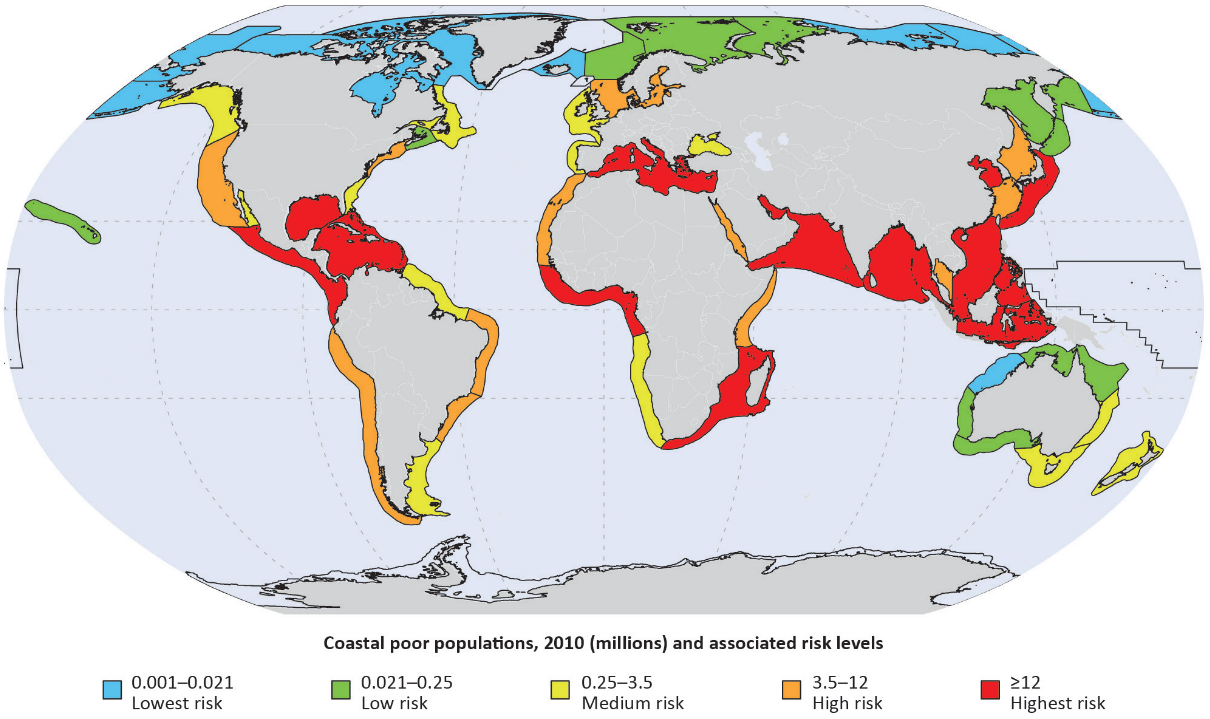
Figure 3.2. Proportion of coastal zone population that is rural. About 42 per cent of global coastal populations live in rural areas. LMEs with rural populations making up 60 per cent or more of the population within 100 km of the coast are: Bay of Bengal, Sulu-Celebes Sea, Northwest Australian Shelf, and Eastern African and high-latitude LMEs. Rural populations in developing and developed countries rely on natural resources for their livelihoods or subsistence. Fishing and other marine harvest is especially important for rural people along coasts of high latitude LMEs, where agriculture is non-existent or limited.



3.2.2.3 Coastal poor

The number of coastal inhabitants considered poor based on national poverty standards reached slightly over 520 million in 2010 (Figure 3.3). This is roughly the same as the combined 2010 populations of Western Europe, the US, and the city of Beijing. In contrast to the distribution obtained with the global coastal population, 57 per cent of impoverished coastal inhabitants live along rural coasts. Ten LMEs account for 67 per cent of the global coastal poor: Bay of Bengal, Arabian Sea, South China Sea, Guinea Current, Mediterranean, Caribbean Sea, Indonesian Sea, Pacific Central-American, Agulhas Current, and the Sulu-Celebes Sea. The risks that coastal poor face in dealing with environmental change are key determinants of societal resilience. For this study, a large number of coastal poor in an LME is an indicator of high socio-economic vulnerability. Data on spatial distribution of the coastal poor would provide qualitatively superior assessment products, but poverty mapping is not available for all coastal countries.

Figure 3.3 Populations below national poverty lines – an indicator of socio-economic vulnerability. The number of coastal residents who live on incomes below their respective national poverty lines is slightly over 500 000 000. Of these, 67 per cent live in the following LMEs (in order of decreasing numbers of poor people): Bay of Bengal, Arabian Sea, South China Sea, Guinea Current, Mediterranean, Caribbean Sea, Indonesian Sea, Pacific Central-American Coastal, Agulhas Current, and Sulu-Celebes Sea.



3.2.3 Economic benefits from LMEs through fishing and tourism

Tourism and fishing are the two economic activities chosen for this study because of their prevalence, regardless of the level of economic development. In addition, the economic impact of these two sectors as bases of livelihoods and income streams have been extensively analysed at various scales.

3.2.3.1 Fishing revenues

Despite the availability of commercial fisheries catch and ex-vessel fish price data, the ability to fully evaluate the economic impact of marine fishing in terms of its contribution to national GDPs and national employment across littoral states remains elusive. Data on production costs and value multiplication along the commodity chain (from harvest to processing and retail distribution) are not periodically monitored across fishing countries. Routine fisheries data gathering is resource-intensive and many developing nations are unable to implement monitoring programmes covering subsistence fishing which plays a critical role for food and employment security.

The figures for fishing revenues reported here are gross value-added estimates provided by Pauly and Lam (this report), converted to 2013 US$ from 2005 US$ in the original data set. If production costs, subsidies, and taxes were available for each fishing country, the valuation could be expanded to include the contribution of fishing to GDP, employment, and income, and to estimate direct fish consumption for evaluating food security for the subsistence sector. The World Bank undertook a major study to estimate 2007 fishing contributions (both marine and inland) to 123 economies, including contributions of subsistence and recreational fisheries (World Bank 2010). Results include an estimated US$274 billion contribution to global GDP from commercial fishing alone (marine and inland), and another US$160 billion from recreational fishing and associated activities such as boat building.

Average annual landed value of marine capture fisheries for the period 2001 to 2010 are shown in Annex Table 3A.2. The ten LMEs with the highest landed fish values are South China Sea, East China Sea, Bay of Bengal, Humboldt

Current, Sea of Okhotsk, Arabian Sea, Yellow Sea, Northeast US Continental Shelf, Mediterranean, and Celtic-Biscay Shelf. The average annual revenues of these ten LMEs account for 58 per cent of the average annual global total of $88 billion (2013 US$).

Dependence on fishing at the LME scale is quantified as the proportion of LME-scale fish protein to total animal protein consumption for LME coastal countries. Using national fish consumption patterns and the contribution of fish protein to the total animal protein of coastal countries, an average fish protein contribution is estimated for each LME. The population of the coastal country is used as a weighting factor. The top ten LMEs where fish contribution to animal protein is highest are Indonesian Sea, Faroe Plateau, Guinea Current, Greenland Sea, Sulu-Celebes Sea, Gulf of Thailand, Sea of Japan, Oyashio Current, Kuroshio Current, and Canadian Eastern Arctic-West Greenland. It should be noted that fish consumption patterns cannot not be attributed solely to marine food fish supply, as fish can be sourced from aquaculture and inland fisheries. Coastal countries with significant non-marine sources of fish include Bangladesh (Bay of Bengal LME), Cambodia (Gulf of Thailand and South China Sea LMEs), Mozambique (Agulhas Current LME), Tanzania (Somali Coastal Current LME), Kenya (Somali Coastal Current LME), and the Republic of Congo (Guinea Current LME).

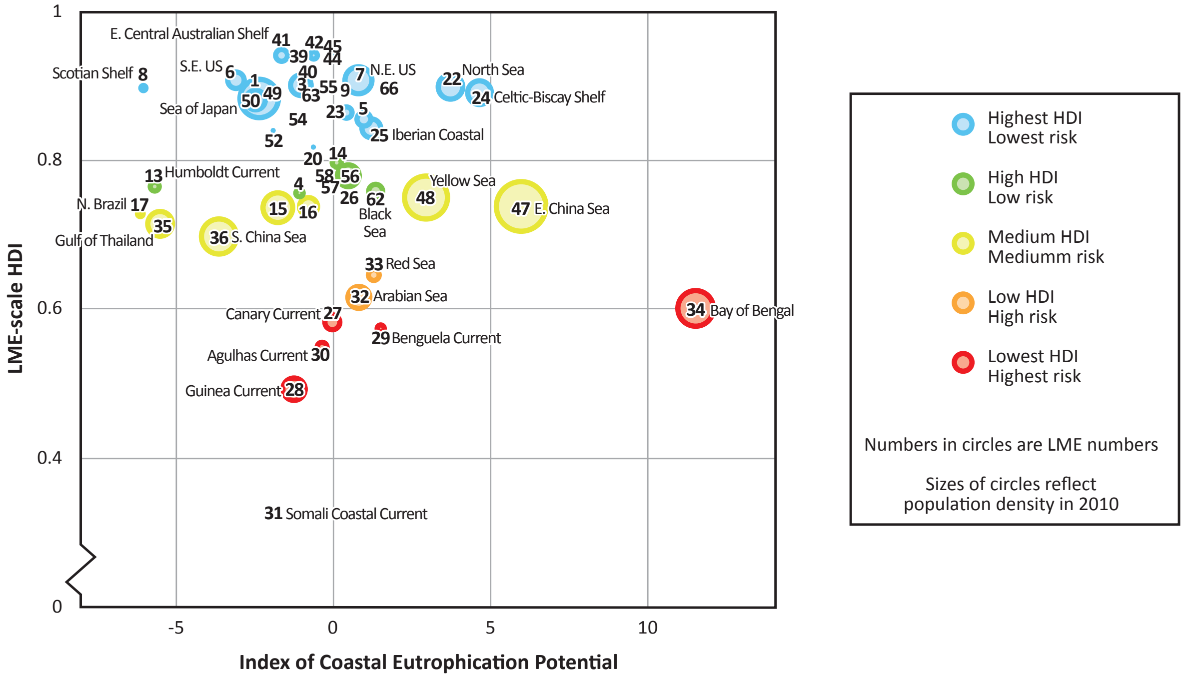
3.2.3.2 Tourism revenues

Tourism is a well-monitored economic sector, despite the nature of the flows of goods and services that make it an inter-sectoral activity, and despite the complexity inherent in its valuation (see the methodology section). The contributions of tourism to GDP and employment are routinely tracked at the national scale. Attempts to identify the contribution of coastal and marine tourism separately from that of inland tourism, require a separate accounting system that may not be possible given that these sub-sectors share goods, services and travel infrastructure with inland tourism activities. A regional tourism accounting system with a focus on coastal sub-national regions is a good approach to acquiring more specific information on revenues, and one that a number of coastal states, including the US and Australia, have implemented.

Annex Table 3-B summarizes the national tourism revenues that have been downscaled to 100 km country coastal segments and then aggregated at the LME scale for the period 2004 to 2013. Globally, the tourism revenues attributed to LMEs are $3 931 billion (2013 US$) – two orders of magnitude more than the gross value added total for fishing. The latter, however, does not take into account income and employment multipliers along the fish commodity chain from ex-vessel prices to retail distribution and associated industries such as fishing gear and manufacture of vessels. The top ten tourism revenue grossing LMEs are the Mediterranean, North Sea, Gulf of Mexico, South China Sea, Celtic-Biscay Shelf, California Current, Yellow Sea, Northeast and Southeast US Continental Shelves, and East China Sea. To determine the average contribution of LME tourism revenues to the GDPs of coastal countries as a metric of economic dependence, the national tourism GDP of each coastal country was weighted by the percentage of a country's contribution to the total LME tourism revenue. In using percentage contribution to national GDPs, it must be noted that LMEs with small aggregate tourism revenues can still contribute significantly to the national GDPs of the surrounding coastal countries, especially if these GDPs are also small. The top ten GDP-contributing LMEs (percentage-wise) are Iceland Shelf and Sea, Caribbean Sea, Gulf of Thailand, New Zealand Shelf, Canary Current, Iberian Coastal, Bay of Bengal, Gulf of California, Mediterranean, and Somali Coastal Current. Both the Iceland Shelf and Sea and Somali Coastal Current LMEs bring in tourism revenues classified as lowest (with a category range of from US$0 to 4.2 billion per year). Nonetheless, tourism revenues contribute 19 and 12 per cent to the GDPs of their respective coastal countries.

Water quality is important for local and international tourism and is a critical indicator for assessment of the sustainability of marine tourism. Worldwide, Honey and Krantz (2007) find that water pollution remains the biggest concern in examining the impacts of coastal tourism, even if land clearance and coastal ecosystem degradation remain the most destructive impacts. Figure 3.4 plots LMEs by their Index of Coastal Eutrophication Potential (ICEP), an indicator of water quality and of risk of harmful algal blooms (Seitzinger and Mayorga, this report). Pairing the ICEP with the HDI for each LME shows the Bay of Bengal as the LME most at risk from eutrophication, but also at risk because its coastal inhabitants are already compromised, having a low HDI (in the 'highest' risk category. The Yellow and East China Seas are comparable to the North Sea and Celtic-Biscay Shelf LMEs with respect to ICEP, but the lower HDIs for the two large Asian LMEs put them more at risk than their developed counterparts. Environmental impacts directly attributable to the tourism economic sector, such as habitat conversion, water pollution including nitrogen loading from coastal tourist facilities, socio-cultural impacts, and revenue leakage (loss of revenue generated by tourism to other countries or regions), should be examined for how they modify socio-economic risks for people and ecological risks for coastal ecosystems.

Figure 3.4 Coastal eutrophication potential and the Human Development Index. This indicator may be used to gauge the sustainability of tourism relative to ecosystem impacts on the LMEs. When paired with HDI, the assessment shows that, for the same level of environmental risk, developing country LMEs are more vulnerable because of their lower level of human development.



3.2.4 Measures of well-being

3.2.4.1 Night Light Development Index

The 2006 Night Light Development Index (NLDI) is based on a geo-referenced product that combines the satellite readings of night lights as a proxy for spatial distribution of economic activity with population distribution. High values of NLDI indicate highly uneven distributions of spatial economic activity, while low values indicate more uniform distribution of night lights and, hence, of economic activity. For this study, both the national and sub-national NLDI estimates were analysed.

Figure 3.5 shows the risk categories based on NLDI: high NLDI indicates high risk of unevenly distributed economic activity. The most NLDI-at-risk LMEs are East Siberian Sea, Agulhas Current, Somali Coastal Current, North Brazil Shelf, Benguela Current, Sulu-Celebes Sea, and Guinea Current (with NLDI ranging from 0.9554 to 0.8599). The lack of connections to the power grid and the highly rural population of East Siberian Sea, result in the highest NLDI rating, representing a highly uneven spatial distribution of economic activity. Country NLDI is inversely correlated with country HDI at about 70 per cent (Elvidge *et al*. 2012). At the scale of LMEs, the inverse correlation is not as strong (42 per cent) because the coarse resolution degrades the country-scale correlation (Figure 3.6). The use of night lights to examine the spatial extent of economic activity is technologically feasible and enables annual monitoring and reporting that would otherwise not be possible with non-continuous, project-based assessments. However, a relatively simple metric at coarse resolution cannot be expected to fully and efficiently capture a nuanced phenomenon such as human development. Calibration of NLDI against HDI or other spatially explicit metrics at finer, sub-national scale would be beneficial.

Figure 3.5 Night light distribution as a spatial proxy for level of economic development (Night Light Development Index). The NLDI measures the co-varying distribution of population and night lights, the latter as a proxy of spatial economic activity. A high NLDI value indicates a highly uneven distribution of people and night lights, while a low value indicates a more uniform spatial distribution.

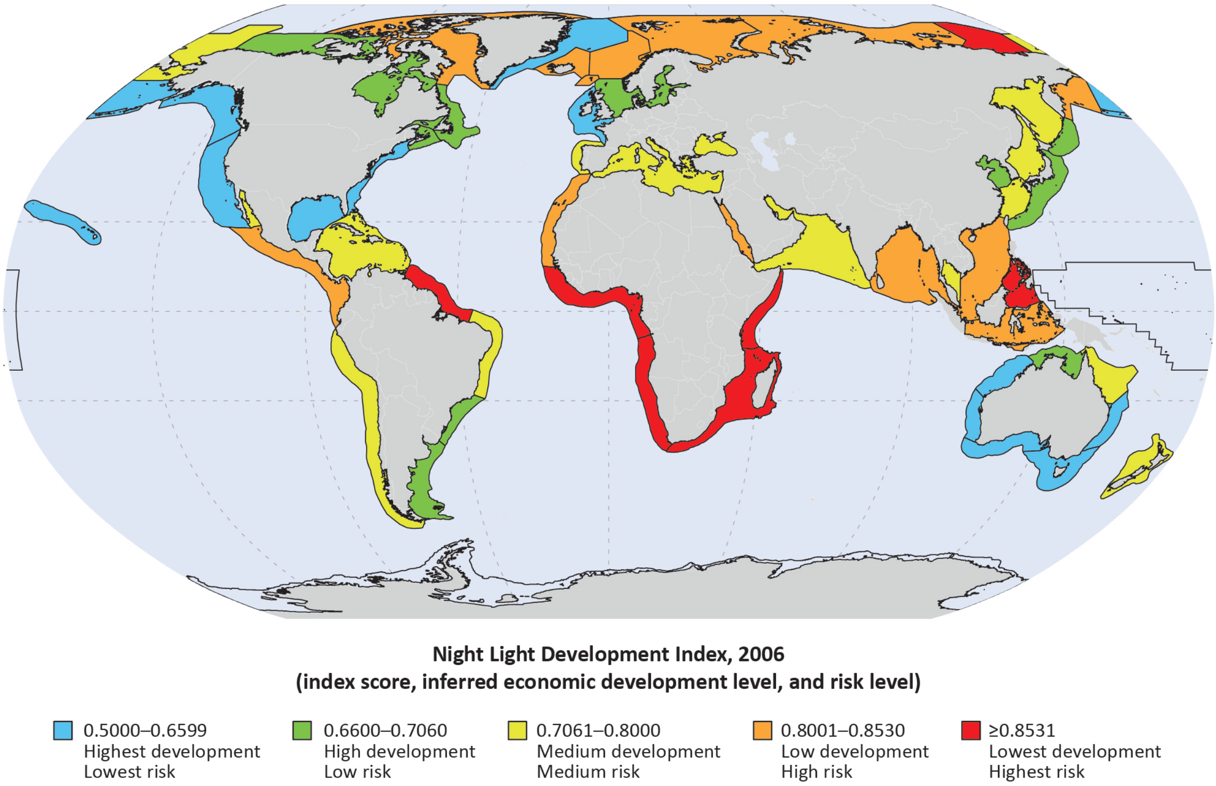
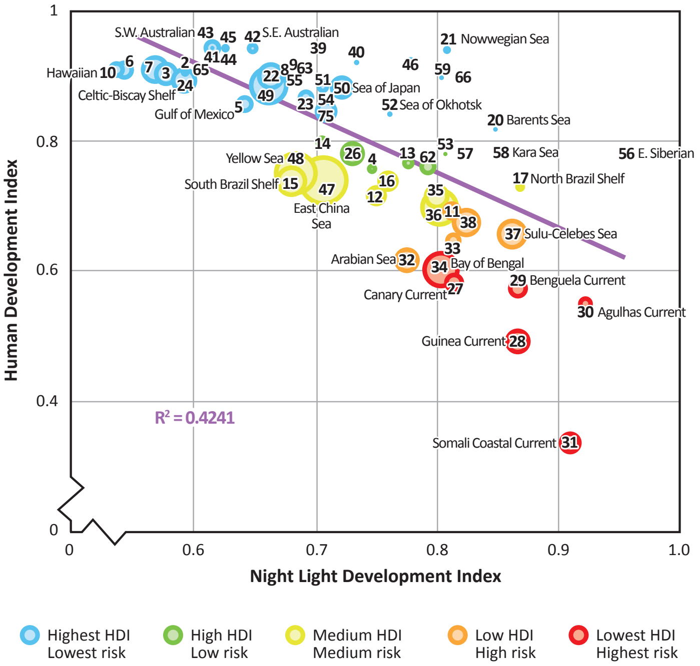


Figure 3.6 Night Light Development Index paired with the Human Development Index. At the country scale, the NLDI is inversely correlated with the HDI at 70 per cent. For LMEs, this correlation is degraded by coarse resolution and which drops to about 42 per cent. Because night-light distribution is an operational product that can be established annually if needed, it offers a cheap monitoring strategy for tracking the extent of spatial economic activity. However, it will need independent verification using the HDI or, better still, using another spatially-explicit metric.



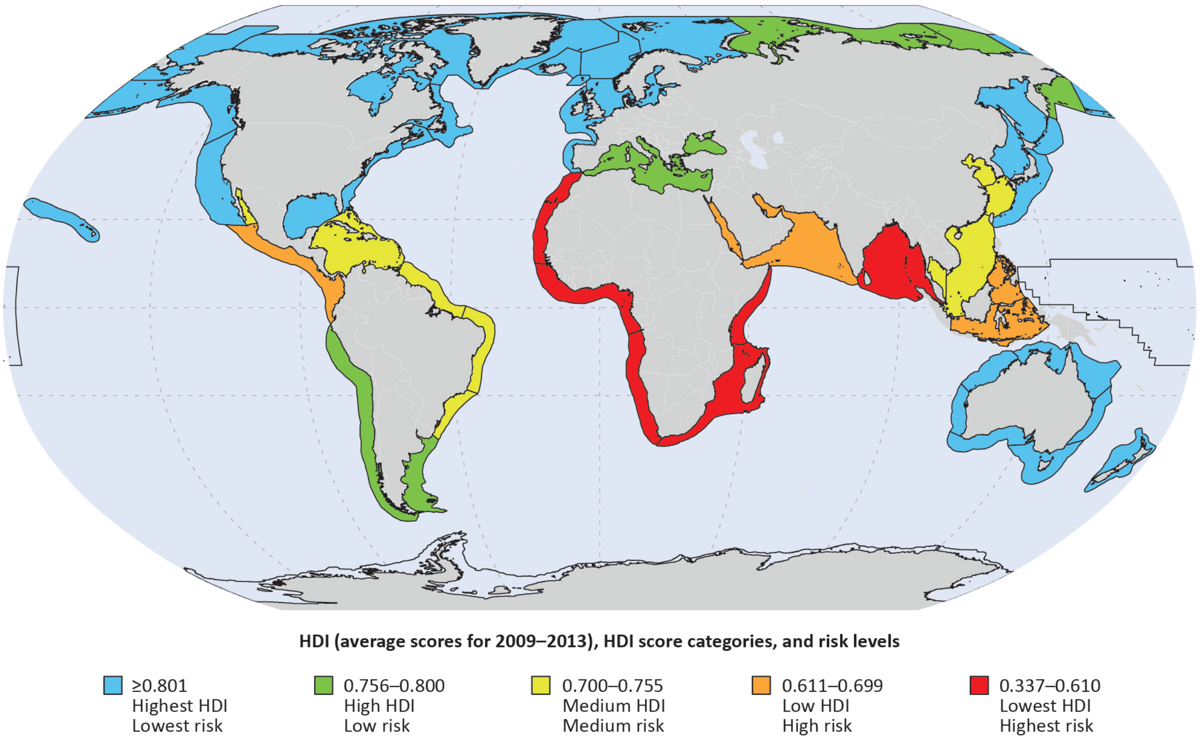
Numbers in circles are LME numbers.
Sizes of circles reflect population density within 100 km of the coast.

3.2.4.2 Human Development Index

The HDI scores for the 64 populated LMEs were estimated using averages (for the period 2009 to 2013) of metrics for education (mean and expected years in school), health (life expectancy at birth), and income (per capita annual gross national income (GNI)). LMEs with the lowest HDI scores are the Somali Coastal Current, Guinea Current, Agulhas Current, Benguela Current, Canary Current, and Bay of Bengal (Figure 3.7). The HDI Gap (1-HDI) measures the deficit between the theoretical (set as 1.0) and the realized HDI. This is a measure of LME-scale well-being.

The 2014 HDI minimum and maximum goalpost values that are used in the calculation of the HDI are as follows: 20 and 85 years for life expectancy at birth; 0 and 15 years for mean years at school; 0 and 18 years for expected years at school; and US$100 and US$75 000 purchasing power parity (PPP, in 2011 US$) for per capita GNI. The measured insufficiencies are assumed to place LMEs at risk even prior to their exposure to hazard-specific risks. Thus, an LME's vulnerability to specific risks may be increased by pre-existing human development-related inadequacies from the start. If development policies are to reduce these prior existing risks, the most strategic HDI component to target is education, as it provides people with the potential to increase income and acquire the knowledge to make prudent choices on health, livelihood, and consumption lifestyles (Samir and Lutz 2014). Education offers a long-term and strategic means to build the competent and resilient human capital needed in the event of adverse environmental and climate change. Thus, even if the magnitudes of specific risks (storms, flooding, droughts, and sea-level rise) are the same, LMEs with larger HDI Gap (1-HDI) due to lower levels of health, education, and income, will have higher total risks.

Figure 3.7 Human Development Index for LMEs. The LME HDI integrates health, education and income metrics and has the lowest assessed values in LMEs of the tropical developing world. The six LMEs with the lowest HDI values (ranked, with lowest first) are: Somali Coastal Current, Guinea Current, Agulhas Current, Benguela Current, Canary Current, and Bay of Bengal.



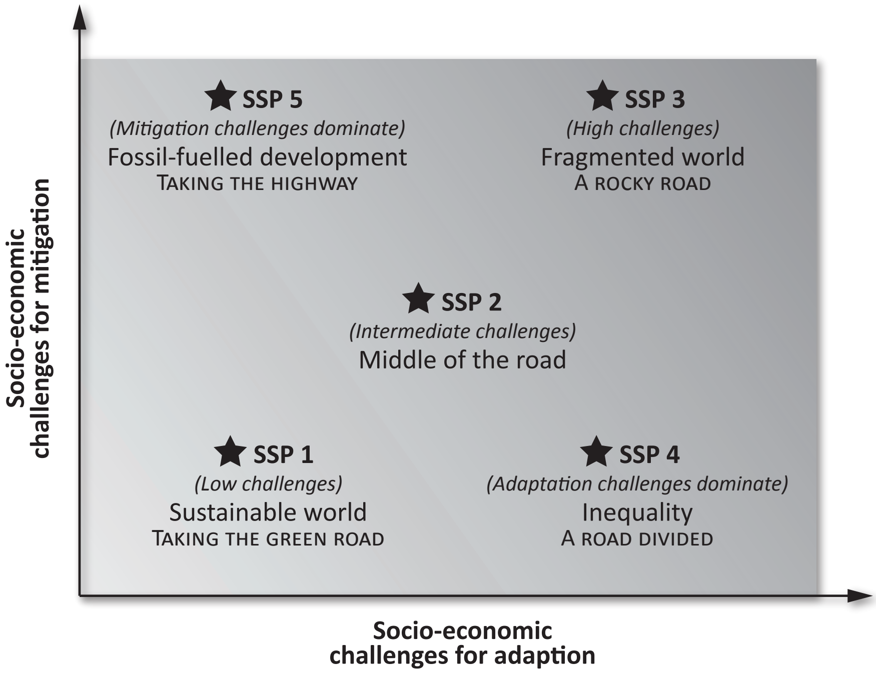
3.2.4.3 Projected Human Development Index in 2100

Shared Socio-economic Pathways

The projected 2100 HDI and HDI Gaps were developed for two contrasting Shared Socio-economic Pathways (SSP) narratives: SSP1 (sustainable world) and SSP3 (fragmented world). SSPs describe five plausible alternative pathways for society and natural systems over the 21st century, in narrative form and in models. They were used by the Intergovernmental Panel on Climate Change (IPCC) scientific community to consider a full range of potential scenarios and required actions during its Fifth Assessment Report (O'Neill *et al.* 2015; Moss *et al.* 2010).

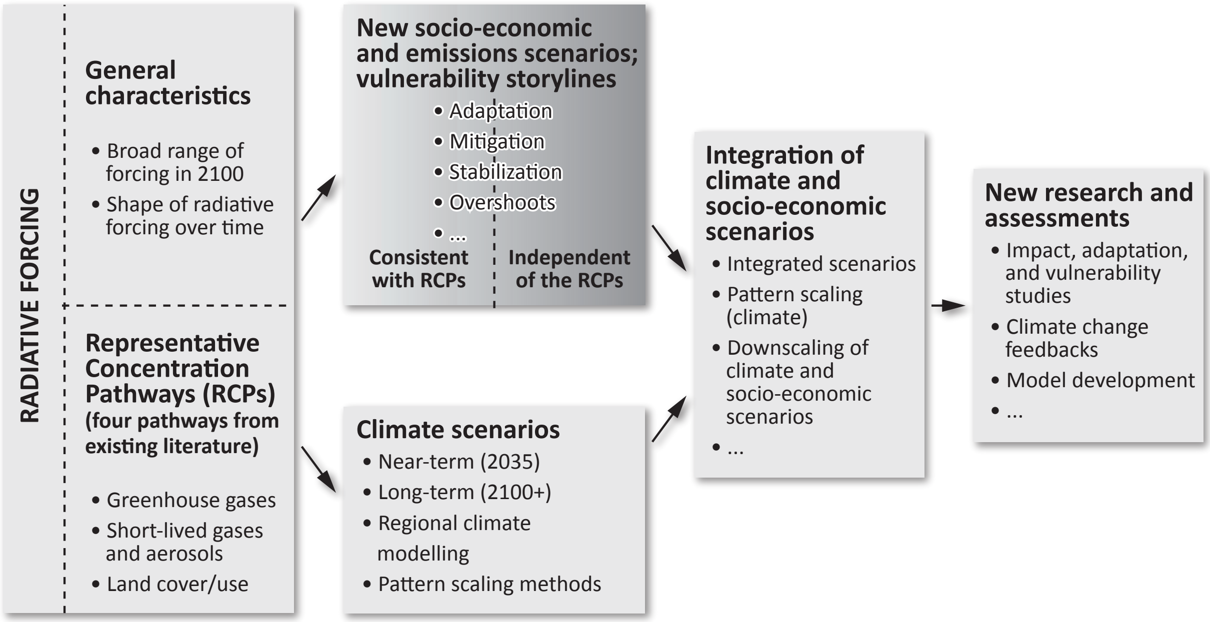
Figure 3.8 is a pictograph of the five SSPs. Selection of SSPs for this analysis was based on maximizing the contrast in assumptions listed in Annex Table 3-C. The physical pathways known as Representative Concentration Pathways (RCPs) are possible climate futures, integrating variables such as the concentration of greenhouse gases and aerosols, and land-use and cover change, that provide the physical forcing functions for integrated scenarios. RCPs and SSPs are combined to examine options for mitigating impacts and ways to reduce vulnerability and increase resilience in the face of climate and global environmental change (Figure 3.9). Development pathways, both physical (RCPs) and socio-economic (SSPs), do not aim to provide predictions. They are cohesive narratives that may be used to define potential outcomes of development choices. The metrics chosen to underpin the 2100 HDI are influenced by the availability of modelled data, as is the case with the other indicators.

Figure 3.8 Shared Socio-economic Pathways. The Shared Socio-economic Pathways (SSPs) provide coherent story lines of human and economic development trajectories (O'Neill *et al.* 2014 and 2015). To examine coastal socio-economic settings in 2100, SSP1 and SSP3 were chosen to provide the modelled metrics for evaluating risk and vulnerability.



Source: O'Neill *et al.* 2015, with permission

Figure 3.9 The use of Representative Concentration Pathways and Shared Socio-economic Pathways in the analysis of impact, adaptation, and vulnerability in relation to global environmental change



Source: Moss *et al.* 2010, with permission

Metrics for Projected HDI (2100) and Projected HDI Gap (2100) for SSP1 and SSP3 pathways

In this study, the metrics chosen to calculate a measure of human well-being are similar to those used in calculating the current HDI: life expectancy from birth, per capita gross domestic product in PPP 2005 US$ (a measure similar to per capita GNI), projected mean years at school, and the modelled female tertiary educational attainment for the age group 20 to 39 years as a percentage of national female population in the same age group (replacing the currently-used expected years in school, for exploratory purposes). The key role of female educational attainment in making choices relevant to the well-being of their households during the childbearing period (20 to 39 years) appears to have profound impacts on child health and mortality, household energy consumption, adaptation, and the quality of participation in governance and democratic processes (Lutz *et al*. 2014; Samir and Lutz 2014). The use of female tertiary educational attainment is not meant to supplant the traditional education metric. It is used here to explore its sensitivity in measuring risks.

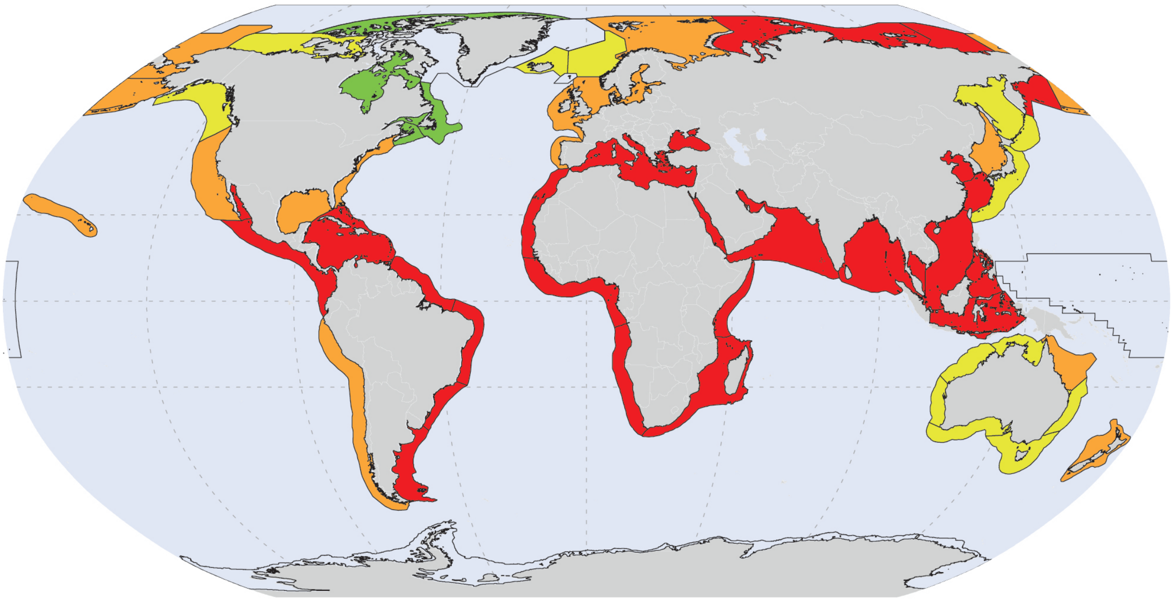
The calculation of the Projected HDI (2100), as discussed in the methods section, includes the use of goalposts to standardize the underlying metrics. The maximum goalposts are aspirational, while the minimum indicate the minimum values for the metrics, which are lower than the lowest of the country values. Once the aspirational goalpost is achieved, the maximum goalpost is used in the calculations. For health, the minimum and maximum life expectancies from birth are 20 and 100 years; for income, the minimum and maximum per capita gross domestic product are $700 and $100 000 in PPP 2005 US$; for mean years at school, the minimum and maximum goalposts are 0 and 18 years; and for female tertiary educational attainment, the minimum and maximum values are 0 and 70 per cent of the female population age 20 to 39 years.

Figure 3.10 shows the resulting HDI for both the sustainable world (SSP1) pathway (bottom panel) and the fragmented world (SSP3) pathway (top panel). Under the SSP1 narrative, education, health and income metrics have high values. In contrast, these attributes have low values under the SSP3 narrative (Annex Table 3-C). Consequently, in SSP1, 58 of 61 data-complete LMEs have HDIs that are highest (above 0.810) and, therefore, small HDI Gaps. Only three African LMEs – Somali Coastal Current, Agulhas Current, and Benguela Current – have HDI scores ranging from 0.747 to 0.773

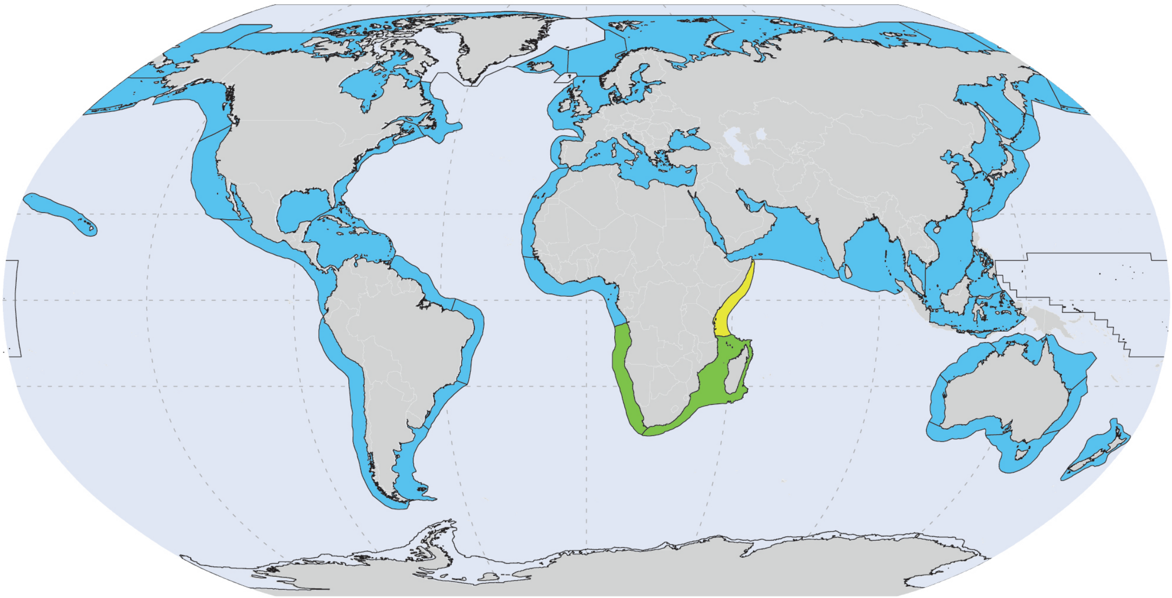
that fall in the ‘medium’ to ‘high’ HDI score categories. In contrast, SSP3 projects a bleaker scenario in which 27 LMEs have HDI scores belonging to the ‘lowest’ HDI score group. No LME reaches an HDI score ranked ‘highest’, and only four LMEs – Scotian Shelf, Newfoundland-Labrador Shelf, Hudson Bay Complex, and Canadian High Arctic-North Greenland (all Canadian LMEs) – reach a ‘high’ HDI rating (0.756 to 0.800).

Figure 3.10 Human Development Index in 2100 based on two Shared Socio-economic Pathways. In a) the fragmented world pathway (SSP3), 27 LMEs have ‘lowest’ HDI scores, corresponding to ‘highest’ risk levels. In contrast, in b) the sustainable world pathway, 58 LMEs have ‘highest’ HDI scores, corresponding to ‘lowest’ risk. The Somali Coastal Current LME, which currently has the lowest HDI score of all LMEs, achieves the ‘medium’ HDI category (and ‘medium’ risk) under SSP1.

a) HDI of LMEs in 2100, following a ‘fragmented world’ pathway (SSP3)



b) HDI of LMEs in 2100 following a ‘sustainable world’ pathway (SSP1)



HDI scores in 2100, HDI score categories, and risk levels

🟦 ≥0.801 Highest HDI Lowest risk

🟩 0.756–0.800 High HDI Low risk

🟨 0.700–0.755 Medium HDI Medium risk

🟧 0.611–0.699 Low HDI High risk

🟥 0.337–0.610 Lowest HDI Highest risk

Annex Table 3-D compares the projections of coastal populations using the 2100 Center for International Earth Science Information Network (CIESIN) population data layer (CIESIN 2013), which is based on the United Nations Development Programme (UNDP) projection using medium variant population growth rate, with the modelled national populations in the context of the sustainable world and fragmented world development pathways. The ratio of population in the 100 km coastal zone to national population obtained from the CIESIN population layer is used to downscale the SSP national population projections to the 100 km coastal populations. In terms of absolute magnitudes, the CIESIN values appear to approximate the SSP3 projections. If population growth is tending towards SSP3 following a medium variant growth rate, there is reason to believe that HDI metrics may be headed along the same pathway, and policy-makers would need to think seriously about how to steer away from SSP3 conditions.

3.2.5 Climate-related risks to LME coastal populations

3.2.5.1 Present-day Climate-related Extreme Events Threat Index

This index includes hazard measures (annual rates of deaths from climate-related events and average annual property losses, both for the period 1994 to 2013), the 2010 population in the 100 km coastal zone as a coarse proxy for exposure; and the HDI Gap (1-HDI, averaged for the period 2009 to 2013) as a vulnerability metric. Climate-related events include cyclones, coastal surges, coastal flooding, and extreme temperatures. Table 3.1 shows that including property losses in an index formula tends to place developed and developing country LMEs in the same risk categories because high property values increase the Index value, and hence the risk, for developed country LMEs. However, this does not account for the fact that, for the same degree of hazard, developing country LMEs have less capacity to cope with extreme events than developed countries. The inclusion of a vulnerability metric such as (1-HDI) provides a means to include this reduced coping ability for poorer countries.

Figure 3.11 Present-day Climate-related Extreme Events Threat Index. The Index includes four metrics: deaths and property losses from cyclones, flooding and extreme temperatures, HDI Gap (1-HDI), and population exposed within 100 km of the coast. The LMEs most at risk are Bay of Bengal, Arabian Sea, South China Sea, East China Sea, Caribbean Sea, Yellow Sea, Sulu-Celebes Sea, Canary Current, Pacific Central American, Somali Coastal Current, Gulf of Thailand, Mediterranean, and Agulhas Current.

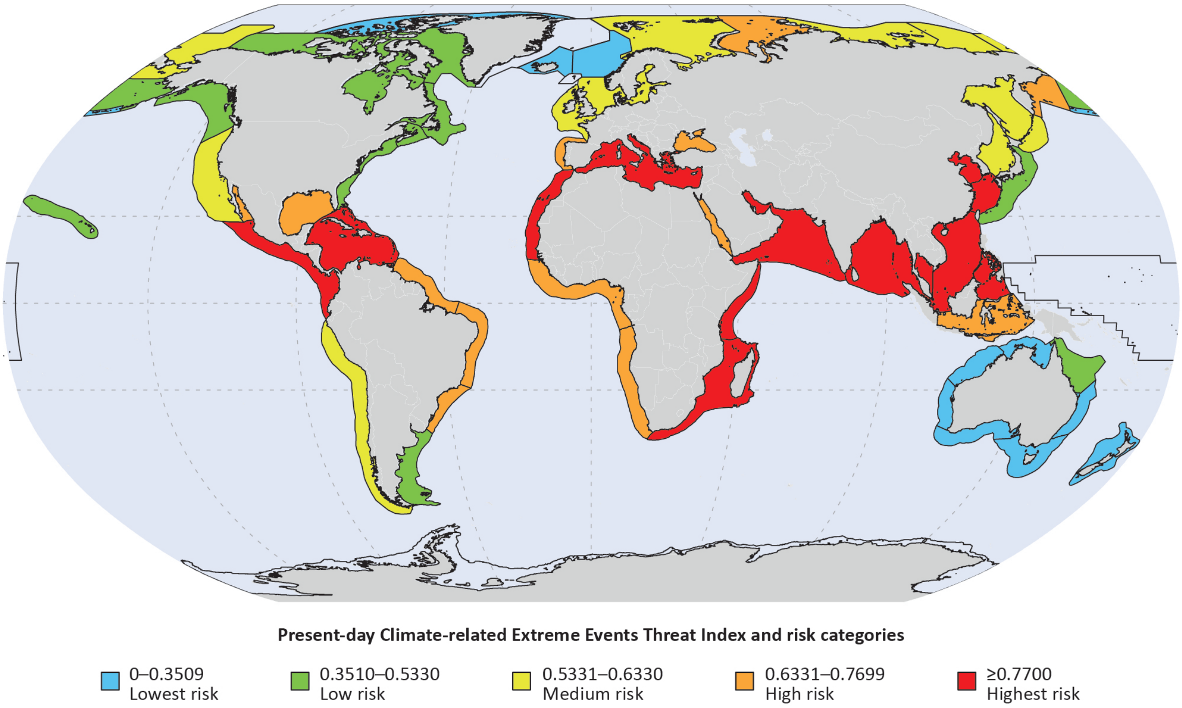


Table 3.1 Comparison of Present-day Climate-related Extreme Events Threat Index values with and without the HDI Gap as a vulnerability measure for the two highest risk categories. Colours represent risk levels (red = highest; orange = high). HDI Gap is 1-HDI.

LME	Index based on deaths, losses, and population exposure	LME	Index based on deaths, losses, population exposure, and HDI Gap
Bay of Bengal	1.0000	Bay of Bengal	1.0000
South China Sea	0.9818	Arabian Sea	0.9389
Yellow Sea	0.9385	South China Sea	0.9091
East China Sea	0.9368	East China Sea	0.8402
Arabian Sea	0.9327	Caribbean Sea	0.8389
Mediterranean	0.9077	Yellow Sea	0.8296
Caribbean Sea	0.9048	Sulu-Celebes Sea	0.8225
Sea of Japan	0.8790	Canary Current	0.8193
Baltic Sea	0.8709	Pacific Central-American	0.8157
North Sea	0.8685	Somali Coastal Current	0.7870
Gulf of Mexico	0.8595	Gulf of Thailand	0.7827
California Current	0.8589	Mediterranean	0.7779
Northeast US Continental Shelf	0.8550	Agulhas Current	0.7703
Black Sea	0.8443	Black Sea	0.7576
Pacific Central-American	0.8414	Guinea Current	0.7476
Celtic-Biscay Shelf	0.8229	Indonesian Sea	0.7432
Gulf of Thailand	0.8228	North Brazil Shelf	0.7250
Southeast US Continental Shelf	0.8181	Red Sea	0.6870
Iberian Coastal	0.8162	Benguela Current	0.6758
Sulu-Celebes Sea	0.8152	South Brazil Shelf	0.6627
Gulf of Alaska	0.8107	East Brazil Shelf	0.6562
Sea of Okhotsk	0.7749	Gulf of California	0.6504
Oyashio Current	0.7617	Gulf of Mexico	0.6438
Insular Pacific-Hawaiian	0.7602	West Bering Sea	0.6424
North Brazil Shelf	0.7589	Kara Sea	0.6401
Canary Current	0.7521	Iberian Coastal	0.6370

Figure 3.11 maps the threat levels for this index in five categories for the 62 LMEs with data. LMEs most at risk to extreme climate events (in decreasing order) are the Bay of Bengal, Arabian Sea, South China Sea, East China Sea, Caribbean Sea, Yellow Sea, Sulu-Celebes Sea, Canary Current, Pacific Central-American LME, the Somali Coastal Current, the Gulf of Thailand, Mediterranean, and Agulhas Current.

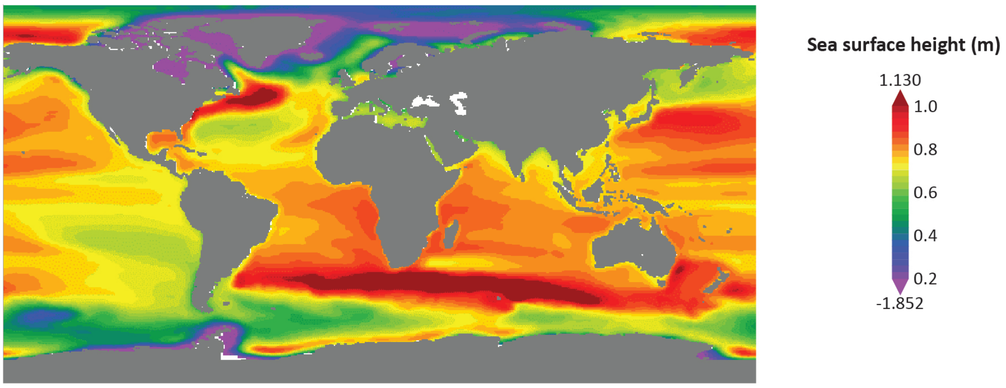
Based on the measures that make up the Present-day Climate-related Extreme Events Threat Index, any intervention to mitigate exposure and HDI-based vulnerability can potentially reduce the overall threat of climate from a socio-economic perspective. Raising low human development metrics is complex in that health, education, and income states evolve out of choices and circumstance, interacting at multiple scales from households, communities, and states. The Human Development Report (2014) stresses that *"universal access to basic social services – education, health care, water supply and sanitation, and public safety – enhances resilience"*, and that this is an achievable goal, even at an early stage of a state's development, which may be accomplished over a reasonably short period, for example, in less than a decade.

3.2.5.2 Sea-level Rise Threat Index under SSP1 and SSP3 scenarios

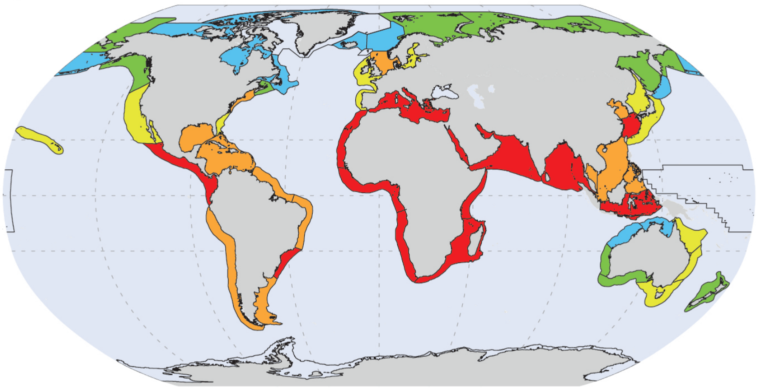
The Sea-level Rise (SLR) Threat Index for 2100 integrates maximum sea-level rise, population living within 10 m elevation above sea level and 10 km from the coast, and projected HDI Gap (1-HDI). The regionalized maximum sea-level rise estimates at LME scale are based on the RCP 8.5, with global warming reaching 8.5 watts per m^2 in 2100. This metric is a constant in calculating both SSP1 and SSP3 SLR Threat Indices. Figure 3.12(a) shows the contours of sea surface height in metres under RCP 8.5.

Figure 3.12 Projected mean sea surface height in 2100 and Sea-level Rise Threat Index in 2100 for two shared Socio-economic Pathways. The projected sea surface height in each LME is used as a measure of hazard. This measure is the same for both SSPs. Differences in the Sea-level Rise Threat Index between the two scenarios are due to differences in HDI Gap (a measure of vulnerability), and population size living in the 10 m elevation by 10 km coastal strip. Following the SSP3 (fragmented world) pathway (b), 13 LMEs have 'highest' and 12 have 'high' threat levels. Following the SSP1 (sustainable world) pathway (c), 48 LMEs have lowest threat levels. Notably, the Bay of Bengal, Arabian Sea, Canary Current, and Guinea Current have low threat levels from sea-level rise under this sustainability pathway.

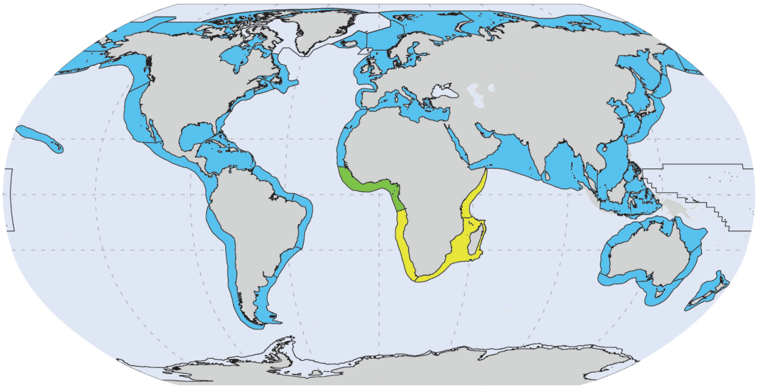
a) Mean sea surface height in 2100
(projected using RCP 8.5; source: University of Hamburg Integrated Climate Data Center).



b) Sea-level Rise Threat Index in 2100 for SSP3



c) Sea-level Rise Threat Index in 2100 for SSP1



Sea-level Rise Threat Index

🟦 0–0.4750
Lowest risk

🟩 0.4751–0.5200
Low risk

🟨 0.5201–0.5800
Medium risk

🟧 0.5801–0.6525
High risk

🟥 ≥0.6526
Highest risk

Most of the coastal areas will experience sea-level rise, while some locations near ice sheets will experience land uplift caused by melting ice sheets and, thus, sea-level fall. Within SSP1 and SSP3 pathways, estimates of population exposure in the 10 m by10 km coastal zone are very different, with a global total of 308 million inhabitants for SSP1 and 507 million for SSP3. Under SSP1 (Figure 3.12(b)), 56 LMEs achieve the highest HDI category, while 25 LMEs under SSP3 have lowest to low HDI values (Figure 3.12(c)). Thus sea-level rise threat is amplified by the size of population exposure and the degree of HDI-based vulnerability. Mitigation measures may include attempts to reduce population size within the 10 m by 10 km coastal zone and to implement shoreline defence through hard engineering (infrastructure) and soft engineering (coastal ecosystem restoration). More importantly and over the long term, enhancing human development strategically through education (which influences lifestyle choices, for example, fewer children, greater participation in democratic processes) and consumption patterns, and providing social safety nets such as pension and unemployment insurance, would reduce persistent vulnerability.

3.2.6 Contemporary Threat Index

This index was developed to determine which LME coastal populations are most threatened by extreme climate events and by LME environmental degradation, both of which exacerbate their core socio-economic vulnerability. The Contemporary Threat Index is calculated as the geometric mean of measures of socio-economic dependence (coastal population, fish protein consumption, and LME tourism contribution to coastal country GDP), lack of adaptive capacity (the HDI Gap), and environmental risk (risk of losses and deaths from climate-related extreme events, and risk scores for five indicators of the state of fish and fisheries and four indicators for the state of pollution and ecosystems, from Kleisner *et al.* (this report). For the Barents Sea and Norwegian Sea LMEs, the Index excludes the fisheries indicators.

This index highlights three interrelated factors that determine the level of overall environmental threat to coastal populations. Even without climate risk and risks associated with degrading LMEs, coastal populations may be at risk because of their dependence on LME services for food and livelihood, and because of limited capacities to adapt and seek opportunities in non-LME-based income-generating activities. Climate-related extreme events and changing ecosystems are therefore additional burdens. Disease and civil unrest can add to these burdens.

For transboundary LMEs (for which governance was assessed) the Contemporary Threat Index was evaluated to include the average of governance completeness and engagement as the fourth factor. In 41 of 47 shared LMEs, risk levels increased with the inclusion of governance metrics, and risk levels decreased in 6 LMEs.

Variables not included in the Index include the proportion of the coastal population that is rural and the proportion that is poor. Both rural and urban sectors of the population would be affected by climate-related extreme events and by ecological changes in LMEs. Therefore, the population size within the 100 km coastal zone is the more appropriate variable to include. In addition, as the proportion of coastal poor and the HDI are correlated at 47 per cent (R^2 value of 0.47), the HDI Gap is retained as a proxy for lack of adaptive capacity.

LMEs most threatened, in order of decreasing risk, are the highly populated tropical LMEs: Bay of Bengal, Canary Current, Gulf of Thailand, South China Sea, Sulu-Celebes Sea, Somali Coastal Current, Indonesian Sea, Guinea Current, Arabian Sea, Caribbean Sea, East China Sea, Yellow Sea, and Agulhas Current (Table 3.2).

Table 3.2 Contemporary Threat Index for each LME. Colours represent risk levels (red = highest; orange = high; yellow = medium; green = low; blue = lowest).

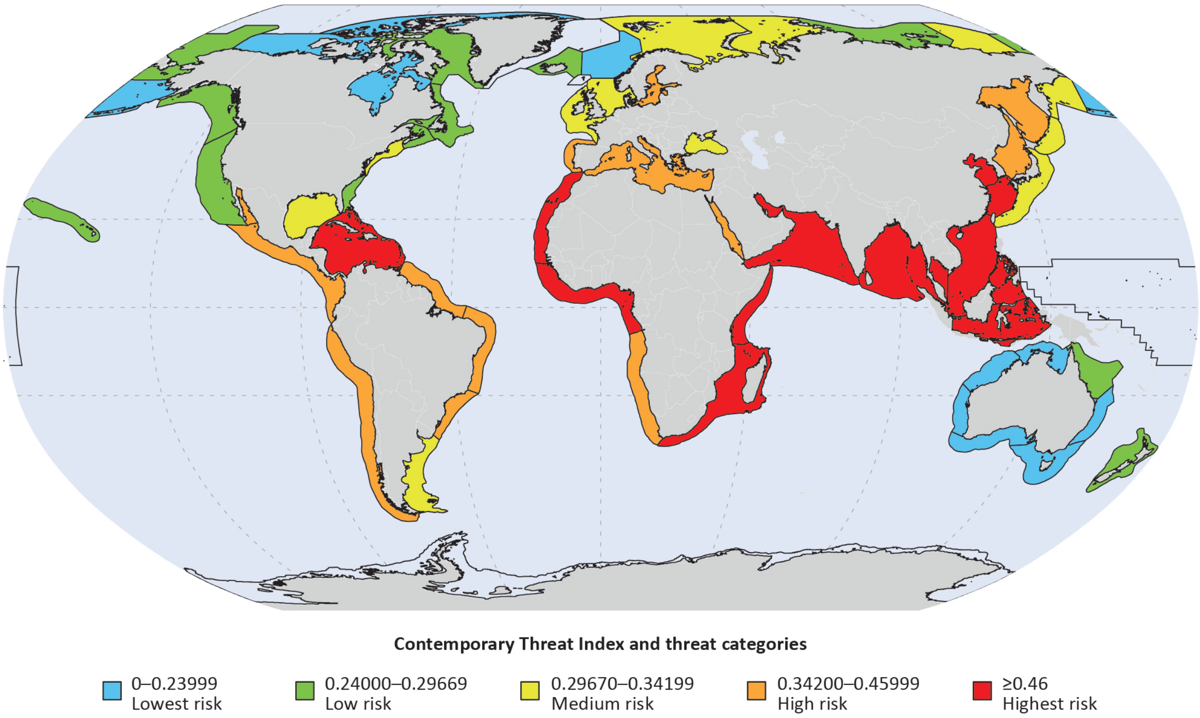
LME	Contemporary Threat Index	LME	Contemporary Threat Index
Bay of Bengal	0.592	Patagonian Shelf	0.327
Canary Current	0.544	Oyashio Current	0.321
Gulf of Thailand	0.527	Black Sea	0.310
South China Sea	0.524	East Siberian Sea	0.299
Sulu-Celebes Sea	0.522	Northeast US Continental Shelf	0.297
Somali Coastal Current	0.514	Laptev Sea	0.297
Indonesian Current	0.509	California Current	0.292
Guinea Current	0.500	Southeast US Continental Shelf	0.291
Arabian Sea	0.483	Northern Bering-Chukchi Seas	0.291
Caribbean Sea	0.481	Iceland Shelf and Sea	0.267
East China Sea	0.480	Canadian Eastern Arctic-West Greenland	0.266
Yellow Sea	0.474	Gulf of Alaska	0.266
Agulhas Current	0.469	Insular Pacific-Hawaiian	0.262
Mediterranean	0.440	Northeast Australian Shelf	0.251
Pacific Central-American	0.440	Newfoundland-Labrador Shelf	0.246
Benguela Current	0.421	Scotian Shelf	0.246
Iberian Coastal	0.398	New Zealand Shelf	0.242
North Brazil Shelf	0.396	East Bering Sea	0.235
Red Sea	0.393	Southeast Australian Shelf	0.223
South Brazil Shelf	0.390	East-Central Australian Shelf	0.221
Gulf of California	0.384	Beaufort Sea	0.218
East Brazil Shelf	0.379	West-Central Australian Shelf	0.216
Humboldt Current	0.364	Southwest Australian Shelf	0.215
Sea of Japan	0.351	North Australian Shelf	0.206
Baltic Sea	0.348	Norwegian Sea	0.201
Sea of Okhotsk	0.343	Hudson Bay Complex	0.201
Barents Sea	0.342	Northwest Australian Shelf	0.198
Gulf of Mexico	0.339	Aleutian Islands	0.193
Kuroshio Current	0.338	Canadian High Arctic-North Greenland	0.146
Kara Sea	0.336	Greenland Sea	Incomplete data
West Bering Sea	0.330	Faroe Plateau	Incomplete data
Celtic-Biscay Shelf	0.329	Antarctic	Incomplete data
North Sea	0.328	Central Arctic Ocean	Incomplete data

Table 3.3 and Figure 3.13 highlight the mean attributes and spatial distribution of LMEs by Contemporary Threat Index category. In general, the metrics of socio-economic dependence, lack of adaptive capacity, and extreme-event mortality follow decreasing trends with decreasing threat levels. Mean property losses with climate-related events are highest for the 'low' threat category, which is dominated by developed states (for example, Southeast US Continental Shelf, Scotian Shelf, and the New Zealand Shelf LMEs). Fisheries exploitation scores are highest for the 'medium' threat category (for example, Gulf of Mexico, Celtic-Biscay Shelf, Patagonian Shelf LMEs). Pollution and ecosystem scores are highest for the 'highest' risk category.

Table 3.3 Average values of attributes of LMEs by risk category of Contemporary Threat Index. All values are averages for the LMEs in the respective risk category for the Index

Contemporary Threat Index	Number of LMEs	Dependence on LME ecosystem services			Lack of adaptive capacity	Environmental risk (climate, ecosystem changes)			
		2010 coastal population (millions)	Fish contribution to animal protein (%)	Tourism contribution to coastal country GDPs (%)	HDI Gap (1-HDI)	Deaths per year (due to storms, flooding, extreme temperature) 1994–2013	Property losses per year (million US$ PPP) 1993–2012	Fisheries scores	Pollution and ecosystem scores
Lowest	12	1.7	9.8	9.1	0.074	114	10 777	0.237	0.454
Low	12	6.1	13.1	8.9	0.111	672	17 115	0.290	0.551
Medium	12	34.6	14.9	8.1	0.162	1 824	8 736	0.338	0.594
High	13	45.5	14.2	9.8	0.242	1 443	2 473	0.289	0.565
Highest	13	126.3	27.8	11.7	0.373	2 257	10 699	0.305	0.622

Figure 3.13 Contemporary Threat Index. This index combines indicators of present-day LME states (based on indices in the Fish and Fisheries module and the Pollution and Ecosystem Health module) with current climate event-related risks, and integrates these measures of environmental risk with measures of dependence of coastal populations on LMEs and a measure of the capacity to adapt to change.



3.2.7 Assessment of Western Pacific Warm Pool States

The WPWP is a thermally dynamic region of the Western Pacific defined by the annual average sea surface temperature isotherm 28 °C and above. Within this shifting region are 14 oceanic island states that receive support from the Global Environment Facility: Cook Islands, Federated States of Micronesia, Fiji, Kiribati, Marshall Islands, Nauru, Niue, Palau, Papua New Guinea, Samoa, Solomon Islands, Tonga-Tokelau, Tuvalu, and Vanuatu (Honey and Sherman 2013). Although not an LME, the WPWP states are included in this study because they are inhabited coastal areas. Because of the limited data available for island states in general, only five island states (Fiji, Samoa, Solomon Islands, Tonga, and Vanuatu) are assessed. The normalization process allows comparisons among these five.

The populations of the five island states together accounted for 85 per cent of the aggregate estimate for the 14 GEF beneficiary states in 2010. Nearly 90 per cent of the population is rural, with relatively high rates of poverty (regionally referred as hardship). National poverty head count ratios are highest for Vanuatu at 40 per cent, and are 31 per cent for Fiji, 23 per cent for the Solomon Islands, and 20 per cent for Samoa (http://www.ruralpovertyportal.org/region/home/tags/oceania). There are no numerical data for Tonga's poor, although its outer islands (such as the Ha'apai island group) are considered least developed and poor. As a result, the range of HDI values among these five island countries cuts across the three lower HDI classification groups with Fiji at the top having a 'medium' 2013 HDI score (0.724) and Solomon Islands having a score in the 'lowest' category (0.491) (Table 3.4).

The Present-day Climate-related Extreme Events Threat Index is highest for Solomon Islands because of that island state's low HDI (high HDI Gap). Fiji has the next highest threat level because it has the highest cyclone-related annual mortality rate and highest annual property losses incurred during the period 1994 to 2013. The differences between SSP1 and SSP3 scores of the Sea-level Rise Threat Index is related to the differences in projected HDI scores, since sea-level rise and population estimates are the same for both scenarios. Solomon Islands is the most vulnerable of the five oceanic states in both scenarios, and Samoa the least. Projected RCP 8.5 sea-level rises reach about 0.81 m in 2100. As indicated for LME coastal countries, investing in education offers a strategic and long-term approach to reducing human vulnerability. It is particularly important for the Solomon Islands where education metrics such as mean years in school and the female tertiary educational attainment for present and projected scenarios are at the low end of the range. A long-term mitigation plan that answers to issues of habitability within the projected sea-level rise scenarios is needed.

Table 3.4 Assessment of Pacific island states within the Western Pacific Warm Pool. The WPWP is a thermally dynamic region of the western tropical Pacific defined by the annual average sea surface temperature isotherm 28°C or higher. Because of limited data coverage for oceanic small island states, only five could be assessed in this study. The data are normalized in the computation of the present-day and scenario-based 2100 Sea-level Rise Threat Index, so that these values are comparable only among the five island states assessed here.

Western Pacific Warm Pool island state	2010 population	2013 HDI	Present-day Climate-related Extreme Events Threat Index	Sea-level rise RCP8.5 2100 (m) near state capitals	SSP1			SSP3		
					2100 population	2100 HDI	Sea-level Rise Threat Index	2100 population	2100 HDI	Sea-level Rise Threat Index
Fiji	854 098	0.724	0.5196	0.7923	600 167	0.849	0.3804	600 167	0.4733	0.4761
Samoa	183 081	0.694	0.3104	0.7828	102 000	0.869	0.1113	102 000	0.5383	0.1265
Solomon Islands	535 699	0.491	0.5597	0.7911	796 833	0.721	0.6549	796 833	0.3539	0.6549
Tonga	104 260	0.705	0.2395	0.8097	67 500	0.869	0.2108	67 500	0.5497	0.2080
Vanuatu	245 786	0.616	0.2292	0.7931	369 333	0.852	0.3252	369 333	0.3899	0.5090

3.3 Discussion and conclusions

Describing human populations has progressed from using metrics of wealth like GDP to measures of well-being such as the iconic Human Development Index (HDI), and to new measures of vulnerability. The profound impacts of episodic or seasonal climate extreme events and decadal ecosystem changes (for example, fish stock collapses or food webs that are changing in response to chronic nutrient loading) on human security are triggering this focal shift (Stiglitz *et al.* 2009). In coastal areas worldwide, the confluence of climate and ecosystem changes and their interactions with food and livelihood security, and rising demand for fish and marine-based amenities worldwide, raise questions about how risks and vulnerabilities may be measured and presented to inform current policy and effect policy change to minimize risk.

While the use of indicators in assessments is an evidence-based method, it must be borne in mind that the choices experts make during index construction introduce subjectivity to indicator-based assessment. Results from assessments must therefore be examined together with consideration of the validity of the methods used. Results are also always subject to further validation using finer scale spatial data.

3.3.1 Trends using the Contemporary Threat Index

Demographic, economic, and well-being indicators have been used individually to describe the 64 populated LMEs, as discussed above. In addition, three threat indices are used to quantify risk. The Present-day Climate-related Extreme Events Threat Index and the 2100 Sea-level Rise Threat Index both estimate disaster risk by factoring in exposure, hazard level, and vulnerability (measured by the HDI Gap). The third risk measure, the Contemporary Threat Index, includes three indicators in addition to HDI Gap to quantify vulnerability: population size, dependence on fish protein, and dependence on LME tourism for income. Inclusion of these indicators is justified because the affected populations interact with coastal ecosystems through food and income dependence. Annex Table 3-B shows that mean population, mean fish protein, and mean LME tourism dependence follow a remarkably similar pattern in decreasing from 'highest' to 'lowest' threat levels, and the pairwise correlations among these three are low (r^2 ranging from 7 to 10 per cent). Given this low level of redundancy, these three indicators may be used together in index construction. The average of their transformed and normalized scores is used as a metric of dependence on LME ecosystem services. Results show that the Indonesian Sea LME has the highest dependence, followed by the Gulf of Thailand LME, and the Bay of Bengal LME. The least reliant, using these measures, is the Canadian High Arctic-North Greenland LME. However, for this and other LMEs, sectors of the population that have the highest reliance on ecosystem services may be overlooked using these measures, even at the scale of coastal-country segments. These sectors may include subsistence fishers, small-scale tour operators, and small-scale fish traders. Only fine-scale sub-national assessments may be able to show this reliance. Using sub-national data, the vulnerable sub-populations may be identified, and the disaster and environmental risks they face may be better quantified for targeting mitigation in terms of regions and timing.

The HDI Gap, as previously discussed, measures unrealized human development potential relative to aspirational goalposts in education, health, and income. The extent of these inadequacies at national or sub-national scales contributes to the overall vulnerability of a coastal population. Ideally, outcomes of good governance that address human development inadequacies or increase overall adaptive capacity should be included in the Index. Numerically, outcomes of good governance should be incorporated into the measure (1-adaptive capacity) so that outcomes of good governance lead to decreasing risk with increasing value of adaptive capacity. Governance is assessed only for transboundary LMEs (Mahon *et al*. this report). In applying the Contemporary Threat Index to transboundary LMEs, we found that including governance metrics of engagement and completeness of governance instruments resulted in greater risk in most LMEs. Transboundary water management, which is in its infancy, requires a fairly involved level of coordination among agencies within a country, and among countries which have variable capacities for environmental governance. In general, inadequate transboundary water management contributes to increasing risk. Inclusion of governance metrics reduced the risk levels in six LMEs: Pacific Central-American, Mediterranean, Guinea Current, Benguela Current, West Bering Sea, and Northern Bering-Chukchi Seas. The dependence measure (based on coastal population, protein from fish, and reliance on LME tourism) and the HDI Gap together quantify vulnerability as the social component of risk in this index.

The third element of contemporary risk is the average of climate risk and risk due to ecosystem states. Conceptually, changes that erode ecosystem health and integrity amplify the risks coastal populations face when extreme events occur. The LMEs that exhibit the highest risks due to both climate extreme events and degrading ecosystem states are the East China Sea, Yellow Sea, North Sea, South China Sea, Baltic Sea, and Bay of Bengal.

3.3.2 Comparison with similar indices

The Coasts at Risk Index (Coasts at Risk 2014) assesses risk, vulnerability, and exposure to coastal hazards, both climatic and geological in nature, at the coastal country scale. Vulnerability is estimated as the mean of the indices for susceptibility, lack of coping capacity, and lack of adaptive capacity. The resulting Vulnerability Index is multiplied by an Exposure Index to derive the Coast at Risk Index. Although this index and the Contemporary Threat Index share some common indicators, the use of exposure as the main weighting factor for the Coasts at Risk Index has the effect of highlighting the vulnerability of small island states. The top ten country coasts with highest risk (based on the Coasts at Risk Index) are Antigua and Barbuda, Tonga, Saint Kitts and Nevis, Vanuatu, and Fiji, Brunei Darussalam, Bangladesh, Philippines, Seychelles and Kiribati. The matching LMEs for these would be the Caribbean, South China Sea, and Bay of Bengal. The Seychelles and the Pacific Islands do not have corresponding LMEs. The differences in scale and weighting factors between the two indices highlight the subjective nature of index construction. Results of Coasts at Risk and this study are not necessarily comparable.

The Transboundary Waters Assessment Programme (TWAP) Risk Index (Kleisner *et al.* this report) ranks 64 populated LMEs based on the HDI Gap and the average of nine environmental indicators (four addressing fish and fisheries, and five measuring pollution and ecosystem health). The Contemporary Threat Index uses the same factors and adds the influence of socio-economic dependence metrics and extreme climate-event-related property losses and deaths for 62 populated LMEs. A comparison of the resulting risk categories shows that 43 of the 62 LMEs (70 per cent) have the same levels of risk based on the two indices. Ten LMEs have risk levels one category higher using the Contemporary Threat Index. This reflects the influence of high levels on climate-event-related property losses and deaths. Another nine LMEs have risk levels one category lower using the Contemporary Threat Index because socio-economic dependence is low or climate-event-related losses and deaths are low, or both, for these LMEs. The HDI Gap appears to provide a robust basis for risk assessment for 70 per cent of the LMEs. For 19 LMEs, the additional socio-economic metrics included in the Contemporary Threat Index allowed adjustments in risk categories by one level higher or lower, at the most.

3.3.3 Mitigating risk and vulnerability

Reducing risk by minimizing the vulnerability of human and social capital and maintaining healthy ecosystems to conserve natural capital are two strategic and mutually reinforcing principles of risk management. Neumeyer (2001) maintains that human and social capital must be developed at rates capped by the natural rates of production (growth and reproduction) if natural capital stocks are to be conserved for future generations. Human development, while aiming to reduce vulnerability, must be sustainable – that is, not at the expense of natural capital. It is unsustainable if a country's manufactured and natural capital stock net depreciation is greater than its investment. The pursuit of sustainability must require a de-emphasis on economic growth and a sharper focus on the twin and inherently integrated social and environmental goals (Howarth 2012). In the most recent Sustainable Society Index Report, Van de Kerk and Manuel (2008 and 2014) show a negative correlation between human and environmental well-being (r^2 value of 55 per cent) and higher incomes coinciding with higher well-being and lower environmental well-being (correlation r^2 values of 70 per cent). While correlation does not impute causation, a deeper examination of why human and environmental well-being appear mutually exclusive is warranted. Both may have to be calibrated by a sustainability factor before trends may be appropriately compared.

The Human Development Report (2014) notes that persistent vulnerability prevalent among the elderly, women, and children at all life stages must be addressed. Provision of universal safety nets to safeguard full employment and ensure access to education, health care and basic services may be the optimal approach for this. Vulnerability cannot be remediated without taking into account that poverty and inequality must be reduced. Hence, universal safety programmes to allow opportunities for human development among those experiencing chronic deprivation are necessary components of environmental risk management.

In the context of ecosystem management for LMEs, it is imperative that the social component of risk (vulnerability) is addressed directly through integrated programmes where people and environment are fully acknowledged as integral elements of a whole ecosystem (Howarth 2012). The GEF may use its partnerships with the UN Environment Programme, the UN Development Programme, and international NGOs in designing strategic and integrated action plans to reduce environmental degradation and human vulnerability to both climate and environmental change. The processes through which these action plans evolve must include democratic participation of the most vulnerable groups, and therefore become meaningful exercises of engagement in civil society, a key element of human development (Campbell *et al.* 2006).

3.3.4 Data and process requirements for future assessments

As previously mentioned, the LME scale of analysis may be a necessary but not an optimum scale for assessing vulnerability. The global-scale comparisons presented here must be followed by finer-scale studies using geo-referenced indicators of social and economic attributes as they relate to environmental change. Such assessment is probably best implemented regionally. Participating countries would provide a thesis of their respective country coastal segments together with maps of resource use, poverty distribution, time-series statistics on spatially explicit occurrence of extreme events, and time series of changes in ecosystem states together with information on the economic impacts these changes have on livelihood systems. Regional estimates of GDP contributions of fisheries, tourism, and other LME-based economic activities are extremely important. At the regional scale, the spatial match among assessments, monitoring, and adaptive management may be closest, and optimal for setting quantifiable management targets.

3.4 Methodology and analysis

The application of national data to the LME scale requires the use of scaling-up factors that take into account the proportion of either the population or the area of the country segment relative to the total of all country segments that make up the LME’s 100 km coastal width (or another measure of width). These scaling factors were derived using Geographic Information System (GIS) analysis and available spatial products. They were used in computing LME-scale indicator values, notably in the calculation of revenues and the metrics that are used as indices.

Input data and analytical methods for each of the 13 major indicators used in assessing the socio-economic features of LMEs and for the assessment of the WPWP states are presented in the sections that follow. Annex Table 3-A lists the indicators and the sources of input data and summarizes the methods.

3.4.1 Coastal population and area by country coastal segment (100 km wide)

Input data

The spatial population estimates for 2010 are based on 2000 census data. They are projected to 2010 using the UNDP average national-level growth rates assuming UN medium estimates. Population counts for 2100 were calculated using the International Institute for Applied Systems Analysis (IIASA) Greenhouse Gas Initiative (GGI) Downscaled Spatially Explicit Socio-Economic Scenario Data at 0.5-degree resolution from 2000 to 2100, in decadal increments. A 100-year growth rate was determined on a 1 km pixel basis to obtain the 2100 population projections within a framework of socio-economic scenarios defined and used by the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (2007). The urban–rural delineations are based on the 1995 determination of urban centres (based on buffered settlement points for which the total population is greater than 5 000), and are assumed to remain the same in area through to 2100. The coastlines of the population layer have been reconciled with the high-resolution 3 arc second Shuttle Radar Topography Mission (SRTM) satellite-defined coastline.

Analytical methods

Using GIS analysis of CIESIN 2013 global population layers resolved at 1 km for 2010 and 2100, first a buffer was defined from the landward boundaries of the LME (the shoreline) to 100 km inland and the corresponding regional area grid was clipped. A fixed distance of 100 km was chosen for a number of reasons: it allows tracking of changes in the spatial distribution of coastal populations through time; it captures both human and environmental interactions that directly influence changes in LME comparisons with previous global estimates; and it does not preclude studies from examining biophysical processes and social interactions at finer scales and along the hydrological continuum from watershed to the coast, which varies with location. The regional area grid was used to identify and define the corresponding country coastal segments of 100 km width that make up an LME coastal area. The area raster was converted to points with area values, with urban and rural areas identified. The area raster was overlaid on the population grid to extract population values for the corresponding area points, again distinguishing the rural and urban components. Points with area and population values were summarized and tabulated for each country coastal segment. All population and area values were summed across all country coastal segments that make up an LME coastal area. The analysis was iterated for the populated 64 LMEs (all LMEs with the exception of Central Arctic Ocean and Antarctic). Coastal population as a percentage of national population, together with the absolute population numbers, is a proxy for the level of stress on marine ecosystems.

Level of confidence

High for 2010 population and area estimates; medium for 2100 population.

3.4.2 Coastal population in the area up to 50 km from shore and up to 10 m elevation, 2100

Input data

The 2100 population data layer was used to derive coastal populations in increments of elevation and coastal distance. These populations are vulnerable to storms, coastal flooding, and sea-level rise. A Global Digital Elevation Model (GDEM) called ACE2 was chosen as the most accurate global database for elevation because it blends altimeter and satellite readings to give more accurate elevation estimates than provided by either method alone, especially in areas where the vegetation canopy can interfere with satellite measurements in reckoning reference to the true geoid (the shape of the ocean surface influenced by Earth's gravitation and rotation). ACE2 GDEM is available at 3, 9, and 30 arc seconds, and at 5 arc minutes resolution. The 30 arc second (1 km at the equator) resolution was chosen to coincide with the 1 km resolution of the population data layers.

Analysis

Using GIS analysis of the CIESIN (2013) global population layer for 2100, as described above, a country-by-country clipping of country coastal segments to 50 km was first implemented, and 50 km-from-shore area grids were obtained. The coastal-country segment area grid, population layer, and the ACE2 DEM layer were analysed together to obtain population values at the intersection of elevation (m) and coastal distance (km): populations at ≤1, ≤2, ≤3, ≤5, 5 to 10 m, and ≥10m elevation; and at 0 to 2 km, 2 to 4 km, 4 to 6 km, 6 to 10 km, 10 to 15 km, 15 to 20 km, 20 to 30 km, 30 to 40 km, and 40 to 50 km from shore. The values for coastal-country segments were summed to obtain LME population values, by elevation, within the 50 km coastal zone. This population value at 10 m by 10 km is used to indicate exposure to coastal disasters such as storms and sea-level rise.

Level of confidence

Medium to high for elevation estimates; variable by location.

3.4.3 Coastal poor, 2000s

Input data

National poverty head counts as percentages of national populations were obtained from the World Bank Development Indicators database, covering the period 2008 to 2013. Where country data for poverty in developed countries were missing, additional data were obtained from the Organisation for Economic Cooperation and Development (OECD) Income Distribution and Poverty database for OECD countries, and from individual country statistics offices.

Analysis

National poverty head counts as percentages of national population were averaged over the period 2008 to 2013 when more than one value was available. These percentages were used to obtain the number of poor in each country coastal segment within 100 km from shore. The country segment poor were summed to obtain the number of LME coastal poor. Sub-national poverty mapping offers more accurate estimates of the location of the coastal poor and such maps have been produced for major countries in the developing world. However, the absence of a global data product to support a proper spatially-explicit poverty assessment at the global scale, with commonly accepted standards of what constitutes poverty, is a major challenge. Thus, the national poverty head counts calculated from country-specific poverty lines, and their application in coastal areas, is in need of confirmation using spatially-explicit sub-national poverty data. Coastal poor, as a percentage of national population or of coastal population, indicates the level of well-being. High values correspond to low states of well-being.

Level of confidence

Low to medium

3.4.4 Fishing revenues for the period 2001 to 2010

Input data

Data on catch (tonnes) and landed value (2005 US$) by fishing country, by LME for the period 1950 to 2010, were provided by the Sea Around Us (www.seaaroundus.org; 2014 dataset for each LME). The catch data were originally derived from Food and Agriculture Organization (FAO) fisheries statistics and were disaggregated into time series in 0.5° spatial grid cells, following a rule-based algorithm (Pauly and Lam, this report). The data include mainly industrial catch, as subsistence fisheries are not routinely included in national fisheries reports to the FAO.

Analysis

The annual catch and landed value by fishing country in each LME were averaged over the ten-year period. The sums of average annual catch and landed values at the country scale across coastal countries of an LME provide the basic metrics for valuing fishing at the LME scale. Landed value is also called gross value added (GVA), which is derived from the multiplication of total catch by fish price. To calculate fishing GDP, data on production costs (fees, fuel, and maintenance and repair of fishing vessels and fishing equipment) and on taxes and subsidies are needed. These required data are not routinely gathered at the country scale, so fishing GDP calculations are not necessarily part of the National Account Systems of many coastal states. A systematic evaluation of the full economic contribution of fishing to a country's GDP, including its direct and direct impacts on income, employment, and state revenues, therefore remains a challenge to this and subsequent LME assessments. In the absence of global data on production costs, this study provides the valuation of LME-scale fisheries at the level of GVA as a first-order economic value of the food provisioning ecosystem service that LMEs provide. Landed value is expressed in 2005 US$ and is converted to 2013 US$ to be comparable with calculated values of LME tourism values.

Level of confidence

Medium

3.4.5 Average LME fish contribution to animal protein (2011)

Input data

Data on national-scale fish contribution to animal protein as a percentage for 2011 were obtained from FAO.

Analysis

National-scale input data were weighted using the country segment population proportion, relative to the total LME population. Products were summed across LME coastal countries to obtain average LME fish contribution to animal protein, expressed as a percentage. Coastal country segment populations are more likely to have higher fish consumption rates, and thus higher percentages of fish-derived animal protein in their diets. However, fish consumption rates at the sub-national level are not routinely monitored. The higher the level of fish consumption, the higher the level of dependence on the LME's fishery resources, and the greater the likelihood for fish to be exploited with increasing human population over time.

Level of confidence

Medium

3.4.6 Tourism revenues for the period 2004 to 2013 (in 2013 US$)

Input data

Country tourism data, including tourism GDP and the sector's contribution to employment, were obtained from the World Tourism and Travel Council (WTTC).

Analysis

Unlike fishing, tourism as an economic activity is generally well tracked by coastal states. However, the nature of tourism presents a number of challenges in valuing coastal and marine tourism in a spatial manner. Many countries have adopted a tourism satellite accounting system to allow more efficient planning and tourism product development. A satellite account is a method for assessing the economic contribution of an economic sector that is not defined as an industry in a country's national account system. Tourism integrates many economic sectors (including construction, transport, accommodation and food services, and real estate) in providing tourism experience to inbound tourists and in supporting outbound tourism (Frechtling 2010). It does not lend itself easy to spatially explicit analysis without the use of elaborate econometric tools. To properly assess the contribution of tourism to national economies, countries follow the International Recommendations for Tourism Statistics 2008 adopted by the United Nations Statistical Commission. Some countries have also attempted to expand their tourism satellite accounting systems to include a regional dimension. A regional tourism satellite accounting system would be ideal for analysing coastal and marine tourism, but this type of system has higher requirements for input data and analysis than most countries can currently afford.

Hoagland and Jin (2008) estimated maritime industry activity indices for LMEs using country data with temporal coverage from 2002 to 2004. To aggregate country data to LMEs, they used the coast length as a weighting factor. They noted that this weighting procedure did not resolve *"the issue of attributing all of a nation's marine activities to an LME when only a portion of that nation has been assigned to the LME"* (Hoagland and Jin 2008). Despite these limitations, the marine activity indices remain as reference values for the time and data the study covered. The methods for estimating fisheries and tourism revenues in this study are not comparable to those in Hoagland and Jin (2008), due to the difference in methods employed by this study to scale national data to coastal segment scale (aggregation of spatially-explicit population data at the LME scale).

In this study, the national tourism data, specifically tourism GDP, is scaled to the 100 km coastal area by using scaling factors in ordered priority, depending on data availability. Regional sectoral GDP for food and accommodation as a percentage of national GDP is the preferred scaling factor, followed by regional GDP (for all economic sectors). The least preferred scaling factor is the proportion of the country coastal segment population in relation to the coastal country national population.

By far the most commonly available data set for scaling is regional GDP (total for all economic sectors). The total regional GDP for sub-national regions that form part of the country coastal segment was obtained as a percentage of national GDP and was used to calculate the country coastal segment share of the national tourism GDP. The sum of country coastal segment tourism GDP shares is the LME total tourism revenue, since GDP is appropriate only for country measures. Where no regional GDP data were available, the least preferred scaling factor of coastal segment population as a percentage of national population was used. Where possible, gaps in the WTTC database were filled using data from country tourism databases. Like fishing, average annual tourism revenue at the LME scale indicates the monetized value of amenities and recreation provided by an LME and does not necessarily, by itself, indicate risk or threat relative to sustainability. Other metrics that track the environmental impacts of tourism, such as water pollution and coastal development, are required to infer whether tourism is on a sustainable path.

Level of confidence

Variable by LME. Where regional GDP was used as the scaling factor, the confidence level is medium, and where the percentage coastal segment population was used, the confidence level is low.

3.4.7 Average LME tourism contribution to coastal states GDPs

Input data

The contribution of tourism to national GDP as a percentage and amount over the period 2004 to 2013 was obtained from the WTTC.

Analysis

For each LME, an average tourism contribution to the GDPs of its coastal states was calculated as the sum of the national tourism GDP of each coastal country, weighted by the country's share of the LME tourism. This provides an LME-scale metric of dependence on LME tourism. Each coastal country's tourism revenue value is expressed as a percentage of national GDP, a measure of economic dependence on coastal/ marine tourism.

To get the weighted average of dependence across coastal countries, each dependence metric was weighted by the percentage contribution each country makes to the LME's total tourism revenues. For single-country LMEs, the dependence metric (percentage coastal tourism in regional GDP) was multiplied by 100 per cent because a single country accounts for all LME tourism revenue. For multi-country LMEs, the dependence metric was multiplied by a country's percentage contribution to LME tourism revenues. The sum of the products is the weighted mean dependence of an average coastal country to LME tourism revenues.

The greater the degree of dependence, the greater the likelihood that the amenities services of an LME are used without the needed safeguards to make tourism environmentally sustainable. Increased dependence on tourism may also create a less diversified livelihood portfolio, and one that may become increasingly subject to the vagaries of discretionary consumer spending.

Level of confidence

Medium

3.4.8 Night Light Development Index (NLDI 2006)

Input data

The NLDI is the third major spatial input data set used in this socio-economic assessment for coastal populations of LMEs. This index is based on the spatial co-distribution of night-time irradiance (light) as a proxy of economic activity and population at 1 km resolution. It is analysed using the Lorenz curve approach, which plots the cumulative percentage of population against the cumulative percentage of irradiance (Elvidge *et al.* 2012). The higher the NLDI value, the more uneven is the distribution of economic activity – as would be the case for developing economies. In more developed regions, the NLDI would assume lower values, indicating more even distribution of economic activity relative to population distribution. A major advantage of the NLDI is that night-time illumination is an operational satellite product that can be used to provide relatively inexpensive updates of the Index. However, its limitation is that a single spatial indicator is unable to capture the complexity of the spatial distribution of economic activity as a measure of well-being. Rural areas that are not connected to energy grids and not lighted are automatically not measured. The potential to blend this indicator with other spatial measures of well-being may be addressed in future research.

Analysis

The sub-national scale of the NLDI product provides values for the NLDI for each state or province of individual countries. The NLDI of coastal sub-national divisions were averaged to yield the coastal-country segment NLDI. Where data were absent at the sub-national scale, the national NLDI value was used for the coastal-country segment NLDI. These country segment NLDIs were each multiplied by the percentage area of the relevant LME in relation to the total LME area. The resulting products were summed to yield the LME NLDI. A high value of NLDI corresponds to a low level of economic development.

Level of confidence

Medium

3.4.9 Contemporary LME Human Development Index (2009 to 2013) and HDI Gap

Input data

Human Development Index Reports have been produced every year since 1992 at various scales, but most widely at the country scale with global coverage (UNDP 2015). The Human Development Index itself has not changed since 1992, except for the minimum and maximum goalposts used to standardize the data. The latest set of goalposts for the 2014 report is used in this analysis. All data were obtained from the UNDP reports website at http://hdr.undp.org/en.

Analysis

The four input metrics of HDI – life expectancy from birth, mean and expected years in school, and the per capita GNI for each country segment– were first individually averaged for the period 2009 to 2013. To up-scale the country segment metrics to the corresponding LME metrics, the value of each country average HDI metric was weighted by the percentage of the population living in each country segment relative to the total LME population within 100 km of the coast. The weighted values for each metric were summed to obtain the corresponding LME HDI metric. The metrics were standardized using the minimum and maximum goalposts established by the HDI report, the latest values of which are reported in the HDI 2014 report: 20 years minimum and 85 years maximum life expectancy from birth; 0 years minimum and 18 years maximum expected years in school; 0 years minimum and 15 years maximum mean years in school; and PPP 2011 US$100 minimum and US$75 000 maximum per capita GNIs (HDR 2014).

The two standardized metrics for education – mean and expected years in school – were averaged to generate an LME Education Index. The standardized metric for health based on life expectancy became an LME Health Index, and the standardized natural logarithm of per capita GNI became the Income Index. The geometric means of these three indices were used to obtain the LME HDI for the period 2009 to 2013, which was computed for each of the 64 LMEs with resident coastal populations. LME HDI measures the well-being of coastal inhabitants. The aspirational maximum goalposts for longevity, expected and realized years in school, and income, if all achieved, give a maximum HDI of 1.0. The HDI Gap (1-HDI) is used in this study as a metric for estimating combined human-development-related insufficiencies in health, education, and income. These lead to pre-existing risks that may be exacerbated by specific risks due to changes in climate, adverse environmental and political changes, and natural disasters. The HDI Gap is therefore included as a risk factor in calculating present and future climate-related risk or threat indices (below).

Level of confidence

High

3.4.10 Indicators for calculating 2100 LME HDIs and underlying metrics within the Shared Socio-economic Pathways Scenarios

Analytical framework for future development scenarios

In preparation for the Fifth Assessment Report, in 2008 the Intergovernmental Panel for Climate Change (IPCC) initiated a parallel scenario development process whereby the biophysical pathways of climate change are conceptualized alongside pathways of societal change (Moss 2010). The RCPs identify four levels of radiative forcing based on the combined effects of greenhouse gases, aerosols, and land cover and use. The RCPs are basic forcing functions in generating climate scenarios. The SSPs describe five trajectories of future changes in_demographics, human development, economy, policies and institutions, environment and natural resources, and technology, each with its set of challenges for dealing with climate change (O'Neill *et al.* 2012 and 2015; Figure 3.8).

Annex Table 3-C lists the thematic elements for three SSPs. The list includes metrics used in the computation of the Human Development Index. In this study, HDI metrics in SSP1 and SSP3 (longevity, expected mean years in school and female tertiary education for 20 to 39 years of age, and income) are used to compute HDI, which is the basis required for comparing human-development-related risks and risks from sea-level rise in 2100. SSP1 describes a sustainable future where human development features such as education, health investments, and equity are well developed. These same features are poorly developed for SSP3 (a stalled-development pathway). Population growth, fertility, and mortality are low for SSP1, and reach high levels for SSP3.

The metrics for the five SSPs have been modelled and are available for use as an SSP database with projections of population, urbanization, and GDP. The database is available for download with registration at https://secure.iiasa.ac.at/web-apps/ene/SspDb/dsd?Action=htmlpageandpage=about.

Input data

SSP elements that can be used in developing HDI-like indices are obtained from the SSP database (2012). These include national population, life expectancy at birth, mean years at school as total for both sexes, tertiary educational attainment of females of childbearing ages (20 to 39 years) as a percentage of total female population in this age bracket, and per capita GDP in PPP 2005 US$. The tertiary education of females was chosen to replace the expected years at school metric that was not included among those modelled for the SSPs. The inclusion of the metric on female tertiary educational attainment is exploratory and allows an examination of how it influences the HDI values in each of the SSP scenarios. Modelled national GDP and population data for SSP1 and SSP3 are from the OECD models (2011).

Analysis

The percentage of population in 2100 each country segment contributes to the total LME population, as discussed for the first indicator, above, weights the metrics for each country coastal segment. It should be noted that calculations of HDI use contemporary goalposts in standardizing underlying metrics, which are considered meaningful up to 2025 (HDR 2014). As there are no aspirational goalposts established for the year 2100, a practical method was used to determine these. The minimum goalposts were set to bracket the minimum modelled values for both SSPs, and the maximum goalposts were set arbitrarily by the authors following trends in the modelled data and those set for the contemporary HDI (which are good to 2025). For 2100, minimum and maximum goalposts for female tertiary educational attainment were set at 0 and 70 per cent of the 20 to 39 age group. Minimum and maximum goalposts for life expectancy were set at 20 and 100 years, and minimum and maximum goalposts for per capita GDP were set at PPP 2005 US $700 and $100 000. The geometric mean of the mean number of years in school and the females with tertiary education as a percentage of the total number of females in the 20 to 39 years age group was used because of the differences in units. Geometric means are numerically smaller than arithmetic means. The standardization process to obtain the education, health, and income indices for each LME were as described above for the contemporary HDI. Finally, the geometric mean of the three indices yielded the 2100 LME HDI for each of the two socio-economic pathways. High values of SSP HDIs connote high levels of human well-being.

Level of confidence

Not applicable since these are scenario-based values and are not meant to be predictive, but rather to be consistent with a cohesive set of assumptions and parameters about predefined development pathways. The SSP HDIs in this study aim to compare the levels of risk or threat to coastal populations in the context of a sustainable world pathway and a fragmented world trajectory.

3.4.11 Present-day Climate-related Extreme Events Threat Index (2010)

$$\text{Climate-related Extreme Events Threat Index}_{2010} = [(1\text{-HDI}) \times (\text{population}_{2010}) \times (\text{average annual deaths}) \times (\text{average annual property losses})]^{1/4}$$

where (1-HDI) is the HDI Gap (or human-development-related insufficiency);
exposure is represented by LME coastal population; and
average annual deaths and property losses are hazard proxies.

Input data

Country data on climate-related mortalities associated with cyclones, flooding, and extreme temperatures were obtained from the EM-DAT international disaster database (www.emdata.be) for the period 1994 to 2013. Property losses data were accessed from the GermanWatch Climate Risk Index database for years 1993 to 2012 (Kreft and Eckstein 2014). LME Coastal Population (2010) and (1-HDI 2009 to 2013) are derived LME-scale data previously derived from analysis and calculations for the indicators and indices described above.

Analysis

The mortality and property loss data were averaged for the period 1993 to 2013. For countries with multiple LMEs, the data were simply used for each LME, as these events have no associated geographic coordinates. Country data were aggregated at the LME scale. LME values of mortality, property loss, and population were log-transformed. The LME HDI Gap and the log-transformed metrics were standardized to a value range of 0.1 to 0.9 (since a value of 0 would lead to a geometric mean of 0). The geometric mean of the four metrics is the Present-day Climate-related Extreme Events Index. For LME populations with the same degree of exposure and hazards, those with large HDI Gaps (that is, high human-development-related pre-existing risks) will experience higher levels of climate-related threat.

Level of confidence

Medium

3.4.12 RCP 8.5 Sea-level Rise Threat Index under SSP1 and SSP3 scenarios in 2100

SLR Threat Index$_{\text{RCP 8.5, SSP}}$ = [(max SLR) X (1-SSP HDI) X Population in 10 m by 10 km coastal zone)$^{1/3}$

where max SLR = Maximum sea-level rise at RCP 8.5 and represents the hazard;
1-SSP HDI is the HDI Gap for the SSP scenario; and
population in 10 m by 10 km coastal zone represents exposure.

Input data

Regionalized sea-level rise data for RCP 8.5 scenario (where radiative forcing reaches 8.5 watts per m^2 in 2100) were accessed from the Integrated Climate Data Center of the University of Hamburg, and the minimum and maximum sea-level rise for the coastline of each LME were obtained using GIS analysis. Values of the HDI Gap for both SSP1 and SSP3 development pathways were calculated previously (section 3.4.11). Populations projected to 2100 under both development pathways for the 100 km and 10 m by 10 km coastal areas were derived using population scaling factors computed from the GIS analysis of the CIESIN (2013) 2100 spatial population layer. Values were standardized from 0.1 to 0.9 to avoid having zeros that yield index values of zero.

Analysis

RCPs drive the climate models to predict resulting global warming, sea-level change and a host of other physical responses of the earth system, and were used in preparing the most recent IPCC Fifth Assessment Report. RCP 8.5 refers to a radiative forcing of more than 8.5 watts per m^2 in 2100, resulting in the highest warming: 4.5°C temperature increase over pre-industrial levels (Moss *et al.* 2010). This pathway also projects rising greenhouse gases, and is the most extreme of the four RCPs. The SLR Threat Index was developed to illustrate how risk changes with one RCP scenario of sea-level change in combination with two SSP scenarios.

To estimate exposure for either development pathway:

SSP exposure in 10 m by 10 km coastal segment =

(Coastal segment 2100 population in 10 m by 10 km) X (2100 SSP national population)
(2100 national population)

Level of confidence

Not applicable. Index values are scenario-based that are not meant to be predictive, but rather to be consistent with a cohesive set of assumptions and parameters about predefined concentration (RCP) and development (SSP) pathways. The Threat Indices for SSP1 and SSP3 are used to compare threats relative to quantification of SSP HDI metrics.

3.4.13 Contemporary Threat Index

Input data

The input data for most of the indicators included in the Contemporary Threat Index are described in previous sections. Measures of ecosystem state are risk scores for fisheries and for pollution and ecosystems, described by Kleisner *et al.* (this report, Annex Table 8-D). These are based on indicators selected from the chapters of the Fish and Fisheries module and the Pollution and Ecosystem Health module of this report.

For transboundary LMEs for which governance architecture was assessed by Mahon *et al.* (this report), the geometric mean of the three factors and mean governance metric (average of engagement and completeness measures), was calculated

Analysis

The Index was calculated as follows:

Contemporary Threat Index = Geometric mean (***dependence, lack of adaptive capacity, environmental risk***) where

> ***Socio-economic dependence*** = Average (coastal population (2010), mean per cent fish protein contribution to animal protein, mean per cent LME tourism contribution to coastal country GDPs)
>
> ***Lack of adaptive capacity*** = 1-HDI (or HDI Gap) based on education, health, and income achievements
>
> ***Environmental risk*** = Average (extreme climate-related events losses and deaths, mean (fish and fisheries indicators, pollution and ecosystem health indicators))
>
> Note: In the case of transboundary LMEs for which governance completeness and engagement are assessed, the average of these two indicators provide a fourth factor in the evaluation of Contemporary Threat Index. For the Barents and Norwegian Seas LMEs, the Index excludes the fisheries indicators.

The LMEs were ranked using the Contemporary Threat Index which integrates threats caused by extreme events and ecosystem degradation, and exacerbating existing constraints to human development, and state of transboundary water governance (where applicable). Implicitly, the desired level of human development is one with a more diversified economic portfolio resulting in less dependence on LME ecosystem services for income. With higher educational achievement, a society can generate income including those which use diverse and high skilled labour-based economies rather than direct exploitation of marine living resources or the amenities these provide.

3.4.14 Assessment of the Western Pacific Warm Pool island states

Input data

The same input data needed to characterize and assess present-day climate and 2100 scenario-based sea-level rise threats for the LMEs were assembled for the island states of the Western Pacific Warm Pool. Because of the limited coverage of existing data, of the 14 island states in the region that receive support from the Global Environment Facility, only Fiji, Samoa, Solomon Island, Tonga, and Vanuatu are assessed. Input metrics for index computation were standardized from 0.1 to 0.9.

Analysis

The analysis is as described for the previous indicators and indices.

References

Baxter, J. (2002). How much does parental education explain educational attainment of males and females in Australia? Negotiating the life course discussion paper series, Discussion Paper DP-015, October 2002. Demography and Sociology Program, Research School of Social Sciences, Australian National University, 36 pages

Berry, P.A.M., Smith, R.G. and Freeman, J.A. (2007). Towards a new global digital elevation model. IUGG 2007 Earth: Our changing planet, Perugia, Italy, 2-13 July 2007

Bremner, J., López-Carr, D., Suter, L. and Davis, J. (2010). Population, poverty, environment, and climate dynamics in the developing world. *Interdisciplinary Environmental Review*, 11 (2/3), 112-126.

Campbell, J., Whittingham, E. and Townsley, P. (2006). Responding to coastal poverty: should we be doing things differently or doing different things? Chapter 21 (eds. Hoanh, C.T., Tuong, T.P., Gowing, J.W., and Hardy, B.). *Environment and Livelihoods in Tropical Coastal Zones*. CAB International

Coasts at Risk*: An assessment of coastal risks and the role of environmental solutions* (ed. Michael, W.). A joint publication of United Nations University – Institute for Environment and human Security (UNU-EHS), The Nature Conservancy (TNC) and the Coastal Resources Center (CRC) at the University of Rhode Island Graduate School of Oceanography, 2014

Day, J.C. and Newburger, E.C. (2002). The big payoff: educational attainment and synthetic estimates of work-life earnings. Current Population Reports, July 2002, US Census Bureau, US Department of Commerce, Economics and Statistics Administration

Elvidge, C.D., Baugh, K.E., Anderson, S.J., Sutton, P.C. and Ghosh, T. (2012). The Night Light Development Index (NLDI): a spatially explicit measure of human development from satellite data. *Social Geography* 7, 23-35. http://www.soc-geogr.net/7/23/2012/sg-7-23-2012.pdf

Frechtling, D. (2010). The tourism satellite account: A Primer. *Annals of Tourism Research* 37(1), 136-153

Glomsrød, S. and Aslaksen, I. (eds.). *The Economy of the North*. Statistics Norway, 2006. https://oaarchive.arctic-council.org/handle/11374/31

Heineck, G. and Riphahn, R.T. (2007). Intergenerational transmission of educational attainment in Germany: The last five decades. German Institute for Economic Research Discussion Paper No. 738

HDR (Human Development Report). (2014). UNDP, New York

Heltberg, R., Siegell, P.B. and Jorgensen, S.L. (2009). Addressing human vulnerability to climate change: Toward a 'no-regrets' approach. *Global Environmental Change* 19, 89-99

Hoagland, P. and Jin, D. (2008). Accounting for marine economic activities in large marine ecosystems. *Ocean and Coastal Management* 51, 246-258

Honey, K.T. and Sherman, K. (2013). The Western Pacific Warm Pool assessment approach for the Transboundary Waters Assessment. Background Brief. April, 2013. NOAA Large Marine Ecosystem Program, Narragansett, RI, USA

Honey, M. and Krantz, D. (2007). Global trends in coastal tourism. World Wildlife Fund Marine Program

Howarth, R.B. (2012). Sustainability, well-being, and economic growth. *Minding Nature* 5(2), 32-39

Institute of Well-being (2009). How are Canadians really doing? The First Report of the Institute of Well-being. http://ywcacanada.ca/data/research_docs/00000014.pdf

IOC-UNESCO and NOAA. LME assessment methodology (this report)

IPCC (2007). *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Inter-Governmental Panel on Climate Change* (eds. Metz, B., Davidson, O.R., Bosch, P.R., Dave, R. and Meyer, L.A.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Kleisner, K.M., Talaue-McManus, L., Halpern, B.S., Kershaw, P.J., Lam V.W.Y. and Sherman, K. Identifying patterns of risk among large marine ecosystems using multiple indicators (this report)

Kreft, S. and Eckstein, D. (2014*).* Global Climate Risk Index 2014. Who suffers most from extreme weather events? Weather-related loss events in 2012 and 1993-2012. *GermanWatch,* 28 pages, http://germanwatch.org/en/7659 (accessed 19 December 2013)

Lutz, W., Muttarak, R. and Striessnig, E. (2014). Universal education is key to enhanced climate adaptation. *Science* 346, 1061-1062

Moss, R.H., Edmonds, J.A., Hibbard, K.A., Manning, M.R. and others (2010). The next generation of scenarios for climate change research and assessment. *Nature* 463, 747-756

Neumayer, E. (2001). The human development index and sustainability – a constructive proposal. *Ecological Economics* 39, 101-114

OECD (2011*).* Compendium of OECD well-being indicators. http://www.oecd.org/std/47917288.pdf (accessed 9 January 2013)

O'Neill, B.C., Carter, T.R., Ebi, K.L., Edmonds, J. and others (2012). Pathways for climate change research, Meeting Report of the Workshop on the Nature and Use of New Socioeconomic. Boulder, CO, November 2-4, 2011. http://www.isp.ucar.edu/socio-economic-pathways. (accessed 8 February 2013)

O'Neill, B.C., Kriefler, E., Ebi, K.L., Kemp-Benedict, E. and others (2015). The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change*, doi:10.1016/j.gloenvcha.2015.01.004

Oppenheimer, M., Campos, M., Warren, R., Birkmann, J., Luber, G., O'Neill, B., Takahashi, K. (2014). Emergent risks and key vulnerabilities. In: *Climate Change 2014: Impacts, adaptation, and vulnerability. Part A: Global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (eds. Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, K.L., Ebi, Y.O., Estrada, R.C., Genova, B., Girma, E.S., Kissel, A.N., Levy, S., MacCracken, M., Mastrandrea, P.R., and White, L.L.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1039-1099

Pauly, D. and Lam, V.W.Y. The status of fisheries in large marine ecosystems, 1950-2010 (this report)

Samir, K.C. and Lutz, W. (2014.) The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. *Global Environmental Change*, doi:10.1016/j.gloenvcha.2014.06.004

Smith, L.M., Case, J.L., Smith, H.M., Harwell, L.C. and Summers, J.K. (2013). Relating ecosystem services to domains of human well-being: Foundation for a U.S. index. *Ecological Indicators* 28, 79-90

Seitzinger, S.P. and Mayorga, E. Nutrient inputs in large marine ecosystems (this report)

Stiglitz, J.E., Sen, A., Fitoussi, J.P. (2009). *Report by the (French) Commission on the Measurement of Economic Performance and Social Progress,* 292 pages. http://www.stiglitz-sen-fitoussi.fr/en/index.htm (accessed 8 January 2013)

UNEP (2006). *Marine and coastal ecosystems and human well-being: A Synthesis report based on the findings of the Millennium Ecosystem Assessment.* UNEP. 76 pages

Van de Kerk, G. and Manuel, A.R. (2008). A comprehensive index for a sustainable society: the SSI – the Sustainable Society Index. *Ecological Economics* 66, 228–242

Van de Kerk, G. and Manuel A.R. (2014). *Sustainable Society Index SSI – 2014*. Sustainable Society Foundation, The Hague, The Netherlands

Wisner, B., Blaikie, P., Cannon, T. and Davis, I. (2003) *At Risk. Natural hazards, People's Vulnerability and Disasters*. Second edition. Routledge, New York

World Bank (2010). *The hidden harvests. The global contribution of capture fisheries*. Prepared by the World Bank, Food and Agriculture Organization, WorldFish Center

Annex

Annex Table 3-A Socio-economic indicators, methods, and data sources used in assessing risk and vulnerability of coastal populations next to LMEs. See the methodology section for more details.

Demographics sub-theme

Indicator	**Time period**	**Underlying metrics**	**Methods**	**Confidence level**	**Data sources**
1. **Coastal population** and area of country segment within 100 km coastal zone (spatial)	2010, 2100	Rural and urban fractions of coastal populations	GIS analysis; scaling factor: none Population and area estimates for country coastal segments are used as scaling factors for majority of the socio-economic indicators assessed in this chapter for baseline conditions.	High for 2010 population and area estimates; medium for 2100 population.	CIESIN population layers for 2010 and 2100 (2013) (http://sedac.ciesin.columbia.edu/data/set/lecz-urban-rural-population-land-area-estimates-v2; registration required).
2. **Coastal population by elevation** up to 10 m and by distance from shore up to 50 km (spatial)	2100	Coastal populations in increments of elevation and coastal distance	GIS analysis; scaling factor: none Proportion of population living within 10 km and within 10m elevation in 2100 relative to national population is used to derive populations for SSP1 and SSP3 scenarios in 2100.	Medium to high for elevation estimates, variable by location.	Derived from CIESIN 2013 spatial population layers with additional ACE2 Digital Elevation Model available at http://tethys.eaprs.cse.dmu.ac.uk/ACE2/ (registration required) (Berry *et al*. 2008).
3. **Coastal poor**	2008–2013	Head count below national poverty line	National poverty head count as percentage poor of national population; averaged for period 2008-2013. Scaling factor: none	Low to medium; spatial poverty maps are needed to verify spatial distribution of the poor.	World Bank development indicators 2014 (http://data.worldbank.org/data-catalog/world-development-indicators); OECD income distribution and poverty (www.stats.oecd.org); Pacific island country poverty statistics (http://www.ruralpovertyportal.org/region/home/tags/oceania).

Economic activities sub-theme

Indicator	**Time period**	**Underlying metrics**	**Methods**	**Confidence level**	**Data sources**
4. **Fisheries revenues** (spatial)	2001–2010	Catch and landed value	Computation of 10-year mean fishing revenues to evaluate food provisioning ecosystem service by LMEs; includes mostly industrial catches.	Medium	Fisheries data from FAO fisheries statistics re-analysed using time series by the Sea Around Us (Pauly and Lam, this report).
5. **Fish contribution to animal protein**	2011	Fish consumption per capita	Country-scale estimates of fish protein aggregated to LME scale; country-segment population as a proportion of total LME coastal population used to weight national data on fish contribution to animal protein. Coastal-country segments may consume fish at higher rates than indicated by national averages.	Medium	FAO (http://faostat3.fao.org/download/FB/FBS/E)
6. Tourism revenues	2004–2013	Tourism revenues	Computation of LME tourism revenues based on national tourism GDPs.	Variable, depending on data used to scale down to the coast (regional tourism GDP, regional total GDP, regional coastal population)	World Tourism and Travel Council 2014 (http://www.wttc.org/datagateway/); Country regional GDP from national statistics offices as listed at http://unstats.un.org/unsd/methods/inter-natlinks/sd_natstat.asp.

7. Tourism contribution to GDP	2004–2013	Contribution to GDP and employment	Coastal state contribution to tourism revenues (as a proportion of total LME tourism revenues) used to weight the percentage contribution of tourism to total GDP for each country; country products are summed to obtain mean LME-scale values.	Medium	As above
Human well-being sub-theme					
Indicator	**Time period**	**Underlying metrics**	**Methods**	**Confidence level**	**Data sources**
8. Night Light Development Index (spatial)	2006	Satellite data of night lights at sub-national and national scales; population data	GIS analysis of sub-national and national measures of the co-distribution of night-time irradiance and population distribution at 1 km resolution; data are missing for small island states and rural areas not connected to power grids. Scaling factor: proportion of coastal-country segment area to total LME coastal area	Medium	NLDI layer (Elvidge *et al.* 2012); NOAA (http://ngdc.noaa.gov/eog/dmsp/download_nldi.html)
9. Contemporary Human Development Index	2009–2013	National data on health, education, and income	Application of national metrics of health (life expectancy from birth), education (mean and expected years in school), and income (Gross National Income per capita) to coastal population. Metrics are missing for some territories and islands where input data are incomplete or non-existent. Scaling factor: proportion of country-segment population relative to LME population	Medium	Human Development Report 2014 (http://hdr.undp.org/en)
10. Projected Human Development Index 2100	2100 under SSP1 and SSP3	Modelled data for health, education, and income	Application of modelled national metrics to coastal populations; all metrics are projected by SSP1 and SSP3 scenarios and distributed to the coastal-country segments using the CIESIN (2013) population layer for 2100 and the national populations for SSP1 and SSP3 as calibration factors. Health metric is life expectancy from birth; education metrics are mean years in school and female tertiary educational attainment for 20–39 years age group; and income metric is per capita GDP.	Not applicable for scenario-based analyses	IIASA Population Model, SSP Database, 2012 (https://secure.iiasa.ac.at/web-apps/ene/SspDb) Health metric: modelled by Lutz *et al.* (2012); Wittgenstein Centre for Demography and Global Human Capital 2014 (http://witt.null2.net/shiny/wittgensteincentredataexplorer/) Education metrics: data from Samir and Lutz 2012 Income metric: per capita GDP using OECD modelled national GDP and national population, obtained from the SSP database.

Climate-related threats sub-theme					
Indicator	Time period	**Underlying metrics**	**Methods**	**Confidence level**	**Data sources**
11. Present-day Climate-related Extreme Events Index	2010	Climate-related deaths and property losses; coastal population; HDI	Development of an index based on deaths and property losses from climate-related events for the period 1994–2013, the exposed population in the 100 km coastal zone, as calculated for 2010, and the HDI Gap.	Medium	Deaths compiled from EM-DAT disaster database (http://www.emdat.be/database); property losses from GermanWatch Climate Risk Index 2015 (http://germanwatch.org/en/9470).
12. Sea-level Rise Threat Index 2100	2100 under SSP1 and SSP3	Modelled populations exposed to sea-level rise under SSP1 and SSP3 scenarios; HDI for SSP1 and SSP3	Development of a Sea-level Rise Threat Index for 2100 using exposed population in a 10 m by 10 km coastal strip, based on two SSP scenarios and maximum sea-level rise at RCP 8.5, and the HDI Gap.	Not applicable for scenario-based analyses	Sea-level rise modelled data for RCP 8.5 scenario at http://icdc.zmaw.de/1/daten/ocean/ar5-slr.html.
Contemporary threat sub-theme					
Indicator	**Time period**	**Underlying metrics**	**Methods**	**Confidence level**	**Data sources**
13. Contemporary Threat Index	Current	Coastal population; fish protein; tourism contribution to GDP; HDI; climate-related deaths and property losses; LME system states (fisheries and ecosystem risk scores)	Includes indicators for socio-economic dependence on LME services, lack of adaptive capacity, and combined climate-related and ecosystem state risks.	Medium	Sources for most indicators are listed above; LME fisheries and ecosystem scores are from Kleisner *et al.* (this report).

Annex Table 3-B Fishing and tourism revenues. Average annual percentage LME fish contribution to animal protein and average percentage LME tourism contribution to the GDPs of LME coastal countries are indicated by risk colour categories, where a high contribution indicates high dependence on LME ecosystem services. Contribution (and risk) levels: blue = lowest; green = low; yellow = medium; orange = high; red = highest. The 14 LMEs with the highest revenues for each sector are shaded in purple. Data sources are cited in Annex Table 3-A.

LME	Average annual landed fish value (2001–2010) (millions of 2013 US$)	Average annual % LME fish contribution to animal protein of LME coastal countries	Average annual tourism revenues (2004–2013) (millions of 2013 US$)	Average annual % LME tourism contribution to GDPs of LME coastal countries
East Bering Sea	1 152	7.4%	4 240	8.4%
Gulf of Alaska	634	8.3%	14 779	6.1%
California Current	563	7.4%	227 106	8.5%
Gulf of California	206	7.8%	12 874	13.8%
Gulf of Mexico	1 665	7.6%	252 343	9.0%
Southeast US Continental Shelf	247	7.4%	164 160	8.6%
Northeast US Continental Shelf	3 873	7.4%	203 155	8.4%
Scotian Shelf	614	9.7%	5 173	5.2%
Newfoundland-Labrador Shelf	1 154	9.7%	1 483	5.2%
Insular Pacific-Hawaiian	24	7.4%	6 096	8.4%
Pacific Central-American	672	6.9%	48 482	11.9%
Caribbean Sea	810	8.7%	84 768	18.0%
Humboldt Current	5 353	16.2%	19 209	8.5%
Patagonian Shelf	2 486	3.0%	41 105	10.0%
South Brazil Shelf	223	5.4%	113 067	9.8%
East Brazil Shelf	218	5.4%	25 958	9.8%
North Brazil Shelf	561	8.7%	6 541	9.5%
Canadian Eastern Arctic-West Greenland	386.	34.2%	124	3.5%
Greenland Sea	87	39.5%	40	0.0%
Barents Sea	556	15.9%	18 289	6.4%
Norwegian Sea	470	23.4%	6 315	7.4%
North Sea	2 497	10.5%	338 271	10.0%
Baltic Sea	236	11.8%	89 034	8.5%
Celtic-Biscay Shelf	2 742	10.0%	233 075	11.4%
Iberian Coastal	686	20.3%	96 028	15.0%
Mediterranean	3 431	12.2%	478 729	13.1%
Canary Current	2 624	25.1%	39 268	16.2%
Guinea Current	1 330	41.8%	4 798	4.9%
Benguela Current	1 202	16.4%	6 131	7.8%
Agulhas Current	576	19.9%	12 598	8.7%
Somali Coastal Current	103	13.2%	944	12.2%
Arabian Sea	4 131	11.7%	53 385	7.2%
Red Sea	230	9.2%	12 134	6.9%
Bay of Bengal	5 891	32.4%	57 951	14.6%
Gulf of Thailand	1 143	38.0%	33 128	17.0%
South China Sea	10 287	27.5%	234 946	12.1%
Sulu-Celebes Sea	1 596	38.9%	14 403	11.5%

LME	Average annual landed fish value (2001–2010) (millions of 2013 US$)	Average annual % LME fish contribution to animal protein of LME coastal countries	Average annual tourism revenues (2004–2013) (millions of 2013 US$)	Average annual % LME tourism contribution to GDPs of LME coastal countries
Indonesian Sea	1 912	54.5%	53 153	10.5%
North Australian Shelf	275	8.3%	33 729	11.7%
Northeast Australian Shelf	86	8.6%	32 443	11.7%
East-Central Australian Shelf	70	8.3%	50 719	11.7%
Southeast Australian Shelf	221	8.3%	38 113	11.7%
Southwest Australian Shelf	242	8.3%	25 582	11.7%
West-Central Australian Shelf	174	8.3%	15 953	11.7%
Northwest Australian Shelf	200	8.3%	15 953	11.7%
New Zealand Shelf	853	10.6%	24 640	16.3%
East China Sea	6 955	24.3%	146 489	9.1%
Yellow Sea	4 042	25.8%	208 962	9.8%
Kuroshio	1 618	36.4%	102 053	6.6%
Sea of Japan	2 353	36.9%	80 112	6.6%
Oyashio Current	952	36.9%	14 149	6.7%
Sea of Okhotsk	4 549	27.1%	15 231	6.6%
West Bering Sea	715	14.0%	378	6.1%
Northern Bering-Chukchi Seas	328	10.4%	4 759	8.4%
Beaufort Sea	0	8.9%	16 299	6.1%
East Siberian Sea	1	14.0%	1 201	6.1%
Laptev Sea	3	14.0%	3 781	6.1%
Kara Sea	1	14.0%	5 126	6.1%
Iceland Shelf and Sea	488	29.1%	471	19.3%
Faroe Plateau	228	43.2%	265	0.1%
Antarctic	2	no data	1 229	no data
Black Sea	601	8.9%	43 086	10.8%
Hudson Bay Complex	2	9.7%	19 522	5.2%
Central Arctic Ocean	2	no data	17 277	no data
Aleutian Islands	200	7.4%	36	8.4%
Canadian High Arctic-North Greenland	0	10.8%	216	4.3%

Annex Table 3-C A comparison of the elements of Shared Socio-economic Pathways 1 and 3 used in the study. Modified from O'Neill et al. 2015.

SSP element	Sustainable world pathway (SSP1)	Fragmented world/ stalled development (SSP3)
Demographics – population (by age, sex, education)		
Growth	Relatively low	High for high and low fertility countries; low for rich OECD countries
Fertility	Low for high and low fertility countries; medium for rich OECD countries	High for high and low fertility countries; low for rich OECD countries
Mortality	Low	High
Migration	Medium	Not prescribed
Demographics – urbanization		
Level	High	Low
Type	Well managed	Poorly managed
Human development		
Education	High	Low
Health investments	High	Low
Access to health facilities, water and sanitation	High	Low
Equity	High	Low
Social cohesion	High	Low
Societal participation	High	Low
Economy and lifestyle		
Per capita growth	High in low and medium income countries; medium in high income countries	Slow
Inequality	Reduced across and within countries	High, especially across countries
Consumption and diet	Low growth in material consumption, low-meat diets, first in high income countries	Material-intensive consumption
Policies and institutions		
Environmental policy	Improved management of local and global issues: tighter regulation of pollutants	Low priority for environmental issues
Policy orientation	Toward sustainable development	Oriented toward security
Institutions	Effective at national and international levels	Weak global institutions/ national governments dominate societal decision making
Environment and natural resources		
Fossil constraints	Preferences shift away from fossil fuels	Unconventional resources for domestic supply
Environment	Improving conditions over time	Serious degradation
Land Use	Strong regulations to avoid environmental trade-offs	Hardly any regulation; continued deforestation due to competition over land
Agriculture	Improvements in agricultural productivity; rapid diffusion of best practices	Low technology development, restricted trade
Technology		
Development	Rapid	Slow
Transfer	Rapid	Slow
Energy tech. change	Directed away from fossil fuels, toward efficiency and renewables	Slow tech. change, directed toward domestic energy sources
Carbon intensity	Low	High in regions with large domestic fossil fuel resources

Annex Table 3-D Comparing coastal populations projected by the UNDP and population estimates based on Shared Socio-economic Pathways. CIESIN (2013) projections use medium variant population growth. SSP1 is a coherent narrative depicting a sustainable world, while SSP3 is a narrative for a fragmented world rife with regional rivalry. SSP1 population growth is reduced, while SSP3 population grows much faster. The 2100 CIESIN (2013) projections are closer to the SSP3 indicative population sizes. Coastal populations are those living within 100 km of the coast. Colours represent risk levels (red = highest; orange = high; yellow = medium; green = low; blue = lowest).

Large marine ecosystem	Coastal population 2100 (CIESIN 2013)	Rank	Story line coastal population 2100 for SSP1	Rank	Story line coastal population 2100 for SSP3	Rank
Bay of Bengal	501 774 392	1	289 850 745	1	630 139 506	1
Mediterranean	353 577 642	2	281 135 650	2	455 649 483	3
Arabian Sea	316 830 284	3	194 497 439	4	432 856 437	4
Guinea Current	251 496 615	4	229 621 140	3	455 939 424	2
Indonesian Sea	242 699 415	5	149 060 440	6	240 500 861	7
Yellow Sea	225 934 193	6	187 780 814	5	255 251 464	5
South China Sea	213 297 270	7	133 244 117	7	252 484 353	6
East China Sea	166 220 610	8	73 322 826	13	103 175 475	16
Caribbean Sea	126 576 916	9	63 976 980	15	140 614 853	11
Sulu-Celebes Sea	116 545 183	10	95 922 569	9	211 093 008	9
South Brazil Shelf	108 248 326	11	54 235 670	20	105 963 825	15
Red Sea	103 998 449	12	49 504 159	22	111 980 214	13
Pacific Central-American	97 859 738	13	47 047, 14	23	121 475 675	12
Somali Coastal Current	92 037 170	14	57 160, 23	19	143 277 472	10
Kuroshio	91 035 098	15	69 012 447	14	43 687 902	24
North Sea	86 764 309	16	105 022 039	8	59 788 094	18
Celtic-Biscay Shelf	76 595 295	17	90 603 616	10	53 676 129	21
Agulhas Current	75 017 836	18	57 232 872	18	110 477 613	14
Northeast US Continental Shelf	73 602 865	19	83 857 940	12	47 033 729	23
Canary Current	71 913 903	20	86 893 918	11	217 089 110	8
Humboldt Current	68 326 175	21	25 549 628	27	56 036 151	20
Gulf of Mexico	64 430 109	22	61 364 078	16	58 219 268	19
Gulf of Thailand	62 702 332	23	53 017 307	21	62 778 001	17
Sea of Japan	55 696 060	24	37 931 338	24	23 775 441	30
California Current	54 244 644	25	59 806 253	17	37 313 073	26
East Brazil Shelf	49 074 792	26	24 587 948	28	48 039 105	22
Patagonian Shelf	38 646 210	27	15 230 457	33	33 470 117	27
Southeast US Continental Shelf	29 368 453	28	33 378 073	26	18 744 570	31
Baltic Sea	25 679 136	29	36 191 059	25	25 396 062	29
Benguela Current	24 515 118	30	21 604, 878	29	39 078 333	25
Black Sea	18 123 039	31	16 845 938	32	30 932 582	28
Iberian Coastal	14 662 042	32	21 110 232	30	12 508 799	32
East-Central Australian Shelf	12 883 190	33	18 923 909	31	10 466 806	34
North Brazil Shelf	10 865 253	34	5 600 866	37	11 375 071	33
Gulf of Alaska	9 205 202	35	12 629 555	34	6 789 484	36
Southeast Australian Shelf	8 158 529	36	11 983 931	35	6 628 307	37
New Zealand Shelf	5 721 885	37	6 432 423	36	3 828 207	38
Gulf of California	4 945 965	38	2 942 371	41	7 010 392	35

Large marine ecosystem	Coastal population 2100 (CIESIN 2013)	Rank	Story line coastal population 2100 for SSP1	Rank	Story line coastal population 2100 for SSP3	Rank
Insular Pacific-Hawaiian	2 569 510	39	2 921 936	42	1 639 604	43
Southwest Australian Shelf	2 067 494	40	3 036 909	39	1 679 713	40
West-Central Australian Shelf	2 055 745	41	3 019 651	40	1 670 168	41
Newfoundland-Labrador Shelf	1 844 035	42	3 252 182	38	1 662 602	42
Barents Sea	1 101 642	43	1 426 396	44	1 898 857	39
Scotian Shelf	913 809	44	1 630 726	43	833 671	44
Sea of Okhotsk	681 092	45	650 266	46	753 450	45
Norwegian Sea	585 562	46	1 080 509	45	567 227	46
Oyashio Current	412 377	47	322 245	49	201 641	51
Iceland Shelf and Sea	404 432	48	593 600	47	324 328	49
Northeast Australian Shelf	399 548	49	542 371	48	388 747	47
West Bering Sea	196 173	50	230 673	50	371 513	48
Kara Sea	135 355	51	159 159	51	256 336	50
Canadian Eastern Arctic-West Greenland	49 979	52	no data		no data	
Northern Bering-Chukchi Seas	45 969	53	53 116	53	56 641	53
Faroe Plateau	43 668	54	no data		no data	
North Australian Shelf	40 318	55	59 222	52	32 756	55
Laptev Sea	37 888	56	44 551	54	71 753	52
East Siberian Sea	27 383	57	32 199	56	51 858	54
East Bering Sea	26 429	58	30 053	57	16 864	57
Hudson Bay Complex	20 975	59	37 430	55	19 135	56
Northwest Australian Shelf	12 860	60	18 890	58	10 448	58
Beaufort Sea	7 938	61	11 823	59	6 250	59
Aleutian Islands	4 466	62	5 079	60	2, 50	60
Greenland Sea	3 588	63	no data		no data	
Canadian High Arctic-North Greenland	138	64	197	61	100	61
Antarctic			no data		no data	
Central Arctic Ocean			no data		no data	

© Stephen Hass/flickr

Chapter 4
Governance

Lead Authors

Lucia Fanning (Marine Affairs Program, Dalhousie University), Robin Mahon (Centre for Resource Management and Environmental Studies, University of the West Indies)

Contributing Authors

Kimberly Baldwin (Centre for Resource Management and Environmental Studies, University of the West Indies), Selicia Douglas (Marine Affairs Program, Dalhousie University)

Chapter Citation

Fanning, L., Mahon, R., Baldwin, K., Douglas, S. (2016). Chapter 4: Governance: Assessment of governance arrangements for transboundary large marine ecosystems. In IOC-UNESCO and UNEP (2016). *Large Marine Ecosystems: Status and Trends*. United Nations Environment Programme, Nairobi, pp 65–87.

Governance: Assessment of governance arrangements for transboundary large marine ecosystems

SUMMARY

Governance affects what activities people pursue and with what intensity, and if or how value derived from natural systems reaches human communities. As a first step in understanding governance at the Large Marine Ecosystem (LME) level, this assessment evaluates formally established transboundary governance arrangements relevant to fisheries, pollution and biodiversity, including habitat destruction. These arrangements may cover part of the LME, the entire LME, or include all or a part of the LME and extend beyond its boundaries. The assessment looks only at transboundary governance arrangements and their associated architecture, defined as the set of commonly-shared principles, institutions, and practices that affect decision making. It does not evaluate the performance of the governance arrangements, which would require indicators that evaluate whether governance processes are working, stressors are being reduced, ecosystems are sustainable, and, ultimately, whether human well-being is secured or improved.

Three indicators were developed as part of this evaluation of transboundary governance arrangements. The indicators can be used to monitor progress towards good governance in the 49 transboundary (multi-country) LMEs and the Western Pacific Warm Pool (WPWP). Good governance characteristics include the presence of principles of transparency, accountability, collaboration, adaptive management, integration, inclusivity, and participation, principles that are articulated in most current multilateral agreements. The indicators are: **completeness** of the structure of arrangements to address a given issue or issues; **integration** of institutions involved in addressing the suite of identified transboundary issues within a given LME; and **engagement** of countries participating in arrangements that address the identified transboundary issues within the LME. The full analysis that this chapter is based on (Fanning *et al.* 2016) also includes an assessment of the level of 'fit' of arrangements to the geographic area of each LME. For comparison purposes, indicator scores were sorted into five risk categories created by dividing the full range of each indicator into five equal ranges. For all three indicators, the lowest scores represent the highest risk level.

The majority of LMEs have six to eight transboundary issues relating to fisheries, pollution, and biodiversity. Across all the transboundary LMEs and the WPWP, 359 transboundary issues requiring governance arrangements were identified. These are addressed through 347 different arrangements for the implementation of 17 non-binding and 86 binding agreements. The assessment provides a baseline across all LMEs, thereby flagging areas for intervention and for monitoring future changes. The Mediterranean LME has the lowest overall level of risk across the three indicators. This is due in large measure to an overarching integrating mechanism in place to address transboundary areas of concern. Other LMEs with notably low risk levels across the three indicators are the Humboldt Current, Canadian Eastern Arctic-West Greenland Shelf, North Bering-Chukchi Sea, and Beaufort Sea.

Key messages

1. **An average 'medium' risk level for completeness of arrangements across all stages of the policy cycle indicates that there is considerable room for improvement in the design of transboundary governance for LMEs.** Improvements in completeness can be achieved by ensuring that current and new agreements have policy-cycle mechanisms in place that include a wide array of data and information providers, that provide for a strong, knowledge-based policy interface, and that hold decision-makers and those responsible for implementation accountable; and ensuring that monitoring and evaluation mechanisms are implemented, thereby facilitating adaptive management. Some highlights of the analysis of completeness by issue and policy stage are:
    - Fisheries arrangements tend to have high completeness levels but need improvement in levels of institutional collaboration on implementation.
    - Pollution arrangements are low in accountability: few arrangements have repercussions for lack of compliance.
    - Biodiversity arrangements, which are mainly recommendations or decisions that can be opted out of, tend to have the lowest levels of completeness. Accountability is limited for most, and lack of data and information provisions is a serious shortcoming at the LME level.
2. **Levels of institutional integration for arrangements that are in place to address transboundary issues are generally low.** Over 60 per cent of LMEs have very low scores and consequently 'highest' risk levels for this indicator. This points to a need to ensure better collaboration on transboundary governance arrangements if ecosystem-based management is to be effectively implemented in LMEs. The low scores for integration are due mainly to the significant disconnection between organizations involved with fisheries issues in many LMEs and those involved with pollution and biodiversity issues. This finding points to the need to focus efforts on collaboration between these organizations, and/or the creation of overarching integrating mechanisms.
3. **Engagement levels in transboundary arrangements are generally high, reflecting the high level of commitment that countries in LMEs have towards participation in agreements addressing transboundary issues. T**his is positive, but does not guarantee follow-through actions on the part of the countries, especially if there are few to no repercussions for failing to comply with the terms of an agreement. This is of concern since the nature of the agreements, binding or non-binding, influences the level of commitment by countries.

4.1 Introduction

LMEs have been widely adopted as ecologically rational units of ocean space in which ecosystem-based management (EBM) can be applied. The LME approach is based on five modules: Productivity, Fish and Fisheries, Pollution and Ecosystem Health, Socio-economics, and Governance (Sherman and Duda 1999). As usually presented, these modules provide a framework for an indicator-based approach to assessing and monitoring LMEs. Some modules have received more attention than others, both in their conceptualization and in their practical implementation. The Socio-economics and Governance modules are the least well-developed (Sherman *et al.* 2005). To remedy this, greater focus has been placed in recent years on assessing socio-economic and governance characteristics of LMEs (Mahon *et al.* 2010; Hoagland and Jin 2008; Fanning *et al.* 2007; Olsen *et al.* 2006). Mahon *et al.* (2011a) also argued that an indicator category of governance architecture is needed. Assessment of this indicator should precede assessment of the governance process.

This chapter is mainly concerned with the assessment of arrangements for governance at the LME level and its overarching architecture, defined by Biermann and Pattberg (2012) as the set of commonly-shared principles, institutions, and practices that affect decision making. It is based on a more comprehensive report by Fanning *et al.* (2016) which should be consulted for additional information on methodology, terminology, and details of the analyses. Key terms used in this chapter are explained in Box 4.1.

Box 4.1 Explanation of key governance terms used in this chapter

Agreement refers to the multilateral documentation pertaining to any of the key focus areas of the assessment (pollution, fisheries, biodiversity, and habitat modification) with direct relevance to the LME. The term is limited to the content of the document outlining the goals, objectives and clauses detailing the terms and conditions of the agreement.

Arrangement refers to the formal documentation and the institutional structures that have been put in place to implement an agreement.

Effective governance refers to the extent to which societal well-being has been achieved.

Good governance refers to the extent to which the stages of the policy process are in place for each arrangement (level of completeness), whether opportunities exist to facilitate ecosystem-based management (level of integration) and whether or not countries are engaging in existing agreements that are put in place to address transboundary issues (level of engagement). This evaluation is based on criteria that are considered to reflect good governance. They are based mainly on operational principles, such as transparency, accountability, participation, and efficiency, that are considered desirable and that appear in the preambles to many multilateral environmental agreements.

Policy cycle refers to the iterative process of decision making. A generalized cycle includes the provision of relevant data and information that are then provided in the form of analysis and advice to those making decisions. These decisions are then implemented, monitored, and evaluated to determine the level of success in addressing the problem for which the cycle was initiated.

Risk refers to the perceived degree to which the governance indicator might negatively affect processes leading to good governance.

Transboundary issue refers to an area of concern, for example, over-exploitation of fish stocks, marine-based pollution, or loss of biodiversity, that has been identified and documented as affecting more than one country within a given LME and which should be addressed by a clear and distinct policy process.

Understanding the suite of transboundary arrangements relating to an LME may help to determine the best approaches to developing integrated, coordinated, LME-level governance. To that end, this LME governance assessment focuses on the governance arrangements in each transboundary LME (an LME bordered by two or more coastal countries). The assessment is conducted using the TWAP Level 1 governance assessment methodology (Jeftic *et al.* 2011; Mahon *et al.* 2011b), which is described in detail in the full assessment report on which this chapter is based (Fanning *et al.* 2016). This assessment includes all 49 transboundary LMEs and the Western Pacific Warm Pool. Thirty-six of these areas are eligible under Global Environment Facility (GEF). LMEs that are bordered by a single country, regardless of their GEF eligibility, are not included.

By assessing the suite of arrangements addressing the key issues for each LME, gaps and weaknesses in governance architecture can be identified. In this chapter, we report on the entire set of arrangements present within 49 LMEs and the Western Pacific Warm Pool to determine the issues they cover, and the interrelations among the arrangements. Additional analysis of how well the arrangements fit with the geographic area of each LME is reported in an expanded report by Fanning *et al.* 2016. Several of these LMEs have used the GEF International Waters transboundary diagnostic analysis (TDA) and strategic action programme (SAP) processes, identified as an innovative approach introduced by the GEF as a global-scale framework for prioritizing and implementing ecosystem-based governance. While this study recognizes this approach by the GEF in a subset of the LMEs examined, the focus in the TWAP Level 1 governance assessment is on assessing the LMEs at the level of formally established transboundary governance arrangements. The analysis does not include SAPs as formal international agreements because they are project outputs with a set time-frame. However, it does include assessment of any permanent formal outputs of the SAP, such as a transboundary agreement that establishes a commission.

Fanning *et al.* (2007) developed the Large Marine Ecosystem Governance Framework, a conceptual model based on nested policy cycles at multiple levels (local to global) with vertical and horizontal links providing the basis for interplay. The policy cycles comprised five stages considered to be important for adaptive governance: development and provision of advice, decision making, implementation, review and generation, and management of data and information. For two stages, advice and decision making, having sufficient capacity at both the policy level and the management/planning or operational level is important, hence the need to assess these two stages at both the strategic, policy level, and the operational level. The Level 1 governance assessment evaluates whether the critical transboundary issues are covered by governance arrangements that have full policy cycles and a level of integration across the different arrangements in place to address these concerns (Mahon *et al.* 2011b). It is expected to reveal the extent to which the issues are covered, whether there are gaps or overlaps in coverage, and the nature of the arrangements that are in place. The assessment does not evaluate the performance of the arrangements. This would require indicators that determine whether governance processes are working, stressors are being reduced, ecosystems are sustainable, and, ultimately, whether human well-being is secured or improved.

This assessment of governance arrangements for LMEs includes an evaluation of the completeness of the policy cycle, the extent to which there is provision for each stage of the policy process in each arrangement. The evaluation of the completeness indicator is based on criteria that are considered to reflect good governance, including characteristics such as principles of transparency and integration in the decision-making process; inclusivity and participation in the provision of policy-relevant and management-level advice from a cross-section of stakeholders to inform decision making; collaboration and efficiency to assist with implementation; and accountability and adaptive management in terms of monitoring and evaluation. We emphasize that, while the presence of policy processes that meet good governance criteria might be expected to result in better outcomes and impacts, the ultimate tests of effective governance, a causal link between good governance processes and effective governance has not been conclusively demonstrated. As noted above, the criteria for good governance that are used to evaluate the policy processes for the arrangements are based mainly on operational principles that are considered desirable and appear in the preambles to many multilateral environmental agreements.

In addition to the completeness indicator, three analyses relevant to governance architecture were conducted for each selected LME. These are: the level of integration across the organizations responsible for implementing arrangements in place to address the different transboundary issues within a given LME (integration indicator); the level of country engagement in agreements pertaining to issues within the LME (engagement indicator); and the fit of each arrangement for transboundary issues within an LME to the areal extent of the LME. While all four types of analysis contribute to an increased understanding of LME governance architecture, the analysis of fit is not discussed in this chapter, because of space limitations. The full report of the analyses by Fanning *et al.* (2016) can be consulted for additional information on all four indicators. Overall, we have learned that it is a complex process to assess the governance systems of LMEs which are based on an ecosystem management approach rather than being drawn *“according to legal, political, or economic facts”* (Rothwell and Stephens 2010).

The three indicators of governance arrangements reported in this chapter were assessed on the basis of a percentage score for the completeness and engagement indicators, or a decimal score ranging from zero to 1 for the integration indicator. For comparison purposes, the scores were distributed to five categories of risk created by dividing the full possible range of each indicator into five equal ranges (Table 4.1). The risk categories are inversely related to the scores, based on the assumptions that the more complete governance processes are, the more countries are actively engaged in participating in agreements to address transboundary issues within the LME; and the more integrated organizations involved in implementing these agreements are, the more is it likely that processes that meet good governance criteria will be in place. However, the assigned risk category does not necessarily correspond to the level of degradation of the LME based on the governance arrangements in place. This is because the level of degradation and impact on the LME reflects the performance of governance arrangements. This study does not assess governance effectiveness; it assesses the structure or architecture of the governance arrangements to facilitate good governance.

Table 4.1 Risk categories and ranges for the three indicators

Risk rank	Completeness range	Integration range	Engagement range
Lowest	80–100%	0.8–1.0	80–100%
Low	60–80%	0.6 –0.8	60–80%
Medium	40–60%	0.4–0.6	40–60%
High	20–40%	0.2–0.4	20–40%
Highest	0–20%	0.0–0.2	0–20%

4.2 Main findings and discussion

4.2.1 Summary of results by LME and the WPWP

The 49 transboundary LMEs and the WPWP evaluated in this assessment are compared in Table 4.2, based on the scores for the indicators of completeness, integration, and engagement, and on the associated risk levels. The plethora of combinations across the three indicators for individual LMEs suggests the need for further exploration of possible correlations between these indicators. Based on the overall analysis, the Mediterranean LME shows the lowest level of risk across the three indicators, with high completeness scores and very high integration and engagement scores. This is due in large measure to the presence and nature of an overarching integrating mechanism in place to address transboundary areas of concern.

Table 4.2 Number of arrangements, and scores and risk levels for completeness, integration, and engagement indicators for transboundary LMEs and the WPWP. Colour codes indicate lowest (blue), low (green), medium (yellow), high (orange) and highest (red) risk levels. These risk categories are defined in Table 4.1.

a) **LMEs**

LME nam0e	Number of arrangements	Completeness (%)	Integration (0.0-1.0)	Engagement (%)
East Bering Sea	7	70	0.1	93
California Current	6	50	0.0	89
Gulf of Mexico	7	58	0.2	81
Southeast US Continental Shelf	4	65	0.2	81
Northeast US Continental Shelf	6	49	0.0	75
Scotian Shelf	6	50	0.0	63
Newfoundland-Labrador Shelf	6	50	0.0	63
Pacific Central American Coastal	9	65	0.1	85
Caribbean Sea	9	60	0.2	68
Humboldt Current	8	68	1.0	88
Patagonian Shelf	7	82	0.2	58
South Brazil Shelf	4	36	0.0	100
North Brazil Shelf	8	58	0.2	74
Canadian Eastern Arctic-West Greenland Shelf	7	72	1.0	80
Greenland Sea	13	74	0.1	75
Barents Sea	11	74	0.1	75
Norwegian Sea	8	76	0.1	83
North Sea	11	73	0.1	62
Baltic Sea	5	61	0.1	61
Celtic-Biscay Shelf	9	74	1.0	59
Iberian Coastal	9	74	1.0	44

LME nam0e	Number of arrangements	Completeness (%)	Integration (0.0-1.0)	Engagement (%)
Mediterranean	9	78	1.0	85
Canary Current	7	46	0.2	80
Guinea Current	6	54	0.2	78
Benguela Current	6	80	1.0	71
Agulhas Current	7	47	0.1	69
Arabian Sea	9	45	0.1	86
Red Sea	5	52	0.2	65
Bay of Bengal	10	50	0.1	87
Gulf of Thailand	6	50	0.1	75
South China Sea	6	50	0.1	68
Sulu-Celebes Sea	6	50	0.1	71
Indonesian Sea	7	52	0.1	56
North Australian Shelf	6	51	0.1	80
East China Sea	5	43	0.1	83
Yellow Sea	5	33	0.5	83
Kuroshio Current	3	56	0.3	100
Sea of Japan	5	30	0.5	88
Oyashio Current	3	30	0.3	100
Sea of Okhotsk	2	38	0.9	100
West Bering Sea	4	60	0.3	100
North Bering-Chukchi Sea	5	69	1.0	100
Beaufort Sea	3	67	1.0	100
Iceland Shelf	10	78	0.1	90
Faroe Plateau	8	77	1.0	71
Antarctic	8	70	1.0	59
Black Sea	6	77	0.1	74
Central Arctic Ocean	11	73	1.0	78
Canadian High Arctic-North Greenland Shelf	10	77	1.0	75

b) **Western Pacific Warm Pool**

	Number of arrangements	Completeness (%)	Integration (0.0-1.0)	Engagement (%)
WPWP	5	51	1.0	64

4.2.3 Identification of issues and arrangements

In order to classify key transboundary issues or areas of concern identified within the LMEs, ten subcategories relating to fisheries, pollution, and biodiversity were identified. Of these, five are related to fisheries (highly migratory, within the EEZ, in areas beyond national jurisdiction (ABNJ), in both EEZ and ABNJ, and specific species), two to pollution (land-based sources and marine-based sources) and three to biodiversity (general, habitat, and specific). A total of 359 transboundary issues requiring governance arrangements were identified from documentation across the 49 LMEs and the WPWP, and grouped according to their geographic regions (Annex Table 4-A). These issues are addressed through 347 different arrangements for the implementation of 17 non-binding and 86 binding agreements. Raw data for each LME and the WPWP are available in the web-accessible governance database for all measures of governance discussed in this chapter.

The frequency distribution of the LMEs by number of issues shows that the majority of LMEs have six to eight transboundary issues relating to fisheries, pollution, biodiversity, and their subcategories (Figure 4.1). The Greenland Sea LME has 13 identified transboundary issues, followed closely by the Barents Sea, Central Arctic Ocean, North Sea, and the Bay of Bengal. In these five LMEs, all three broad categories of issues are represented, although the subcategory ABNJ is absent in all of them. Given that some 66 per cent of the Central Arctic LME is considered High Seas, ABNJ fisheries could be an area of concern if fisheries activities there were to increase due to climate change. Likewise, given the almost one million km^2 of High Seas in the Bay of Bengal, the absence of arrangements dealing with fisheries in ABNJ indicates a need for the countries in that LME to address this issue. At the other end of the spectrum, only two transboundary issues were identified for the Sea of Okhotsk LME in the West Pacific, one dealing with land-based and one with marine-based sources of pollution.

Figure 4.1 Frequency distribution of LMEs by number of transboundary issues (including the WPWP). The results demonstrate a typical normal distribution in which more than half the LMEs have between 6 and 8 transboundary issues related to fisheries, pollution, and biodiversity. At the two extremes, the Greenland Sea had the most transboundary issues to address (13) while for the Sea of Okhotsk only 2 issues were identified, both related to pollution.

Each of the five LMEs lacking pollution arrangements (California Current, Newfoundland and Labrador Shelf, Northeast US Continental Shelf, Scotian Shelf, and South Brazil Shelf) has only two coastal countries. For all these LMEs except the California Current, the majority of the maritime domain, as much as 99 per cent, rests with one of the two countries. It may therefore be that pollution issues are dealt with by the country that dominates the LME. The extent to which this may be the case, or to which informal bilateral arrangements may exist, should be clarified. In contrast, the two countries in the California Current LME have several non-governmental and multi-partnered organizations that work on pollution issues. While no identifiable transboundary agreement was found to prevent or address land-based or marine-based sources of pollution, the two countries have a long history of working together. In fact, each has an operational plan for mobilizing action to address marine spills once an incident has occurred in each other's EEZ that might threaten the other's maritime and coastal environment.

This preliminary analysis indicates that, from a governance architectural perspective, many arrangements in many of the LMEs were found to be wanting. The assessment provides a baseline across all LMEs, thereby flagging areas for intervention and for monitoring future changes.

4.2.4 Assessing level of completeness

The completeness level of the 347 arrangements in place for governing the 359 transboundary issues across all LMEs and the WPWP was analysed in the full report (Fanning *et al.* 2016) by individual LME level, issues, policy-cycle stage, regions, and jurisdictional levels for each policy-cycle stage. This chapter includes only the results for the first three analyses.

Completeness was assessed by reviewing each arrangement in place in the LME or WPWP for a given transboundary issue and assigning a score based on a scale of 0 to 3 on the level of completeness for each stage of the policy cycle (see the methodology and analysis section for scoring criteria). The scores for each arrangement in the LME were then calculated and averaged to achieve an LME-level score. A similar approach was used to determine the level of completeness by issues and policy-cycle stages.

4.2.4.1 Completeness by individual LMEs and the WPWP

The frequency distribution of average completeness for the arrangements in place to address the suite of identified issues in each LME and the WPWP is presented in Figure 4.2. A global comparison of the completeness indicator for the transboundary LMEs and the WPWP is shown in Figure 4.3. One LME (Patagonian Shelf) is assessed as having 'lowest' level of risk for completeness, 22 LMEs have a 'low' level of risk, 21 LMEs and the WPWP have a 'medium' level of risk, and 5 LMEs are assessed as having a 'high' level of risk. None of the LMEs have a 'highest' level of risk. The overall global average for the completeness score for the 49 transboundary LMEs and the WPWP is 59 per cent, corresponding to a 'medium' risk level, suggesting considerable room for improvement in the design of arrangements in terms of the completeness of the stages of the policy cycle to address key transboundary areas of concern.

Figure 4.2 Frequency distribution of LMEs by average per cent completeness of all arrangements in each LME (including the WPWP). Completeness was assessed by reviewing each arrangement in place in the LME or WPWP for a given transboundary issue and assigning a score based on a scale of 0 to 3 on the level of completeness for each stage of the policy cycle. The overall average score for each LME or the WPWP was converted to a per cent score. Forty of the LMEs were assessed as having a score of 50% or greater.

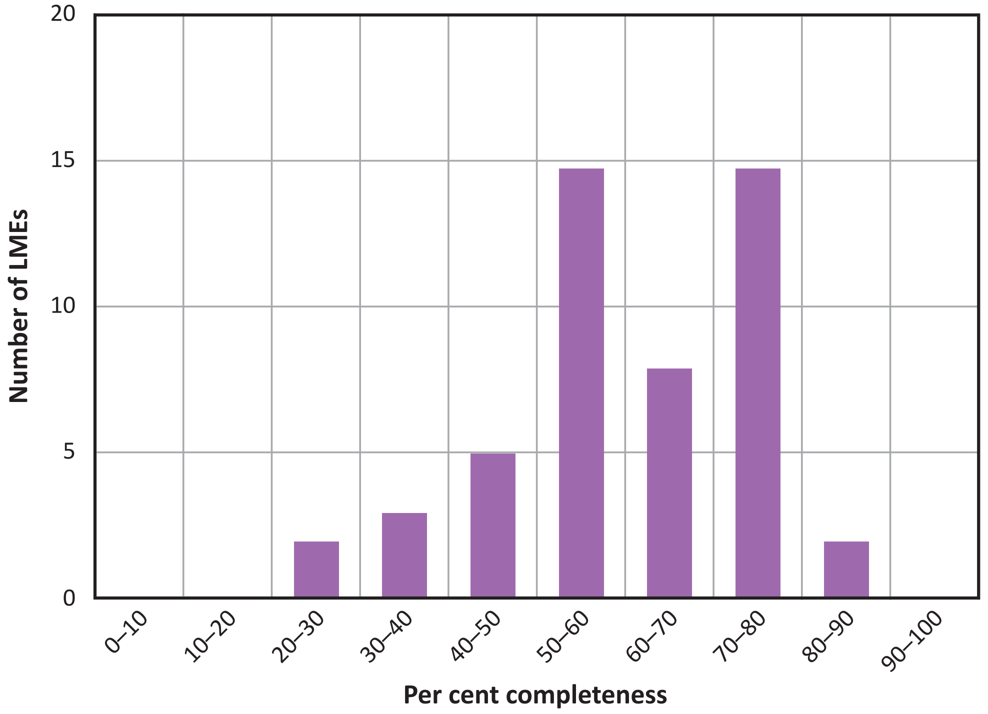
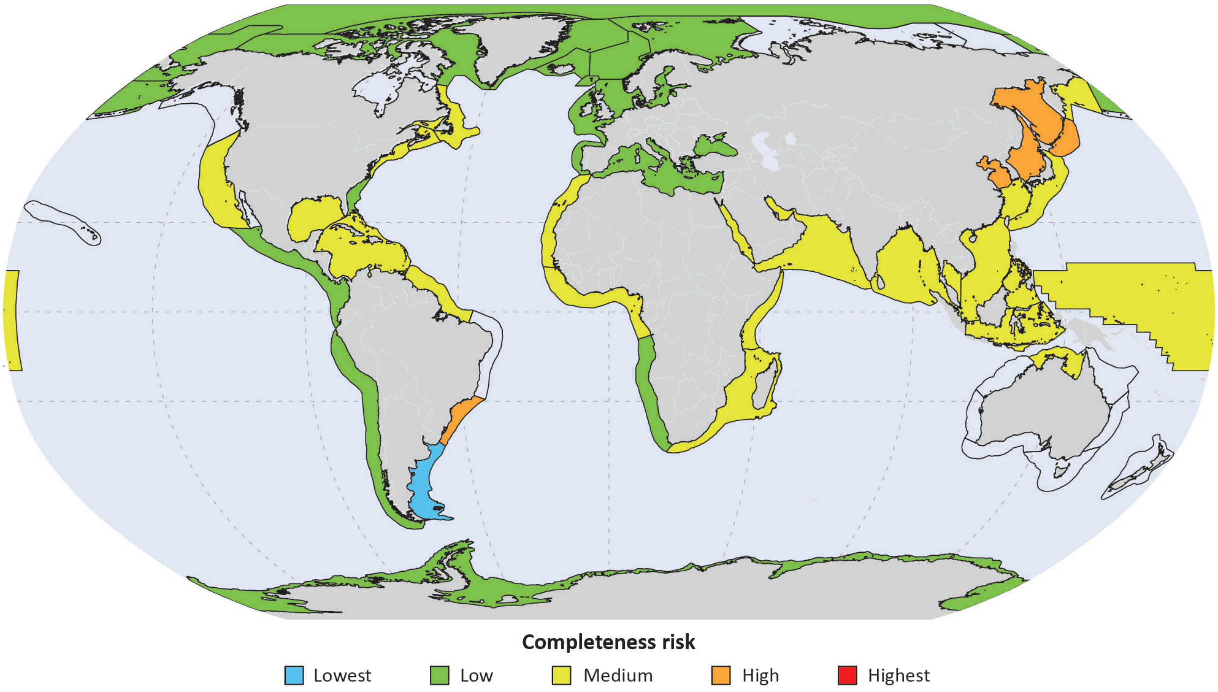


Figure 4.3 Global distribution of levels of completeness and perceived risk for 49 transboundary LMEs and the WPWP. A global comparison of the completeness indicator shows 1 LME (Patagonian Shelf) as having 'lowest' level of risk for completeness, 22 LMEs have a 'low' level of risk, 21 LMEs and the WPWP have a 'medium' level of risk, and 5 LMEs are assessed as having a 'high' level of risk, including the South Brazil Shelf LME. The remaining 4 'high' risk LMEs were found in the western Pacific (Yellow Sea, Sea of Japan, Sea of Okhotsk and Oyashio Current). None of the LMEs have a 'highest' level of risk. The overall average for the completeness score corresponds to a 'medium' risk level, suggesting considerable room for improvement in the design of arrangements in terms of the completeness of the stages of the policy cycle to address key transboundary areas of concern.

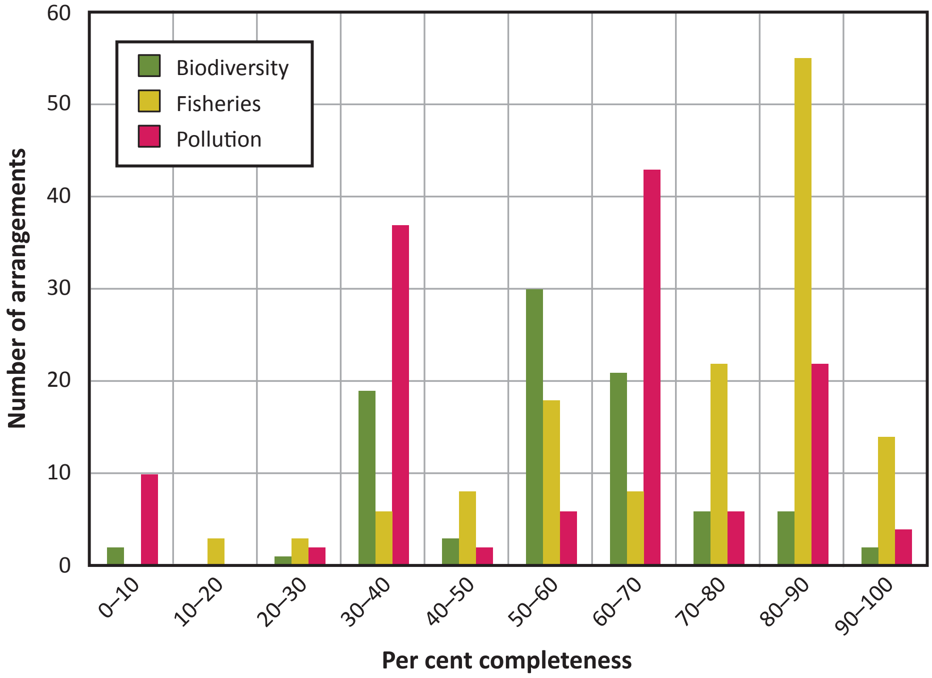


© IMO/flickr

4.2.4.2 Completeness by issues

Fisheries arrangements account for 137 of the 359 issues and show the highest level of completeness (Figure 4.4), especially arrangements that are binding and focus on highly migratory species or other specifically targeted species. Arrangements related to transboundary pollution, regardless of subcategory, show the second highest level of completeness. In general, biodiversity arrangements show the lowest completeness. As is the case for pollution, there are LMEs with no formal transboundary arrangements in place for general biodiversity concerns. Only 88 arrangements were identified as addressing the 90 biodiversity issues in the 49 LMEs and the WPWP.

Figure 4.4 Completeness distribution of fisheries, pollution, and biodiversity arrangements across all LMEs and the WPWP. Fisheries arrangements (137 of a total of 347 transboundary arrangements) show the highest level of completeness; 67 of the 137 are rated at 80–100 per cent for completeness. Arrangements related to transboundary pollution issues show the second highest level of completeness, while biodiversity arrangements scored the lowest.

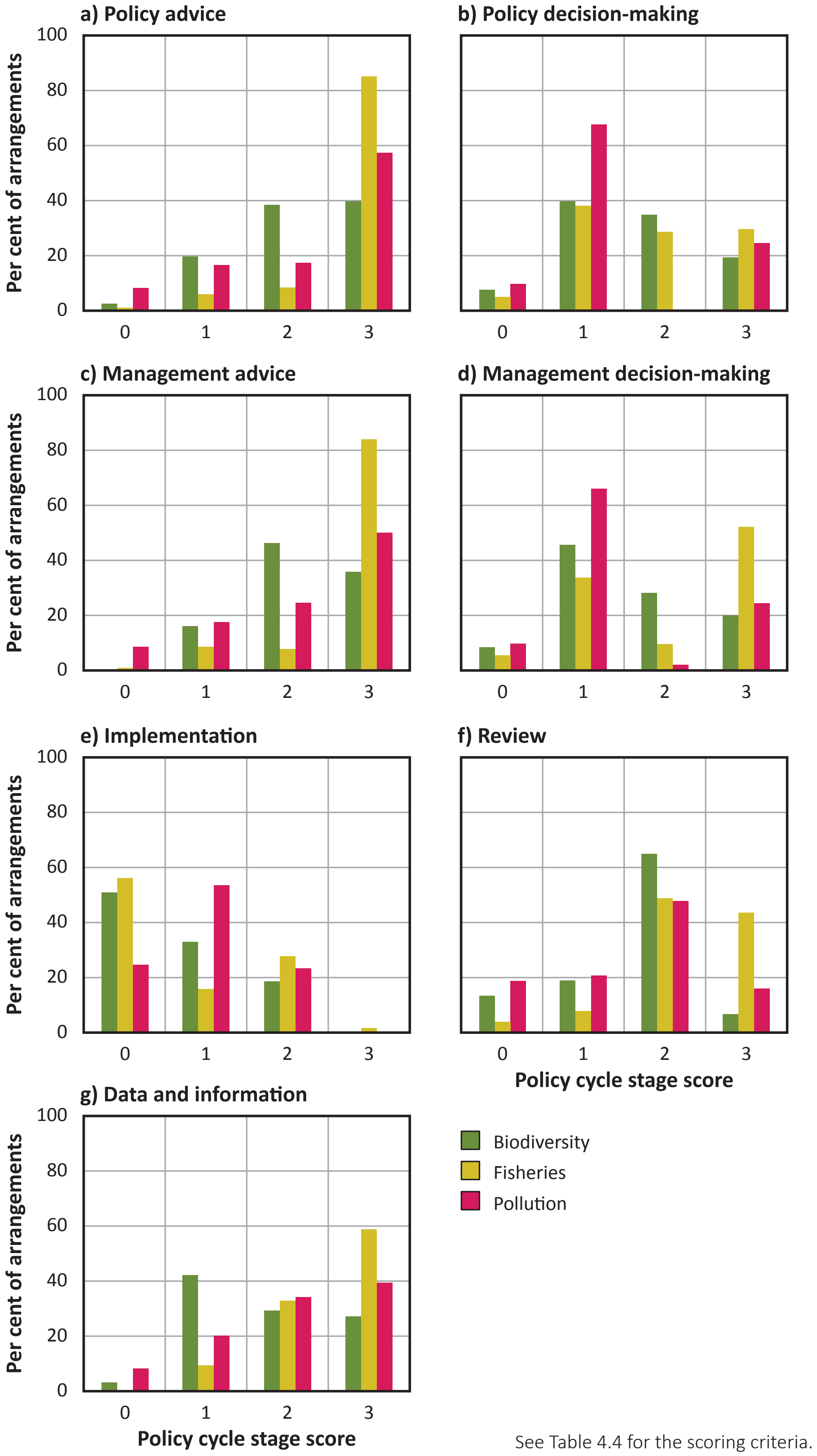


4.2.4.3 Completeness by policy-cycle stage scores

The analysis of policy-cycle stage scores by issue shows differences in strength among issues (Figure 4.5). For policy and management advice stages (Figure 4.5(a) and (c)), the distribution of scores appears similar among issues, although scores for fisheries and pollution arrangements are higher than for biodiversity arrangements. This may be due to the number of agreement for fisheries and pollution that have clearly defined science–policy mechanisms, compared to biodiversity agreements in which the science–policy interface is often identifiable but not specified in the agreement.

For both policy and management decision-making stages (Figure 4.5(b) and (d)), fisheries arrangements clearly score highest, with decisions made for pollution being mainly recommendations for contracting parties, while biodiversity mechanisms are mainly recommendations or decisions that contracting parties can choose to opt out of. In contrast, more than half of the fisheries arrangements have no involvement in implementation, which is mainly at the level of contracting parties. Thus fisheries arrangements score the lowest among the three categories of issues for the implementation stage (Figure 4.5(e)). The high number of fisheries arrangements with a score of two is attributed to the regional-level support in place for highly migratory and ABNJ species. The majority of the arrangements, regardless of issues, have regional review (score of 2) included in the agreements (Figure 4.5(f)), but few pollution and biodiversity arrangements have review mechanisms with built-in repercussions for non-compliance (score of 3).

Figure 4.5 The distribution of scores for each of the seven policy-cycle stages for arrangements addressing fisheries, pollution, and biodiversity across all LMEs and the WPWP. Differences across stages of the policy cycle are displayed, highlighting where attention should be focused to promote good governance in arrangements addressing fisheries, pollution and biodiversity. In general, the implementation stage appears to be the weakest for all three issue categories. This analysis points to specific areas that require action – for example the need to strengthen the review stage for pollution and biodiversity arrangements.



See Table 4.4 for the scoring criteria.

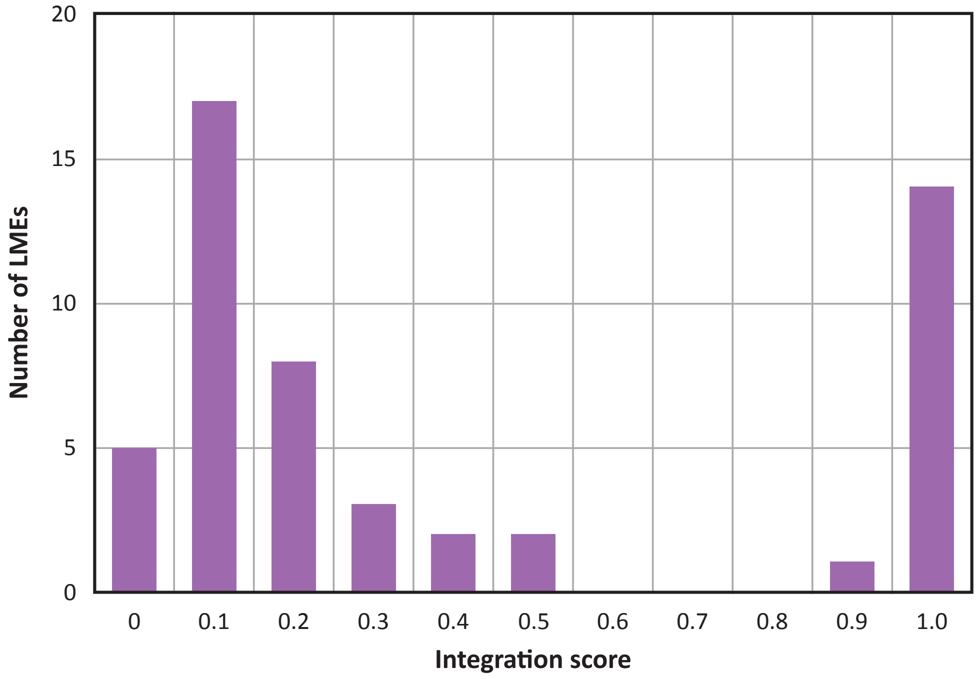
For the data and information stage of the policy cycle (Figure 4.5(g)), almost half of the fisheries agreements specify mechanisms that include centralized review and checking of the data prior to distribution for use by contracting parties. Thus, the highest scores for this stage are awarded to fisheries arrangements. This is probably because, for transboundary stocks, it is necessary to bring data together if meaningful analysis is to be carried out. Biodiversity and pollution arrangements display the full range of mechanisms, from no data and information mechanism, to a few arrangements requiring data and information to be centrally collected and managed. However, national reporting and compilation of national reports, without additional quality control at the regional level, appear to be the most common arrangements for biodiversity issues, while the majority of fisheries and pollution agreements have regional-level review. This is probably because of the accepted, inherent transboundary nature of pollution and fisheries.

Overall, the differences among policy-cycle stages and issues shown in Figure 4.5 provide insight into where attention should be focused to promote good governance. For fisheries, attention to collaboration in implementation of measures is clearly needed. For pollution, the analysis points to the need for strengthening agreement in the area of accountability, since few of these arrangements have any repercussions associated with lack of compliance. For biodiversity, a high proportion of agreements show both limited accountability requirements and the lack of data and information requirements at the regional level, which may be a serious shortcoming for addressing this issue at the LME level.

4.2.5 Level of integration as a proxy for implementing an EBM approach

The analysis of integration across the arrangements within each LME and the WPWP was done in two steps, resulting in a bimodal distribution (Figure 4.6). The first step was to determine whether countries in the region had developed an overarching integrating mechanism to address transboundary issues. If so, a score of 1 was assigned for integration. If not, scores for integration across all the arrangements within a given LME or the WPWP were derived, based on

Figure 4.6 Distribution of integration scores for LMEs (including the WPWP). Integration was assessed by reviewing the organizational responsibility assigned to each stage of the policy cycle for each arrangement in place for addressing transboundary issues within an LME or for the WPWP. A score of 0 was assigned if different organizations were responsible for the identified transboundary issues at a given policy cycle stage, and a score of 1 was assigned if the same organization was identified as being responsible or the LME had an integrating mechanism in place. The bi-modal distribution illustrates the generally poor level of integration among transboundary issues within 35 of the LMEs, while some 14 LMEs and the WPWP had an integrating mechanism in place.



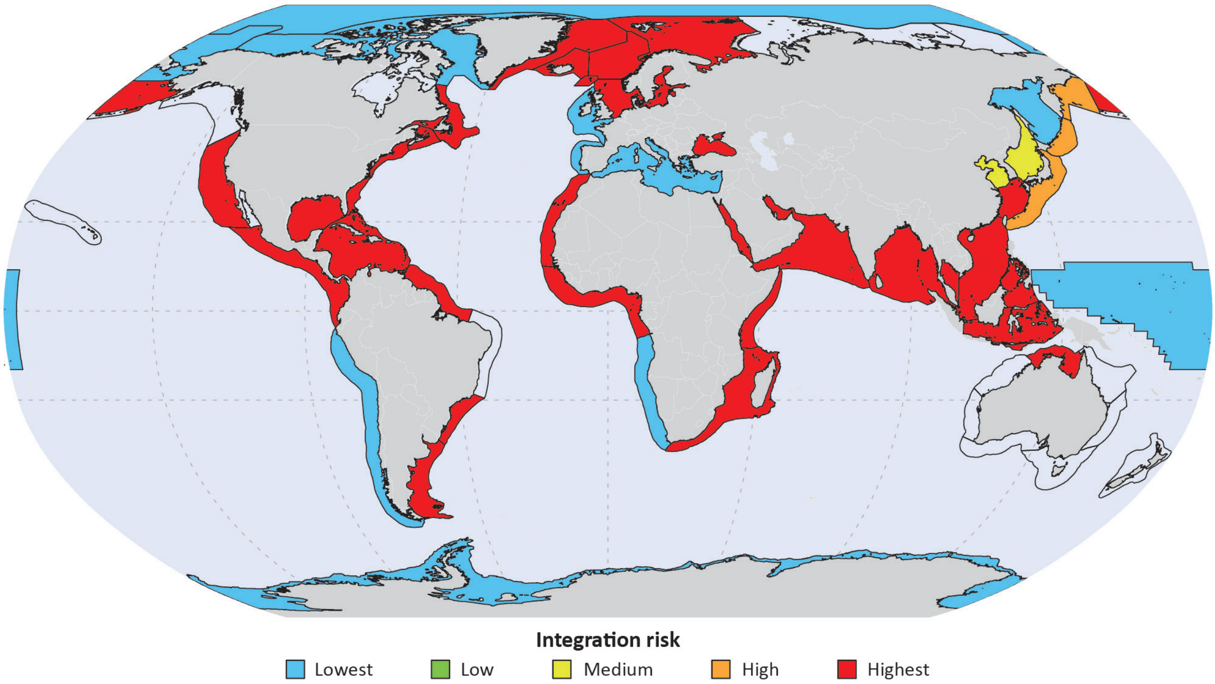


Figure 4.7 Global distribution of levels of integration and perceived risk for 49 transboundary LMEs and the WPWP. A global comparison of the integration indicator assigns the 'lowest' level of risk to six LMEs in the North Polar region; the Antarctic, Benguela Current, Humboldt Current, and Mediterranean LMEs; LMEs adjacent to countries in the European Union; and the Western Pacific Warm Pool, with its Pacific Islands Forum and Council of Regional Organizations of the Pacific. In contrast, 31 LMEs were assigned the highest level of risk, indicating that an individual sectoral approach to developing and implementing issue-specific agreements may be in place for these LMEs.

identifying the organizations responsible for each stage of the policy cycle for each of the arrangements in place to address all transboundary issues within the LME or the WPWP. A score of 0 was assigned if different organizations were responsible for the identified transboundary issues at a given policy cycle stage, and a score of 1 was assigned if the same organization was identified as being responsible. The average of the scores for all arrangements was then calculated as the integration score for the LME. Details on the methodology for scoring integration levels is provided by Jeftic *et al.* (2011). A global comparison of the integration indicator among the 49 assessed transboundary LMEs and the WPWP is shown in Figure 4.7.

Based on these final integration scores, 13 LMEs and the WPWP are in the highest category, corresponding to the 'lowest' level of risk. Prominent among these are the six LMEs located mainly beyond the Arctic Circle in the North Polar Region, where the Arctic Council is considered to be the overarching integrating mechanism. Others are the Antarctic LME, with the Antarctic Treaty System; the Benguela Current, with its Commission; the Humboldt Current, in which the Permanent Commission for the South Pacific connects the work of the Lima Convention with that of the living marine resources Convention and its action plan; the Mediterranean, with its Mediterranean Commission for Sustainable Development; the LMEs encompassing countries in the European Union; and the Western Pacific Warm Pool, with its Pacific Islands Forum and Council of Regional Organizations of the Pacific.

For the remaining LMEs the arrangements in place for addressing transboundary issues share few organizations across similar stages of their policy cycles. The 'highest' level of risk with respect to integration is assigned to 31 LMEs. This suggests that an individual sectoral approach to developing and implementing issue-specific agreements may be involved. Awareness of the level of integration may help target interventions to promote ecosystem-based management (EBM) within a specific LME, especially if agreements allow for amendment.

For LMEs and the WPWP that show a high degree of integration (a preliminary indication of good architectural design), further analysis is required to understand the basis for this score. A high score for integration may result when only a few issues are dealt with by a few individual arrangements, as is the case for the Sea of Okhotsk. It may also be due to the genuine effort on the part of countries within an LME or regional grouping to develop and implement mechanisms that facilitate EBM. This appears to be the case for the 14 LMEs where increased attention to the principles of integration and EBM has led to the establishment of an integrating policy-setting mechanism that serves as an umbrella for the issue-specific arrangements in the LME. The benefits and challenges of such an approach will need to be evaluated for each LME. This will require additional input from regional experts to determine whether this should be pursued as a goal across all LMEs, or whether context will serve to limit its application in some LMEs.

Based on a current understanding of the importance of context for evaluating good governance, there is no *a priori* criterion for the extent of integration that would be considered optimal. Nonetheless, the assumption underpinning the indicator is that, without attention to links and interactions between arrangements, it will be difficult to achieve the integrated approach within a system that is needed for EBM. However, in a system with highly diverse issues, one would not necessarily expect all issues to be covered by the same responsible bodies. In fact, depending on complexity and capability, it may be more effective and flexible for arrangements in an LME to have a common responsible organization at the policy-setting stage, but different responsible organizations at technical and operational policy-cycle stages. The results for integration across the LMEs provide some evidence that both scenarios are in play.

4.2.6 The role of country engagement in the assessment of good governance

A total of 103 agreements were identified for the 49 LMEs and the WPWP: 17 non-binding, collaborative agreements and 86 binding agreements, including protocols. Most areas, 32 out of 50, have both binding and non-binding agreements, while 17 LMEs have only binding agreements, and one LME has only a non-binding agreement. Recognizing that the same agreement may be present in more than one arrangement, the 17 non-binding agreements contribute to 70 arrangements, while the 86 binding agreements contribute to 272 arrangements.

© Stephen Hass/flickr

The analysis shows that levels of engagement in LMEs are higher for non-binding than for binding agreements (Figure 4.8). This may be explained by the higher level of accountability expected for binding agreements.

A global comparison of the engagement indicators for the 49 transboundary LMEs and the WPWP is shown in Figure 4.9. Detailed scores for engagement by countries in agreements addressing transboundary areas of concern within a given LME show that none of the LMEs or the WPWP has engagement levels of less than 40 per cent, indicating that none has a 'high' or 'highest' risk level with respect to engagement.

Transboundary agreements were further analysed to determine whether the nature of the agreements (binding or non-binding) affects the level of country engagement. All binding agreements have at least one LME-level arrangement in which none of the countries are engaged (Figure 4.10), which points to a need to assess the reason for this lack of engagement.

For biodiversity arrangements, there is no difference between the levels of engagement in binding and non-binding agreements. Engagement levels range from 0 to 100 per cent, with a median of approximately 60 per cent (Figure 4.10). In contrast, engagement levels for binding arrangements for fisheries range from 0 to 100 per cent, with over half being over 80 per cent, while engagement levels for non-binding fisheries arrangements range from over 80 to 100 per cent, with three-quarters having an engagement score of 100 per cent.

For the binding pollution arrangements, the findings were similar to those for binding fisheries arrangements, with more than half of arrangements having engagement levels of over 80 per cent. No pollution agreements are non-binding, probably because most are protocols under Regional Seas Conventions. This explanation is also applicable to the 56 general binding arrangements addressing more than one issue: most are Regional Seas conventions. All the general non-binding arrangements have 100 per cent engagement levels, suggesting the need to thoroughly

Figure 4.8 Level of overall country engagement in binding and non-binding agreements by number of LMEs (including the WPWP). Engagement was assessed by reviewing the number of eligible countries engaging in relevant binding and non-binding agreements addressing identified transboundary issues in a given LME. It was calculated as a percentage to determine an engagement level across all eligible countries in the LME. The analysis revealed that fewer LMEs were committing to higher levels of engagement for binding agreements than for non-binding agreements. This may be explained by the higher level of accountability expected for binding agreements as compared to a non-binding agreement.

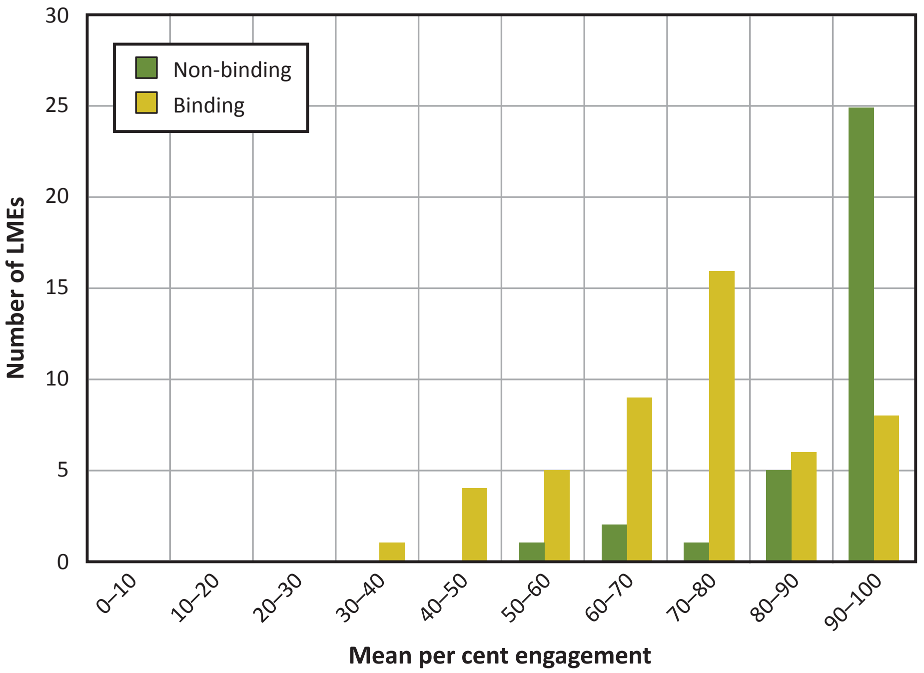


Figure 4.9 Global distribution of levels of engagement and perceived risk for 49 transboundary LMEs and the WPWP. A global comparison of the engagement indicators for the 49 transboundary LMEs and the WPWP show that all have engagement levels greater than 40 per cent; no LMEs are assigned a 'high' or 'highest' risk level.

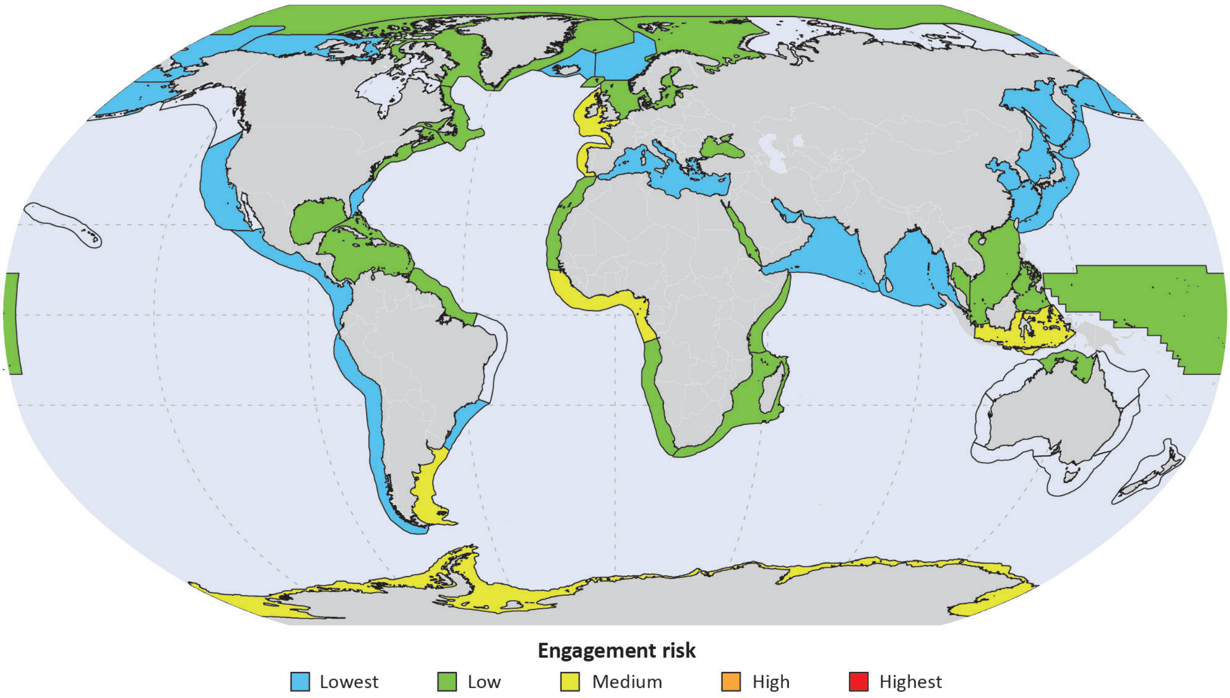
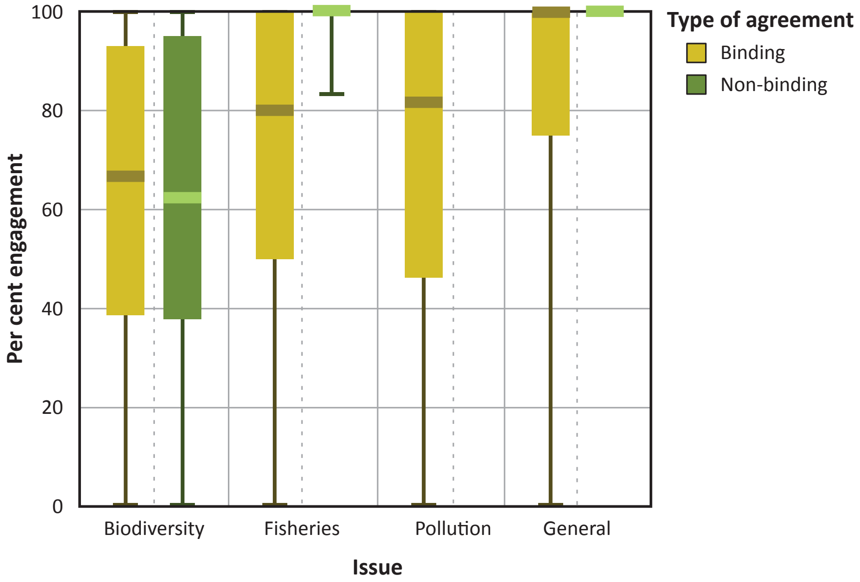


Figure 4.10 Per cent engagement by countries in binding and non-binding agreements for transboundary issues. Overall, the analysis shows that binding agreements have a lower level of engagement than non-binding agreements, regardless of the issue they address. The effort needed by countries engaged in binding agreements to comply with the conditions of the agreement may explain this finding, but this needs to be verified. Despite this, the research has identified that the overwhelming majority of agreements formulated to address transboundary issues are binding: all agreements for pollution, 83 per cent for fisheries, and 70 per cent for biodiversity.



For each category, the vertical line extends from the lowest to the highest value, the horizontal line is the median value, and the colour bar covers the 25th to 75th percentile range of values.

understand the generic and context-specific factors that may account for this success. The high level of engagement in non-binding fisheries agreements provides empirical support to the notion that 'softer' collaborative arrangements may play an important role in achieving regional-level governance outcomes. However, confirmation will require an assessment of the effectiveness of these different types of agreements.

Overall, the analysis shows that binding agreements have a lower level of engagement than non-binding agreements, regardless of the type of issue they address. The effort needed by countries engaged in binding agreements to comply with the conditions of the agreement may explain this finding, but this needs to be verified. Despite this, the research has identified that the overwhelming majority of agreements formulated to address transboundary issues are binding: all agreements for pollution, 83 per cent for fisheries, and 70 per cent for biodiversity.

The assessment of engagement as a measure of good governance focusing on principles of inclusivity, participation, and accountability, points to the need to understand why the developers of policy instruments promote binding agreements over non-binding ones, despite the lower level of engagement. The literature on governance complexity would suggest that, rather than generalizing that one form of agreement is better over another, a more effective, albeit demanding, approach is to examine the context specificity of each LME or group of LMEs, prior to establishing the nature of agreements to address transboundary issues (Mahon *et al.* 2010). Such an approach should also be informed by views of governance (going back some 20 years) that stress that *"governance is more than just government"* (Rosenau 1995). The approach to developing agreements should also include an examination of the cultural, geopolitical, and socio-economic factors, among others, which may influence the architecture of governance responses in some LMEs, for example, those in Southeast Asia and the Caribbean, where the preferred choice seems to follow a collaborative, polycentric, networked approach (Ostrom 2010). Following the thinking of governance theorists, such an analysis would suggest that context-specific conditions affecting the level of complexity and vulnerability of the human and natural subsystems being governed should influence the responses put in place by those who govern (Jentoft 2007; Kooiman 2005).

To summarize, the findings on engagement indicate a need for better understanding of the rationale used by countries for determining their level of engagement for binding versus non-binding issue-specific types of agreements. This would be further informed by analysis of the completeness of the policy-cycle arrangements in place to implement each agreement, as they relate to engagement. An arrangement with a low level of completeness across its policy-cycle stages, suggestive of possible fractures in the policy process, may prove less effective in achieving governance objectives, even with 100 per cent engagement by the countries involved, than an arrangement in which completeness is higher. This applies regardless of the binding or non-binding nature of the agreement.

Finally, with regard to engagement, situations in which some countries are excluded from participating in agreements can potentially affect the success of efforts aimed at addressing issues of regional concern. The analysis found several such cases, ranging from a single country in a given LME to as many as 20 countries, in the case of the Caribbean, not being able to participate in a sub-regional Central American fisheries agreement. In many of these instances of ineligibility, the rationale was related mainly to the sub-LME nature of the agreement, or to the small extent of overlap between two adjacent LMEs that had different arrangements in place for addressing transboundary issues, and was generally not anticipated to lead to significant challenges. However, it seems appropriate to examine the consequences of all such omissions identified in this analysis and, if deemed negative, to rectify the situation through existing agreements and ensure that new agreements prevent such situations from arising. Where relevant, input from LME-level experts should be sought on this issue.

4.3 Conclusion

Here we reiterate that the policy-cycle scoring process mainly assesses whether arrangements in place are structured according to good governance principles. For example, the presence of clearly specified processes and mechanisms across the policy-cycle stages could be seen as likely to improve transparency, accountability, and the ease with which stakeholders are able to engage with the process. Ultimately, these characteristics can be expected to produce better governance results, and they are often cited as desirable characteristics of governance processes (Lockwood *et al.* 2010; Lemos and Agrawal 2006). However, the state of governance research is such that it is not possible to say definitively that these characteristics are necessary for governance to be effective. The degree to which good governance characteristics are correlated with effective governance is an emerging area of research in the field of international governance.

The analysis of the three indicators of completeness, integration, and engagement to assess governance architecture in arrangements addressing transboundary issues in LMEs is a preliminary step towards understanding:

- the extent to which there is integration between arrangements, either through existing institutions and organizations or through specific integrating mechanisms;
- the extent to which governance issues are covered, thereby allowing identification of gaps;
- the match between governance arrangements and issues;
- the extent to which arrangements extend outside the LME;
- the extent to which issues are covered by multiple arrangements that could result in conflict.

The analysis is considered preliminary for three main reasons: the issues identified are based on available published literature, possibly resulting in some newly emerging issues and even existing issues not being captured in the analysis; it focuses exclusively on formal agreements (binding and non-binding) that are currently in place for addressing the identified transboundary issues in the LMEs; and the data collection process is entirely secondary in nature, based on desk-top research, although efforts are made to make use of expert judgement to inform the findings and conclusions reached. Nonetheless, this analysis has identified the potential for assessing governance architecture in LMEs in a number of ways.

From a substantive perspective, this assessment of governance architecture for the 49 transboundary LMEs and the WPWP appears to support the conclusion of heterogeneity among LMEs (Mahon *et al.* 2010). At the same time, it suggests aspects of commonality across LMEs, particularly those relating to the level of completeness of policy cycles to facilitate good governance. The level of engagement by countries that affect or are affected by transboundary issues within the LMEs also appears to be a cross-cutting factor for good governance. However, this indicator may be driven by the binding or non-binding nature of an agreement, the type of issue that the agreement is established to address, and the area of competence or fit of the agreement (Fanning *et al.* 2016) for good governance to be realized.

In addition to its contribution to developing a baseline for governance indicators across LMEs, this assessment may be valuable in informing processes in several ways. First, the indicators examined here can be taken up in the GEF TDA-SAP process. In some LMEs, notably the Benguela and Guinea Current LMEs, SAPs have proved to be valuable precursors to the development of arrangements thought to reflect good governance. Uptake of well-defined governance assessment approaches and indicators in the TDA-SAP process, as done in developing the Caribbean LME SAP (Mahon *et al.* 2014), could significantly strengthen the aspects of the SAP that address the establishment or enhancement of governance arrangements. Second, it would be of benefit to determine whether actors involved in addressing these issues at the transboundary level see the assessment as providing the context or framework within which a structured discussion about governance arrangements in their LME can take place. Third, by using a common framework and methodology, key actors within LMEs can be informed about their LME's position relative to other LMEs. This could facilitate learning across LMEs from exposure to both failure and successes in governance processes being used.

4.4 Methodology and analysis

Methodology was developed to assess three indicators of good governance from the perspective of governance architecture for each LME and the WPWP. These assessed values were used to provide comparisons across the LMEs in order to establish a baseline of the status of governance architecture. The indicators are:

1. **Level of completeness** of the policy cycle for arrangements in place to address issues of concern within each LME. This score is expressed as a percentage.
2. **Level of integration** across institutions in place to address issues of concern within each LME. This score has a range of 0 to 1.
3. **Level of engagement** by countries within each LME in each of the arrangements in place to address issues of concern within each LME. This score is expressed as a percentage.

Assessing level of completeness and integration

The steps followed to determine the levels of completeness and integration in arrangements in place to address transboundary fisheries, pollution, and biodiversity issues in the LMEs are summarized in Table 4.3. Scoring criteria are listed in Table 4.4. Details on the methodology and its application in each of the 49 LMEs and the WPWP are provided in the full technical report by Fanning *et al.* (2016).

Table 4.3 Steps required to assess governance architecture in a system to be governed

Step	Key points
Identify system to be governed	The system to be governed was clearly defined, including definition of geographic boundaries and the countries involved. In the case of this assessment, the system to be governed is considered to be the entire LME (or the WPWP).
Identify issues to be governed	Using information available in existing Transboundary Diagnostic Analyses (TDA), Causal Chain Analyses (CCA), previously published individual chapters on LMEs (Sherman and Hempel 2008) and other written and web-based documentation, stated transboundary issues of concern within the LME or the WPWP with regard to fisheries, pollution, and biodiversity were identified and allocated to ten subcategories, as listed in Annex Table 4-A.
Identify arrangements for each issue	Relevant binding and non-binding agreements were researched in the literature and through the internet, including through databases of international agreements (for example, ECOLEX www.ecolex.org/start.php, National University of Singapore cil.nus.edu.sg/2009/cil-documents-database/, and University of Oslo Faculty of Law treaty database www.jus.uio.no/english/services/library/treaties/). A database of all relevant agreements was created and populated with background information and information relevant to assessing key aspects of governance architecture (Mahon *et al.* 2016). The agreements were evaluated on the extent to which they comprise a complete policy cycle by assigning a four-point score (0 to 3) for each of the stages of the policy cycle (Table 4.4). The extent to which these cycles operate at different jurisdictional levels within the same arrangement to identify linkages was also examined.
Identify clustering of arrangements within institutions	Arrangements within each LME were examined to determine the extent to which they were integrated for policy making and operational purposes and/or share common institutions/organizations at different levels. Scores were calculated based on the presence of the same organizations being involved in multiple issues. Scores ranged from 0 (no commonality among organizations) to 1 (all issues share the same organizations). In addition to evaluating the level of clustering or integration among the stages of the policy cycle for the different issue-specific arrangements, an assessment was made as to whether there was a demonstrated attempt by the countries in the region to develop and support an overarching integrating mechanism for the issues associated with fisheries, pollution, and biodiversity in the LME or the WPWP. If such an integrating mechanism was present, this was noted and an integration score of 1 was assigned to the LME, regardless of the calculated score across all of the arrangements, as it could be argued that the presence of such a mechanism would facilitate an integrated approach within the LME.
Identify linkages	Actual and desirable links within and among arrangements and clusters were identified.

Table 4.4 Scoring criteria for policy-cycle stages for each arrangement

Policy-cycle stage	Scoring criteria
Advisory mechanism (policy and planning/ management)	0 = No transboundary science policy mechanism, for example, COP self advises[1] 1 = Science–policy interface mechanism unclear (irregular, unsupported by formal documentation) 2 = Science–policy interface not specified in the agreement, but identifiable as a regular process 3 = Science–policy interface clearly specified in the agreement
Decision making (policy and planning/ management)	0 = No decision-making mechanism[2] 1 = Decisions are recommendations to countries 2 = Decisions are binding with the possibility for countries to opt out of complying 3 = Decisions are binding
Implementation	0 = Countries alone 1 = Countries supported by a secretariat 2 = Countries and regional/global level support[3] 3 = Implemented through a coordinated regional/global mechanism[4]
Review	0 = No review mechanism 1 = Countries review and self-report 2 = Agreed review of implementation at regime level 3 = Agreed compliance mechanism with repercussions
Data and information (DI):	0 = No DI mechanism 1 = Countries provide DI, which is used as is 2 = DI centrally coordinated, reviewed, and shared[5] 3 = DI centrally managed and shared

[1] *Nothing in documentation indicates a mechanism by which scientific or policy advice is formulated at the transboundary level prior to consideration by the decision-making body.*

[2] *This refers to decisions on matters that will have a direct impact on ecosystem pressures or state. It does not refer to mechanisms for making decisions on the organization itself, such as process or organizational structure.*

[3] *This means support from regional programmes or partner organizations arranged via a secretariat.*

[4] *For example, a coordinated enforcement system with vessels following a common protocol and flying a common flag identifying them as part of the mechanism (for example, the Pacific Islands Forum Fisheries Agency surveillance flag).*

[5] *For both 2 and 3 scores, data are checked for quality and consistency. The difference is that for a score of 3, there is a centralized place where all the data can be found, whether as actual data or metadata.*

4.4.3 Assessing level of engagement

Two variables that are considered important aspects of LME governance were used in the analysis: the nature of the agreement in terms of whether it is a non-binding agreement facilitating collaboration or a binding agreement requiring formal approval by the country; and the level of engagement of member countries in the agreement. The nature of each agreement was obtained from reviewing the text of the agreement. To provide a measure of the level of country engagement in each transboundary agreement relevant to a given LME, the status of each country in relation to each agreement was researched, and the highest level of engagement possible for each agreement was assessed. For binding agreements, countries that have demonstrated the highest level of engagement possible, through ratification, accession, approval, or acceptance, were considered to be ‘bound’ by the agreement. For non-binding agreements, countries providing evidence of their intent to fully participate in such agreements were considered ‘committed’ to the agreement.

4.4.4 Limitations and confidence levels

The indicators for governance are not statistically derived so do not have confidence intervals in the statistical sense. Completeness is based on expert judgement in assigning each policy-cycle stage a score of 0 to 3. Although the criteria for assigning scores should minimize variation among experts, some variation may occur according to how experts interpret both the criteria and the documentation for the arrangement. Integration is based partly on communality of responsible organizations, which should not vary, and partly on interpretation of whether there is an integrating mechanism in place, which may vary among experts. Engagement is based on a count of countries that have signed an agreement and should have no variance.

References

Biermann, F. and Pattberg, P. (eds.) (2012). *Global environmental governance reconsidered*. MIT Press, Cambridge

Fanning, L, Mahon, R., McConney, P. and others (2007). A large marine ecosystem governance framework. *Marine Policy* 31, 434-443

Fanning, L., Mahon, R., Baldwin, K. and Douglas, S. (2016). *Transboundary Waters Assessment Programme (TWAP) Assessment of Governance Arrangements for the Ocean*, *Volume 1: Transboundary Large Marine Ecosystems*. IOC Technical Series 119

Hoagland, P. and Jin, D. (2008). Accounting for marine economic activities in large marine ecosystems. *Ocean and Coastal Management* 51, 246-258

Jeftic, L., Glennie, P., Talaue-McManus, L. and Thornton, J.A. (eds.) (2011). *Volume 1. Methodology and Arrangements for the GEF Transboundary Waters Assessment Programme*. United Nations Environment Programme, Nairobi, 61 pages

Jentoft, S. (2007). Limits of governability: Institutional implications for fisheries and coastal governance. *Marine Policy* 31, 360-370

Lemos, M.C. and Agrawal, A. (2006). Environmental governance. *Annual Review of Environment and Resources* 31, 297-325

Lockwood, M., Davidson, J., Curtis, A. and others (2010). Governance principles for natural resource management. *Society and Natural Resources* 23, 1-16

Kooiman, J., Bavinck, M., Jentoft, S. and Pullin, R. (2005). *Fish for Life. Interactive Governance for Fisheries*. MARE Publication Series 3. Amsterdam University Press, Amsterdam, 427 pages

Mahon, R., Fanning, L. and McConney, P. (2014). Assessing and facilitating emerging regional ocean governance arrangements in the Wider Caribbean Region. *Ocean Yearbook* 28, 631-671

Mahon, R., Fanning, L., McConney, P. and Pollnac, R. (2010). Governance Characteristics of Large Marine Ecosystems. *Marine Policy* 34, 919-927

Mahon, R., Fanning, L. and McConney, P. (2011a). *Observations on governance in the Global Environment Facility (GEF) International Waters (IW) Programme*. CERMES Technical Report 45, 36 pages. (www.cavehill.uwi.edu\cermes)

Mahon, R., Fanning, L. and McConney, P. (2011b). TWAP common governance assessment (eds. Jeftic, L., Glennie, P., Talaue-McManus, L. and Thornton, J.A.), p. 55-61, *Volume 1. Methodology and Arrangements for the GEF Transboundary Waters Assessment Programme*, United Nations Environment Programme, Nairobi, 61 pages

Mahon, R., Fanning, L., Gjerde, K.M. and others (2016). *Transboundary Waters Assessment Programme (TWAP) Assessment of Governance Arrangements for the Ocean: Volume 2 – areas beyond national jurisdiction (ABNJ)*. IOC Technical Series 119

Olsen, S.B., Sutinen, J.G., Juda, L. and others (2006). *A handbook on governance and socioeconomics of large marine ecosystems*. Coastal Resources Center, University of Rhode Island, 95 pages

Ostrom, E. (2010). Polycentric systems for coping with collective action and global environmental change. *Global Environmental Change* 20, 550-557

Rosenau, J.N. (1995). Governance in the twenty-first century. *Global Governance* 1, 13-43

Rothwell, D. and Stephens, T. (2010). *The International Law of the Sea*. Hart Publishing, Oxford, UK

Sherman, K. and Duda, A.M. (1999). An ecosystem approach to global assessment and management of coastal waters. *Marine Ecology Progress Series* 190, 271-287

Sherman, K., Sissenwine, M., Christensen, V. and others (2005). A global movement toward an ecosystem approach to management of marine resources. *Marine Ecology Progress Series* 300, 275-279

Sherman, K. and Hempel, G. (eds.) (2008). *The UNEP Large Marine Ecosystem Report: A perspective on changing conditions in LMEs of the world's Regional Seas*. UNEP Regional Seas Report and Studies 182. United Nations Environment Programme, Nairobi, Kenya, 852 pages

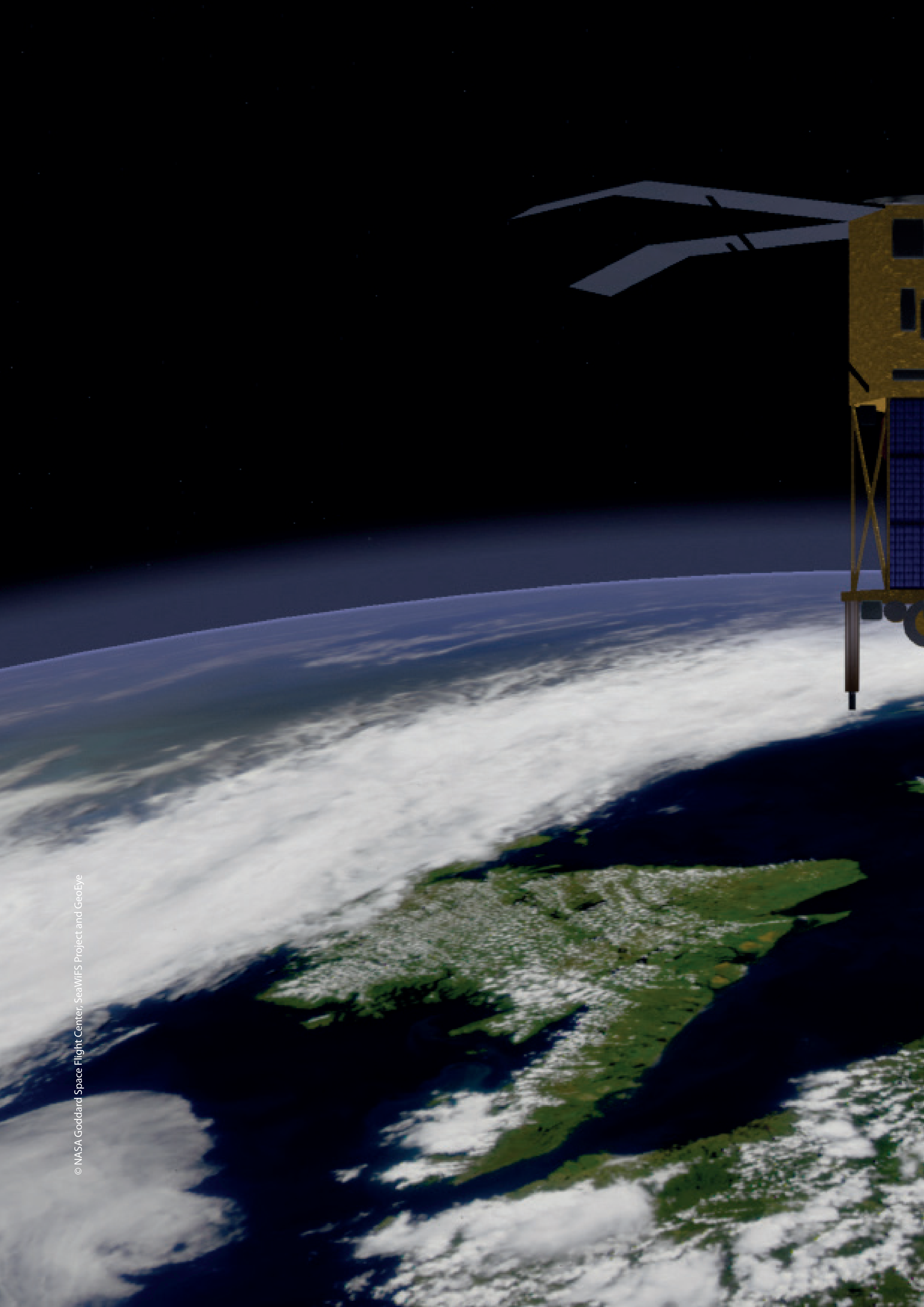
Annex

Annex Table 4-A Breakdown of transboundary issues for transboundary LMEs and the WPWP

Region (number of LMEs/ WPWP)	LME name (or WPWP)	Issue[1]										Total
		Biodiversity			Fisheries					Pollution		
		General	Habitat	Specific	ABNJ	EEZ	ABNJ–EEZ	HMS	Specific	LBS	MBS	
North Polar (10)	East Bering Sea	1						1	3	1	1	7
	Canadian Eastern Arctic-West Greenland	1				1		1	2	1	1	7
	Greenland Shelf	2		1		1	1	1	2	2	3	13
	Barents Sea	2		2			1	1	1	2	2	11
	West Bering Sea	1		1						1	1	4
	Northern Bering-Chukchi Seas	1		1					1	1	1	5
	Beaufort Sea	1								1	1	3
	Iceland Shelf	2					1	1	2	2	2	10
	Central Arctic Ocean	2		2			1	1	1	2	2	11
	Canadian High Arctic-North Greenland	2					1	1	2	2	2	10
Antarctic (1)	Antarctic	1		1			1	1		2	2	8
North Atlantic (11)	Northeast US Continental Shelf						1	1	2	1	1	6
	Scotian Shelf					1		1	2	1	1	6
	Newfoundland-Labrador Shelf						1	1	2	1	1	6
	Norwegian Sea						1	1	2	2	2	8
	North Sea			1		1	1	1	2	2	3	11
	Baltic Sea	1		1					1	1	1	5
	Celtic-Biscay Shelf			1		1	1	1	2	1	2	9
	Iberian Coastal			1		1	1	1	2	1	2	9
	Mediterranean	1	1				1	1		1	4	9
	Faroe Plateau						1	1	2	2	2	8
	Black Sea		1	1		1		1		1	1	6
West-Central Atlantic (4)	Gulf of Mexico		1	1		1	1	1		1	1	7
	Southeast US Continental Shelf			1				1		1	1	4
	Caribbean Sea	1		1		3	1	1		1	1	9
	North Brazil Shelf	1		1		2	1	1		1	1	8
Southeast Atlantic (3)	Canary Current	2				2		1		1	1	7
	Guinea Current	1				2		1		1	1	6
	Benguela Current		1		1	1		1		1	1	6
Southwest Atlantic (2)	Patagonian Shelf		1	1		1		1	1	1	1	7
	South Brazil Shelf			1				1		1	1	4

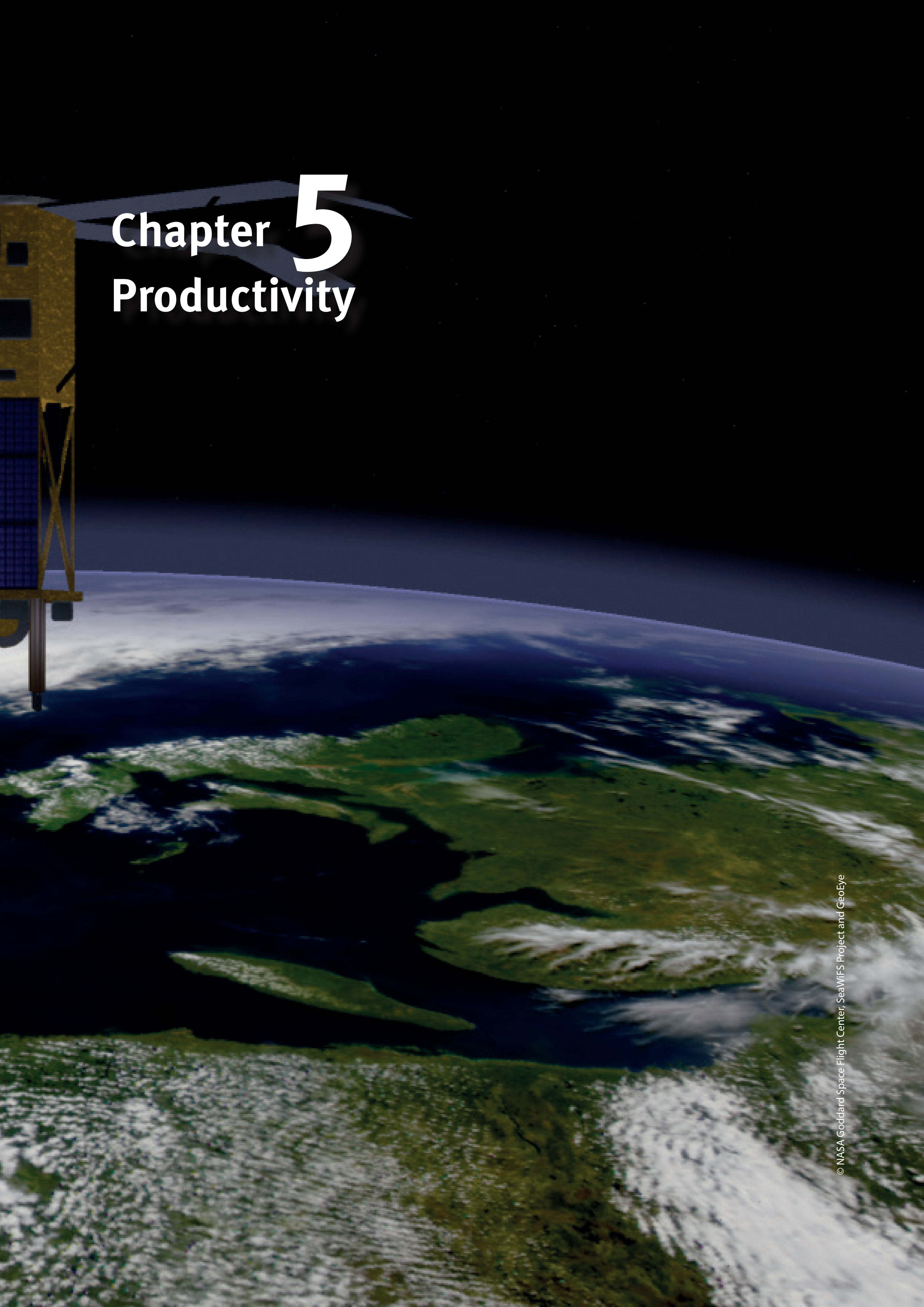
Region (number of LMEs/ WPWP)	LME name (or WPWP)	Issue[1]										Total
		Biodiversity			Fisheries					Pollution		
		General	Habitat	Specific	ABNJ	EEZ	ABNJ–EEZ	HMS	Specific	LBS	MBS	
Northeast Pacific (1)	Californian Current			1				1	2	1	1	6
East-Central Pacific (1)	Pacific Central American Coast		1	1		3		1		1	2	9
Southeast Pacific (1)	Humboldt Current	1		1	1	1		1		1	2	8
West Pacific (5)	Yellow Sea	1	1			1				1	1	5
	Kuroshio Current							1		1	1	3
	Sea of Japan	1	1			1				1	1	5
	Oyashio Current					1				1	1	3
	Sea of Okhotsk									1	1	2
Pacific Islands (1)	Western Pacific Warm Pool	1				1		1		1	1	5
Southeast Asia (6)	Gulf of Thailand		1	1		1		1		1	1	6
	South China Sea		1	1			1	1		1	1	6
	Sulu-Celebes Sea		1	1		1		1		1	1	6
	Indonesian Sea		1	1		1		2		1	1	7
	North Australian Shelf	1		1		1		1		1	1	6
	East China Sea	1				1		1		1	1	5
Indian Ocean (4)	Agulhas Current	1		1	1	1		1		1	1	7
	Arabian Sea	2		1		1		1		2	2	9
	Red Sea	1		1				1		1	1	5
	Bay of Bengal		2	1			2	1		2	2	10
Total number of issues		33	14	43	3	36	21	43	34	61	71	359
Total number of arrangements in place		31	14	43	3	36	21	43	34	56	66	347

[1] *Issue abbreviations: ABNJ = areas beyond national jurisdiction; EEZ = exclusive economic zone; HMS = highly migratory species; LBS = land-based sources; MBS = marine-based sources*



© NASA Goddard Space Flight Center, SeaWiFS Project and GeoEye

Chapter 5
Productivity



© NASA Goddard Space Flight Center, SeaWiFS Project and GeoEye

Chapter 5.1. Primary productivity patterns and trends

Lead Author

John O’Reilly (Independent consultant, Rhode Island, USA)

Contributing Author

Kenneth Sherman (US National Oceanic and Atmospheric Administration, Northeast Fisheries Science Center)

Chapter Citation

O’Reilly, J., Sherman, K. (2016). Chapter 5.1: Primary productivity patterns and trends. In IOC-UNESCO and UNEP (2016). Large Marine Ecosystems: Status and Trends. United Nations Environment Programme, Nairobi, pp 91-99.

Productivity

5.1 Primary productivity patterns and trends

SUMMARY

Primary production, the photosynthesis of organic matter, supports and governs all ecosystem production. It drives the flow of energy through food webs in LMEs and is related to the carrying capacity of LMEs for supporting biological diversity, including fisheries resources. High primary productivity is also an indicator of eutrophication (excessive addition of nutrients), which leads to harmful algal blooms and dead zones in coastal waters around the globe. Ocean primary productivity is responsive to global warming and is closely coupled to climate variability.

Satellite ocean colour data sets covering 16 years (1998 to 2013) were used to estimate average annual primary productivity and chlorophyll (the green pigment involved in photosynthesis) in the world's 66 LMEs and the Western Pacific Warm Pool (WPWP). Daily primary productivity and chlorophyll levels over the entire global ocean were estimated at a spatial resolution of approximately 9 km. Inputs to the productivity model included ocean colour data files from five satellite sensors. Results were used to rank LMEs according to their 16-year average primary productivity. LMEs were then divided into five groups based on these rankings. The confidence level of the primary productivity estimates is high where sampling is adequate, which is the case for most LMEs. Measurements from one satellite sensor were used to estimate 11-year (2003 to 2013) trends in chlorophyll. Accurate assessments of primary productivity and chlorophyll based on satellite data were not feasible for eight high-latitude LMEs, due to low spatial coverage or low sampling frequency. Surveys from ships or airplanes provide better results for these regions.

Key messages

1. **Most relatively high values of primary productivity in the global ocean are in coastal waters, within LME boundaries.** Across the entire global ocean, average annual primary productivity (1998 to 2013) ranges over three orders of magnitude, while it varies by one order of magnitude in the 66 LMEs and the WPWP (from 74 to 755 grams of carbon per m^2 per year). Average chlorophyll concentrations show the same pattern of global distribution.
   - LMEs with highest primary productivity: Baltic Sea (highest), Yellow Sea, North Brazil Shelf, Black Sea, Gulf of California, North Australian Shelf, and Arabian Sea.
   - LMEs with lowest primary productivity: Insular Pacific Hawaiian (lowest), Southwest Australian Shelf, Northeast Australian Shelf, Mediterranean Sea, East Central Australian Shelf, and East Brazil Shelf, plus the WPWP.
2. **No large-scale, consistent pattern of either increase or decrease in chlorophyll was observed (2003 to 2013).** There are 36 LMEs with increasing trends in chlorophyll (measured as chlorophyll a) and 31 with decreasing trends. Trends are weakly correlated with latitude, and most are not statistically significant ($P<0.05$).
   - LMEs with significant increasing chlorophyll trends: Scotian Shelf, Patagonian Shelf, Labrador Newfoundland, and Southeast Australian Shelf LMEs (trends over 11 years of 20, 20, 13, and 1 per cent, respectively). The Baltic Sea LME had a relatively high chlorophyll increase (48 per cent), but this trend is not significant.
   - LMEs with significant decreasing chlorophyll trends: Indonesian Sea, Oyashio Current, and Celtic-Biscay Shelf (trends of -16, -8, and -4 per cent over 11 years, respectively).

5.1.1 Introduction

Primary production, the photosynthesis of organic matter, supports and governs all ecosystem production and plays a pivotal role in ecosystem nutrient and carbon cycling and budgets (Hofmann *et al.* 2008). Primary production drives the trophodynamics (flow of energy through food webs) of LMEs and can be related to the carrying capacity of marine ecosystems for supporting fish resources (Christensen *et al.* 2009; Pauly and Christensen 1995).

Measurements of ecosystem primary productivity are useful indicators of the growing eutrophication problem that is 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 (for example, cholera, vibrios, red tides, and paralytic shellfish toxins) and population explosions of invasive species (Epstein 2000).

Indicators of changing productivity are based on the following physical attributes and biogeochemical constituents: photosynthetically active radiation, water column transparency, chlorophyll *a*, primary production, zooplankton biomass, species biodiversity, ichthyoplankton (eggs and larvae of fish) biodiversity, oceanographic variability (for example, temperature, salinity, density, circulation, and nutrient flux) (Sherman *et al.* 2009; Sherman *et al.* 1998; Sherman 1980), and acidification (Oliver *et al.* 2012). Plankton can be measured over decadal time scales by deploying Continuous Plankton Recorder systems monthly across LMEs from commercial vessels of opportunity (Jossi and Kane 2013; Batten *et al.* 2003; Jossi *et al.* 2003). 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 with appropriate algorithms, can allow time-series visualizations of LME-scale sea surface temperature, hydrographic fronts (boundaries between water masses with different physical properties), chlorophyll concentrations, and primary productivity estimates (Sherman *et al.* 2011).

Chlorophyll *a*, the principal pigment in phytoplankton, can be estimated in surface water from satellite ocean colour sensors by using the blue-green part of the ocean colour spectrum (O'Reilly *et. al.* 2000 and 1998). Chlorophyll *a* is an index of phytoplankton abundance, and, together with light and nutrients, is among the key factors in primary productivity.

5.1.2 Data and methodologies

5.1.2.1 Chlorophyll a and primary productivity estimates

The average levels of chlorophyll *a* and primary productivity for the world's 66 LMEs and the Western Pacific Warm Pool (WPWP) were characterized for a 16-year period (1998 to 2013) using 76 028 satellite data files at a resolution of 9 km. These data are from five sensors: 1) the Ocean Color and Thermal Sensor (OCTS); 2) Sea-viewing Wide Field-of-view Sensor (SeaWiFS); 3) Moderate Resolution Imaging Spectroradiometer on the AQUA satellite (AQUA); 4) Moderate Resolution Imaging Spectroradiometer on the TERRA satellite (TERRA); and 5) the medium-spectral-resolution imaging spectrometer (MERIS), along with the Ocean Production from the Absorption of Light (OPAL) productivity model. Primary productivity is expressed as grams of carbon per m^2 per year. Measurements of primary productivity per unit volume of seawater are integrated over the upper layer of the water column to estimate grams of carbon produced per unit area of the ocean.

Satellite chlorophyll data are the standard chlorophyll products provided by the US National Aeronautics and Space Administration's Goddard Space Flight Center (NASA-GSFC) from the most recent (2012) major data reprocessing, based on Version 6 of the OC-maximum band ratio algorithms (NASA 2013). The correlation between *in situ* chlorophyll *a* and chlorophyll *a* estimates from SeaWiFS (0.909) and MODIS-AQUA (0.925) is relatively high, and the regression slopes between *in situ* and satellite data are close to 1.0 (NASA 2013). Chlorophyll concentrations are expressed as milligrams per m^3 of seawater in the surface layer (the upper metre of the ocean).

Daily estimates of global primary productivity were calculated using the OPAL model, a derivative of the model first formulated by Marra *et al.* (2003). Four key satellite data inputs to OPAL are: 1) the concentration of surface chlorophyll *a*, 2) sea surface temperature, 3) photosynthetically active radiation striking the ocean surface, and 4) the absorption of light by coloured dissolved organic matter. Agreement is excellent between *in situ* ^{14}C-based measurements from MARMAP surveys (O'Reilly *et al.* 1987) and productivity estimates from OPAL in the Northeast US Continental Shelf LME, where *in situ* productivity measurements were made throughout the ecosystem during most months (Table 5.1).

Table 5.1 Comparison between *in situ* and satellite-based estimates of primary productivity for the Northeast US Continental Shelf LME. Comparison is between long-term mean annual *in situ* ^{14}C primary production estimates from MARMAP (O'Reilly *et al.* 1987) and productivity estimates from the OPAL model.

Source of estimate	Sample size	Years	Productivity (grams of carbon per m^2 per year)
In situ measurements	1 243	1977–1982	**355**
Satellite-based measurements	25 573 360	1998–2013	**365**

A total of 76 028 satellite standard mapped image files from five NASA-GSFC satellite ocean colour sensors (OCTS, SeaWiFS, MODIS-AQUA, MODIS-TERRA and MERIS) were used to derive daily estimates of primary productivity over the global ocean. Merging data from these five ocean colour sensors resulted in minimal data gaps in the global productivity estimates, except in 1997. Because sampling was incomplete in 1997 and 2014, average chlorophyll *a* and primary productivity estimates are based on the 16-year period from 1998 through 2013.

Sampling by satellite ocean colour sensors is inadequate for a comprehensive characterization of chlorophyll *a* and primary productivity in the most northern and southern LMEs with short growing seasons, persistent ice or clouds, and partial coverage by satellite sensors that rely on daylight for ocean colour measurements. Gregg and Casey (2007) documented the positive biases in chlorophyll data from ocean colour sensors. Nevertheless, the results for these LMEs, while biased and incomplete, are presented for comparison. *In situ* measurements would be required for more accurate assessment of the productivity and the timing of annual peaks and minima for these systems.

5.1.2.2 Detecting time trends in chlorophyll a

Trends in chlorophyll *a* are based on data from one sensor (MODIS-AQUA), for the 11-year period 2003 through 2013. Data from one sensor were used instead of the merged data from five sensors to minimize sensor-to-sensor biases in the trends. Trends were computed based on linear regressions of the yearly anomalies in annual mean chlorophyll *a,* following the methods outlined by Gregg *et al.* (2005). Tests of whether linear regression slopes differ significantly from zero (no trend) at the 0.95 probability level were computed using the T-Test statistic (Sokal and Rohlf 1995). Trends in chlorophyll *a* were calculated as relative per cent change from 2003 to 2013, computed from the predicted values (***P***) from the linear regression of annual mean chlorophyll *a* versus year as follows:

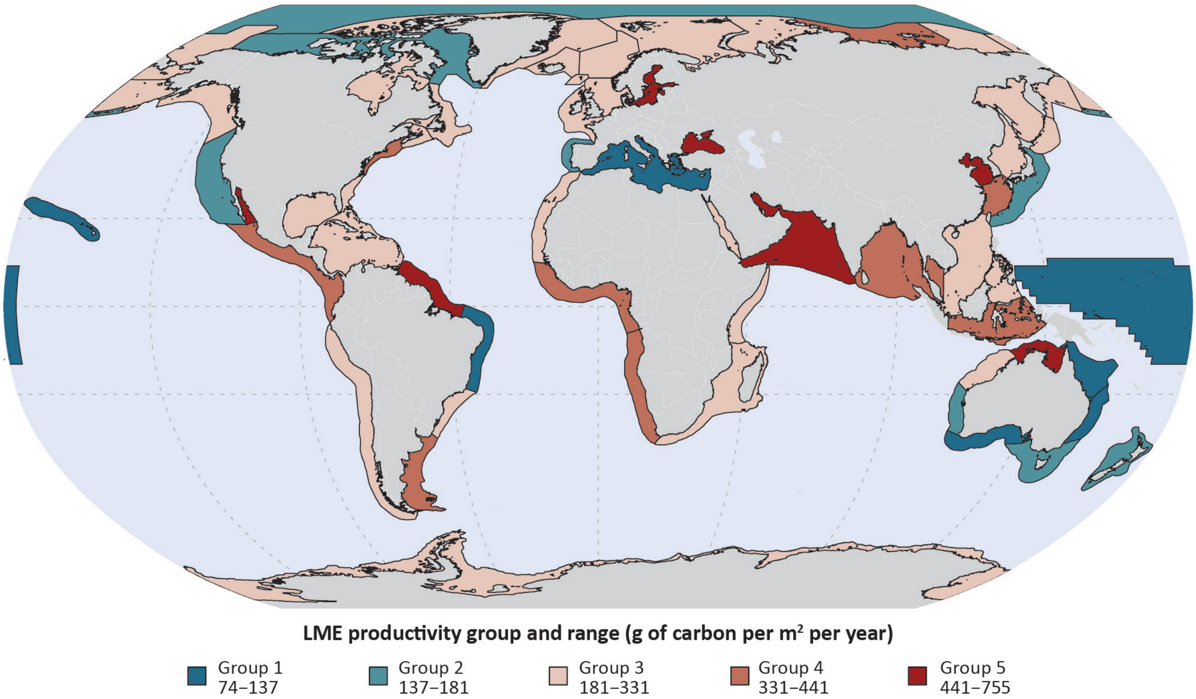
relative percentage change = 100 x **[**last(***P***)-first(***P***)**]/**first(***P***).

5.1.3 Major findings, discussion, and conclusions

5.1.3.1 Spatial patterns in chlorophyll and primary production

Mean chlorophyll *a* throughout the global ocean varies from 0.008 to 100 milligrams per m^3, a range of more than four orders of magnitude (Figure 5.1). Relatively high chlorophyll *a* values (those exceeding 1 to 3 milligrams per m^3) are found near shore, within LME boundaries. Mean chlorophyll *a* is less than 0.02 milligrams per m^3 in the South Pacific Gyre, the Earth's largest oceanic desert, located west of South America at about 25^o S latitude (Claustre and Maritorena 2003).

Figure 5.1 Distribution of average surface chlorophyll *a* throughout the global ocean, 1998–2013. Mean concentrations of chlorophyll *a*, the green pigment involved in photosynthesis and an index of phytoplankton abundance, vary from 0.008 to 100 milligrams per m³, a range of more than four orders of magnitude. The highest values are found near shore, within LME boundaries.



Mean primary production per year (Figure 5.2) ranges over three orders of magnitude, from 1.6 grams of carbon per m² per year (at 17.92°S, 142.17°W) to 6 382 grams of carbon per m² per year (at 6.00°S, 12.33°E, the Guinea Current). As with chlorophyll *a*, the highest primary productivity values (those exceeding 300 grams of carbon per m² per year) are found in coastal waters within LME boundaries.

5.1.3.2 Global primary production

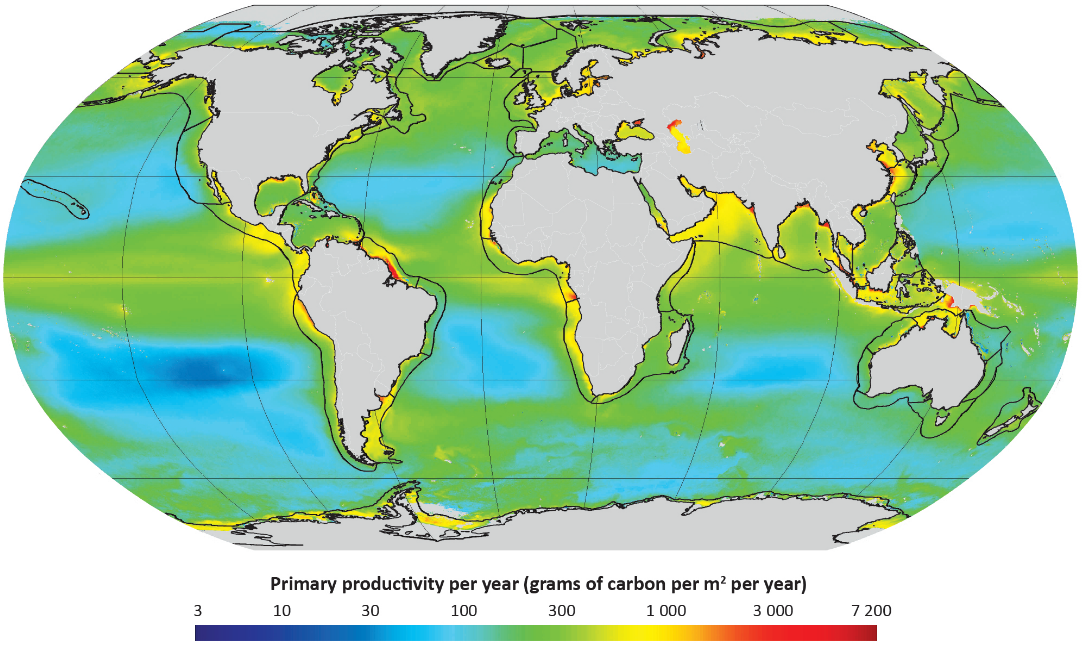
The average annual global ocean primary production for the 16-year period 1998 to 2013, based on five sensors and estimated through OPAL, is 52 x 10^{15} grams of carbon per year. This is lower than the estimate by Behrenfeld *et al.* (2005) of 60 x 10^{15} grams of carbon per year, an estimate based on the Vertically Generalized Production Model and SeaWiFS data for the six-year period 1997 to 2002. The OPAL global production estimate is higher than the estimate of 36.5 to 45.6 x 10^{15} grams of carbon per year by Antoine *et al.* (1996), an estimate based on coastal zone colour data from 1978 to 1986. These global estimates are calculated by integrating primary production values (grams of carbon per m²) over the entire area of the ocean.

5.1.3.3 Classification of LMEs into five groups

It is important to know the productivity status of marine ecosystems, because the magnitude of primary productivity is related to ecosystem services such as fishery production (Rosenberg *et al.* 2014). High primary productivity is generally regarded as a positive ecosystem attribute, except when it results in hypoxia (low oxygen) from decomposing phytoplankton blooms stimulated by anthropogenic nutrient pollution in rivers.

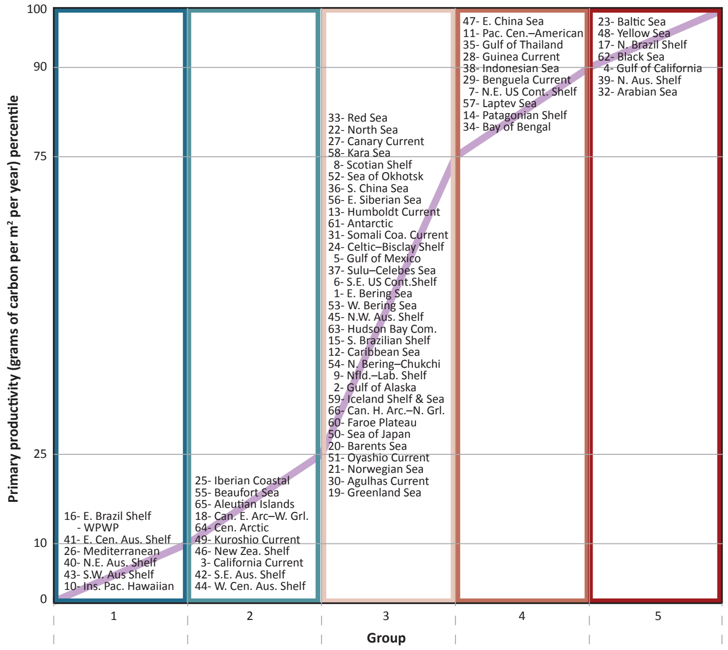
The 66 LMEs and the WPWP were arranged into five groups based on their 16-year mean primary productivity values. There are no *a priori* criteria for grouping primary productivity into discrete ranges, and no established thresholds for indicating either impoverished or excessive levels of primary productivity in open water. Moreover, while the terms 'oligotrophic', 'mesotrophic' and 'eutrophic' are frequently used in the scientific literature, quantitative definitions of primary productivity levels are lacking. Consequently, a statistical approach was used to classify ecosystem primary productivity into five groups, based on the 0, 10, 25, 75, 90, and 100 percentiles.

Figure 5.2 Distribution of average annual primary productivity throughout the global ocean, 1998–2013. Primary productivity, the photosynthesis of organic matter by phytoplankton that supports and governs all ecosystem production, ranges from 74 to 755 grams of carbon per m² per year in the LMEs studied. Most relatively high values of primary productivity in the global ocean are in coastal waters, within LME boundaries.



Values shown are mean net primary productivity per year, based on the OPAL model and satellite ocean colour data; LME boundaries are outlined in white.

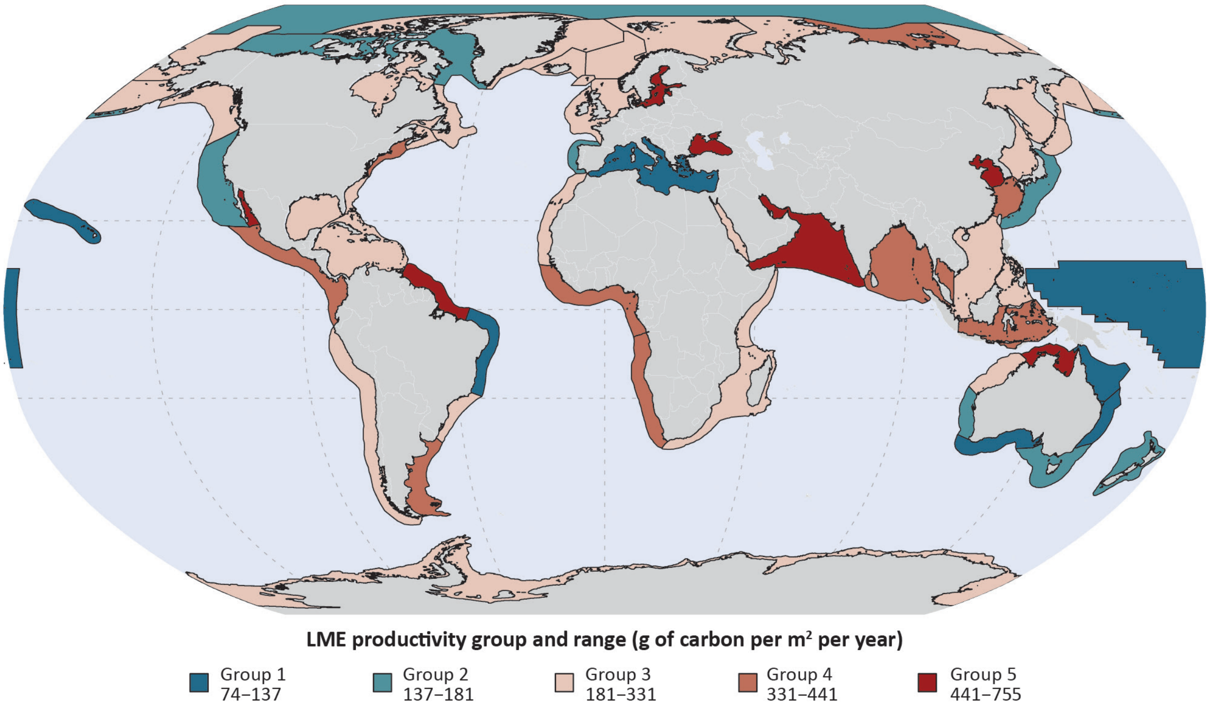
Figure 5.3 Classification of 66 LMEs and the WPWP into five groups by productivity. A statistical approach was used to classify the 16-year average primary productivity into five groups, based on the 0, 10, 25, 75, 90, and 100 percentiles. Most (33) LMEs are in the middle range of primary productivity, Group 3. Figure 5.4 maps the distribution of these productivity groups.



	1	2	3	4	5
Number of LMEs	7	10	33	10	7
Productivity range (g of carbon per m² per year)	74–137	137–181	181–331	331–441	441–755

Classification is based on the magnitude of 16-year mean levels of net annual primary productivity; LMEs are ordered by primary productivity in each group, with the most productive at top.

Figure 5.4 Global distribution of the five productivity classification groups for 66 LMEs and the WPWP. This map shows the distribution of productivity levels by LME. Figure 5.3 contains ordered lists of the LMEs in each group. Group 3 (medium levels of productivity) is the largest, with 33 LMEs.



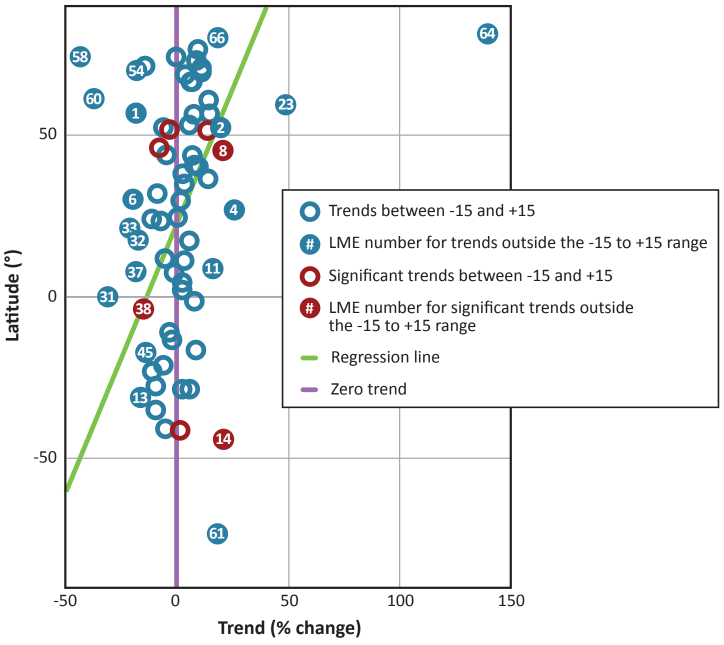
Most LMEs are in the middle range of primary productivity, Group 3, between the 25th and 75th percentiles (Figure 5.3). The seven LMEs with the highest primary productivity, Group 5, are the Baltic Sea, Yellow Sea, North Brazil Shelf, Black Sea, Gulf of California, North Australian Shelf and the Arabian Sea. The seven areas with the lowest primary productivity, Group 1, are six LMEs: Insular Pacific-Hawaiian, Southwest Australian Shelf, Northeast Australian Shelf, Mediterranean, East Central Australian Shelf, and East Brazil Shelf, as well as the Western Pacific Warm Pool. The global distribution of LMEs and the WPWP in these five primary productivity classification groups is mapped in Figure 5.4.

5.1.3.4 LME trends

No large-scale, consistent pattern of either increase or decrease in chlorophyll *a* was observed, with most chlorophyll *a* trends being near zero (Figure 5.5). There are 36 LMEs with positive chlorophyll *a* trends and 31 with negative chlorophyll *a* trends from 2003 to 2013. Trends are weakly correlated with latitude. The four LMEs with statistically significant increasing chlorophyll *a* trends at the 0.95 per cent probability level are the Scotian Shelf, Patagonian Shelf, Newfoundland-Labrador Shelf, and Southeast Australian Shelf (increases of 20, 20, 13, and 1 per cent over the 11-year period, respectively). The Baltic Sea LME shows relatively higher chlorophyll *a* increases (48 per cent), but this trend is not statistically significant. The three LMEs with statistically significant decreasing chlorophyll *a* trends are the Indonesian Sea, Oyashio Current, and Celtic-Biscay Shelf (decreases of 16, 8, and 4 per cent over 11 years, respectively). These results are similar to those presented in an earlier UNEP report (Sherman and Hempel 2008), where nine-year trends were statistically significant in only four LMEs.

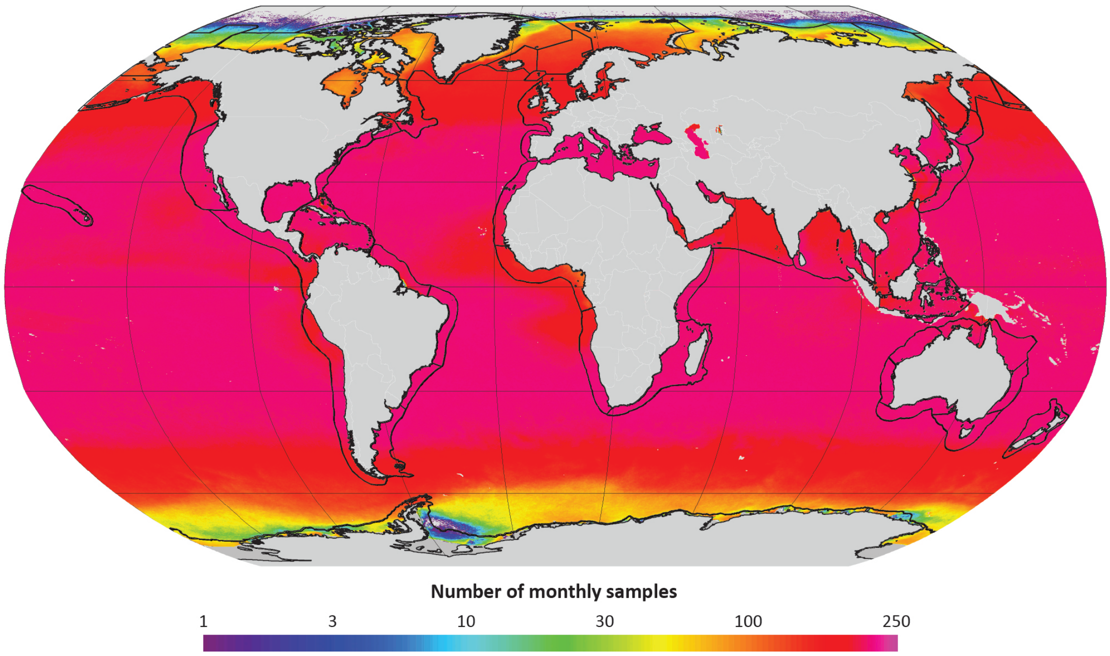
There were relatively few monthly samples from ocean colour sensors in the most northerly and southerly latitudes from 1998 to 2013 (Figure 5.6). Eight LMEs had less than 60 per cent spatial coverage, or were sampled during less than 60 per cent of the 192 months from 1998 to 2013 (Figure 5.7). These LMEs are: Antarctica, Kara Sea, Laptev Sea, East Siberian Sea, Beaufort Sea, Canadian High Arctic-North Greenland, Central Arctic, and Northern Bering-Chukchi Seas. It is therefore unlikely that the status and trends in chlorophyll *a* and primary productivity described in this report for these eight LMEs are reliable or represent true ecosystem conditions. For these ecosystems, remotely-sensed ocean colour measurements, for example from aircraft (Hugo *et al.* 2005; Harding *et al.* 1992), or *in situ* measurements, would be required for more accurate indices of their productivity, phenology and trends.

Figure 5.5 Trends in chlorophyll *a* (2003–2013) in relation to latitude. No large-scale, consistent pattern of either increase or decrease in chlorophyll *a* was observed. There are 36 LMEs with positive chlorophyll *a* trends and 31 with negative chlorophyll a trends, and trends are weakly correlated with latitude. The four LMEs with statistically significant increasing chlorophyll a trends (red circles to the right of the purple line) are the Scotian Shelf (#8), Patagonian Shelf (#14), Newfoundland-Labrador Shelf, and Southeast Australian Shelf. The three LMEs with statistically significant decreasing chlorophyll *a* trends (red circles to the left of the purple line) are the Indonesian Sea (#38), Oyashio Current, and Celtic-Biscay Shelf.



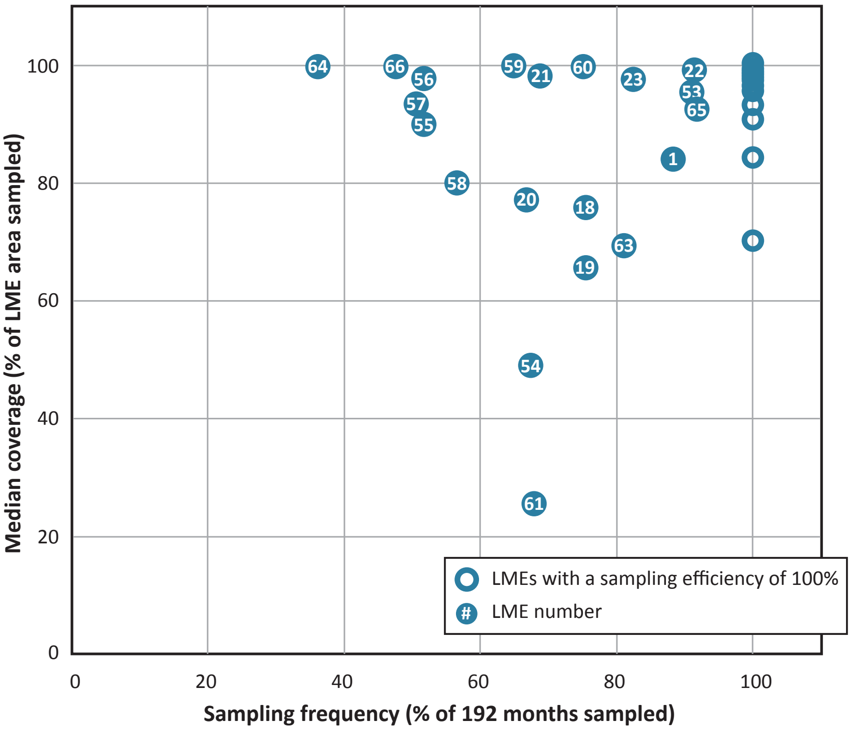
Chlorophyll *a* trends (% relative change) are shown for 66 LMEs
and the WPWP, based on chlorophyll *a* data from the AQUA sensor, 2003–2013.

Figure 5.6 Global distribution of chlorophyll *a* samples, 1998–2013. The confidence level of the primary productivity estimates is high where sampling is adequate, which is the case for most LMEs. However, sampling by satellite ocean colour sensors was inadequate for a comprehensive characterization of chlorophyll *a* and primary productivity in northern and southern LMEs with short growing seasons, persistent ice or clouds, and partial coverage by satellite sensors that rely on daylight for ocean colour measurements.



Sample numbers are over a period of 192 months; sampling was by ocean color sensors.

Figure 5.7 Relationship of LME sampling frequency and coverage, 1998–2013. Eight LMEs had less than 60 per cent spatial coverage, or were sampled during less than 60 per cent of the 192 months from 1998 to 2013. These are: Antarctic (#61), Kara Sea (#58), Laptev Sea (#57), East Siberian Sea (#56), Beaufort Sea (#55), Canadian High Arctic-North Greenland (#66), Central Arctic Ocean (#64), and Northern Bering-Chukchi Seas (#54). It is unlikely that the reported status and trends in chlorophyll *a* and primary productivity for these LMEs are reliable or represent true ecosystem conditions. For these ecosystems, remotely-sensed ocean colour measurements or *in situ* measurements would be required for more accurate indices of their productivity and trends.



Sampling was by five ocean colour sensors for 66 LMEs and the WPWP.

Trends in primary productivity would be expected to follow trends in chlorophyll *a* since chlorophyll *a* is a dominant input to the OPAL productivity model and their averages are correlated (correlation coefficient = 0.63).

5.1.3.5 Limitations and qualitative confidence in the LME productivity indicators

The overall confidence level in the primary productivity indices is high where sampling is adequate, which is the case for most LMEs. The reasons for this confidence level are:

1. The measurement consistency is high within and among LMEs.
2. Ocean colour satellite data provide a very large statistical sample size of approximately 10 000 pixels for each LME.
3. Where both in situ productivity measurements and satellite measurements were made throughout the ecosystem and during most months, such as in the Northeast US Continental Shelf, the agreement is excellent between conventional in situ 14C-based measurements of productivity and productivity indicators from the OPAL model (see Table 5.1).
4. The estimate of annual global ocean production from OPAL (52 x 10^{15} grams of carbon per year) is in agreement with the range previously reported in the scientific literature.

The major limitation of the LME productivity indicators is incomplete sampling, which is the result of inadequate spatial or seasonal coverage of the LMEs by satellite ocean colour sensors. These sensors rely on daylight and cloud-free conditions for measurements of chlorophyll and other variables in surface water. Estimates of ecosystem productivity based on satellite data, and models such as OPAL, rely heavily on these satellite ocean colour chlorophyll estimates and photosynthetically active radiation data. These estimates and models therefore have similar spatial and seasonal limitations.

References

Antoine, D., André, J-M. and Morel, A. (1996). Oceanic Primary Production 2. Estimation at global scale from satellite (coastal zone color scanner) chlorophyll. *Global Biogeochemical Cycles* 10(1), 57-69

Batten, S.D., Clark, R., Flinkman, J. and others (2003). CPR sampling-the technical background, materials and methods, consistency and comparability. *Progress in Oceanography* 58, 175-191

Behrenfeld, M., Boss, E., Siegel, D. and Shea, D. (2005). Carbon-based ocean productivity and phytoplankton physiology. *Global Biogeochemical Cycles* 19, 14 pages

Christensen, V., Walters, C.J., Ahrens, R. and others (2009). Database-driven models of the world's Large Marine Ecosystems*. Ecological Modelling* 220, 1984-1996

Claustre, H. and Maritorena, S. (2003). The many shades of ocean blue. *Science* 302, 1514-1515

Diaz, R.J. and Rosenberg, R. (2008*). Spreading dead zones and consequences for marine ecosystems. Science* 321, 926-929

Epstein, P.R. (2000). Algal blooms and public health*. World Resource Review*, (1993) In: *The state of the world fisheries and aquaculture*. FAO Rome 2000 5(2), 190-206. 142 pages

Gregg, W. and Casey, N. (2007). Sampling biases in MODIS and SeaWiFS ocean chlorophyll data*. Remote Sensing of Environment* 111, 25-35

Gregg, W, Casey, N. and McClain, C. (2005). Recent trends in global ocean chlorophyll. *Geophysical Research Letters* 32(L03606)

Harding, L., Itsweire, E. and Essais, W. (1992). Determination of phytoplankton chlorophyll concentrations in the Chesapeake Bay with aircraft remote sensing. *Remote Sensing of Environment* 40(2), 79-100

Hofmann, E., Druon, J., Fennel, K. and others (2008). Eastern US continental shelf carbon budget Integrating Models, Data Assimilation, and Analysis. *Oceanography* 21(1), 86-104

Hugo, M., Carder, K., Foy, R. and others (2005). Estimating phytoplankton biomass in coastal waters of Alaska using airborne remote sensing. *Remote Sensing of Environment* 98(4), 481-493

Jossi, J., John, A.W.G. and Sameoto, D. (2003). Continuous Plankton Recorder sampling off the east coast of North America – history and status (eds. Reid, B.C., Matthews, J.B.L. and Smith, M.A.), Achievements of the continuous plankton recorder survey and a vision for its future*. Progress in Oceanography* 58, 313-325

Jossi, J.W. and 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. of Commerce Northeast Fisheries Science Center References Document 13-12. Woods Hole, MA, NOAA, NMFS, Northeast Fisheries Science Center, 104 pages

Marra, J., Ho, C. and Trees, C. (2003). An alternative algorithm for the calculation of primary productivity from remote sensing data. *Deep-Sea Research I* 54, 155-163

Melrose, D.C., Oviatt, C.A., O'Reilley, J.E. and others (2006). Comparisons of fast repetition rate fluorescence estimated primary production and 14C uptake by phytoplankton*. Marine Ecology Progress Series* 311, 37-46

NASA (2013). OceanColor Web: Ocean Color Chlorophyll (OC) v6. http://oceancolor.gsfc.nasa.gov/ANALYSIS/ocv6 (accessed 25 May 2015)

Oliver, J.R.D., Widdicombe, S., Hasinger, O. and Laffolley, D. (2012). *Large Marine Ecosystems at Risk from Acidification During Climate Change*. *Frontline Observations on Climate Change and Sustainability of Large Marine Ecosystems*. (eds. Sherman, K. and McGovern, G.). United Nations Development Programme and Global Environment Facility, New York, 188-203.

O'Reilly, J.E., Maritorena, S., Siegel, D. and others (2000). Ocean color chlorophyll *a* algorithms for SeaWiFS, OC2, and OC4: Version 4. NASA Technical Memorandum, 2000-206892(11), 9-23

O'Reilly, J.E., Maritorena, S., Mitchell, B.G. and others (1998). Ocean color chlorophyll algorithms for SeaWiFS. *Journal of Geophysical Research* 103, 24937-24953

O'Reilly, J.E., Evans-Zetlin, C. and Busch, D.A. (1987). Primary Production. Chapter 21, 220-233, *Georges Bank* (ed. Backus, R.H.), MIT Press, Cambridge, MA

Pauly, D. and Christensen, V. (1995). Primary production required to sustain global fisheries. *Nature* 374, 255-257

Rosenberg, A., Fogarty, M., Cooper, A. and others (2014). *Developing new approaches to global stock status assessment and fishery production potential of the seas.* FAO Fisheries and Aquaculture Circular 1086. Rome, FAO, 175 pages

Sherman, K., (1980). *MARMAP, a fisheries ecosystem study in the NW Atlantic: Fluctuations in ichthyoplankton-zooplankton components and their potential impact on the system. Advanced concepts in ocean measurements for marine biology*. (eds. Diemer, F. P., Vernberg, F. J. and. Mirkes, D. Z.). Belle W. Baruch Institute for Marine Biology and Coastal Research. University of S.C. Press, 572 pages

Sherman, K., Belkin, I., Friedland, K.D., O'Reilly, J., and Hyde, K. (2009). Accelerated warming and emergent trends in fisheries biomass yields of the world's large marine ecosystems. *Ambio* 38, 215-224

Sherman, K. and Hempel, G. (eds.) (2008). *The UNEP Large Marine Ecosystem Report: A perspective on changing conditions in LMEs of the world's Regional Seas.* UNEP Regional Seas Report and Studies 182. United Nations Environment Programme. Nairobi, Kenya

Sherman, K., O'Reilly, J., Belkin, I. and others (2011). The application of satellite remote sensing for assessing productivity in relation to fisheries yields of the world's large marine ecosystems. *ICES Journal of Marine Science* 68(4), 667-676

Sherman, K., Solow, A., Jossi, J. and Kane, J. (1998). Biodiversity and abundance of the zooplankton of the Northeast Shelf ecosystem. *ICES Journal of Marine Science* 55, 730-738

Sokal, R.R., and Rohlf, F.J. (1995). *Biometry: The Principals and Practical Statistics in Biological Research.* W.H. Freeman and Company, New York

Chapter 5.2. Sea surface temperature trends in large marine ecosystems

Lead Author

Igor Belkin (Graduate School of Oceanography, University of Rhode Island)

Chapter Citation

Belkin, I. (2016). Chapter 5.2: Sea surface temperature trends in large marine ecosystems. In IOC-UNESCO and UNEP (2016). *Large Marine Ecosystems: Status and Trends*. United Nations Environment Programme, Nairobi, pp 101-109.

5.2 Sea surface temperature trends in large marine ecosystems

SUMMARY

Sea surface temperature (SST) affects ocean primary productivity through its physical effect on water stratification (which in turn affects nutrient availability) and its biological effect on plankton metabolic rates. Global mean SST has risen over the past century, and this is linked with both decreases and increases in primary productivity, depending on the time period and the region. Although many studies address global climate variability, studies on LME-scale climate variations based on a uniform, spatially, and temporally consistent methodology have been lacking until recently. This report extends and updates previous work at the LME scale with the aim of improving understanding of how global-scale climate changes translate into LME-scale changes.

SST is the only oceanic variable measured worldwide since the 19th century, providing the longest instrumental record of ocean climate change. Hadley Centre global climatology data were used to construct long-term SST time-series in 66 LMEs and the Western Pacific Warm Pool (WPWP). Long-term trends were calculated from annual SSTs for each LME. Warming rates between 1957 and 2012 were calculated on the basis of these SST trends. LMEs and the WPWP were then divided into five categories based on the rate of warming. Overall confidence in the results is rated as very high.

KEY MESSAGES

1. **Between 1957 and 2012, SST in all but two LMEs increased.** SST change varied widely between regions, from -0.28°C to +1.57°C in 55 years.
    - LMEs with highest rates of warming: East China Sea, Scotian Shelf, and Northeast US Continental Shelf;
    - LMEs that cooled over this period: Barents Sea and Southeast US Continental Shelf.
2. **The LMEs with the largest increases in SST are mainly in three regions: Northwest Atlantic, eastern North Atlantic, and the Western Pacific.** LMEs with high rates of seawater warming:
    - Northwest Atlantic: US Continental Shelf, Scotian Shelf, and Faroe Plateau LMEs;
    - Eastern North Atlantic: Celtic-Biscay Shelf, North Sea, and Baltic Sea LMEs;
    - Western Pacific: South China Sea, East China Sea, Yellow Sea, and Sea of Japan LMEs.
3. **The observed long-term global ocean warming from 1957 to 2012 was not steady, especially in the North Atlantic and North Pacific.** In these regions, SST tends to alternate between cooling and warming epochs, separated by abrupt regime shifts. In the North Atlantic, the most typical regime shift was a transition from cooling to warming in the 1970s to the 1980s. In the North Pacific, the most conspicuous regime shift from cooling to warming occurred around 1976 to 1977.
4. **After 1998, most LMEs in the North Pacific experienced slowdowns, and even reversals, of late 20th century warming.**
    - LMEs with slowed or reversed rates of warming since about 1998: East China Sea, Yellow Sea, Kuroshio Current, West Bering Sea, East Bering Sea, Aleutian Islands, Gulf of Alaska, California Current, and Gulf of California;
    - Three LMEs in the subarctic Northwest Pacific with no signs of slowed warming since 1998: Sea of Japan, Oyashio Current, and Sea of Okhotsk.

5.2.1 Introduction

Sea surface temperature (SST) is placed in the Productivity module because of its effects on ocean productivity. A growing body of knowledge suggests that changes in phytoplankton biomass and productivity are related to ocean warming (Lewandowska *et al*. 2014; Polovina *et al*. 2011 and 2008; Boyce *et al*. 2010; Behrenfeld *et al*. 2006). At least two distinct mechanisms are implicated: a physical effect of warming on vertical stratification and nutrient flux, and a biological effect on plankton metabolic rates. For example, rising SSTs are linked to an overall global decline in phytoplankton productivity since the late 1990s through changes in ocean circulation and stratification of water layers, restricting nutrient availability in surface waters (Behrenfeld *et al*. 2006). On the other hand, increased primary production observed in some temperate areas is largely a response of increased phytoplankton growth to warming surface waters (Polovina *et al*. 2011).

The Earth's climate has become substantially warmer since the 19th century. Based on the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, the global mean surface air temperature increased by 0.74°C while the global mean SST rose by 0.67°C over the last century (Trenberth *et al.*, 2007). The most recent global assessment (Hartmann *et al*. 2013) discusses estimates of SST trends based on specific data sets and time periods selected for trend analysis. These estimates are generally consistent with Trenberth *et al.* (2007). The world ocean's mean temperature in the layer from the surface to 3 000 m deep increased by 0.037°C between 1955 and 1998 (Levitus *et al.*, 2005). The heat content of the top 2 000 m of the world ocean increased by 24.0±1.9 x 10^{22} Joules (±2 standard errors) between 1955 and 2010, corresponding to a rate of increase of 0.39 watts per m^2 and a rise in temperature of this layer of water of 0.09°C, when averaged over its entire volume (Levitus *et al.*, 2012).

The nature and extent of changes to the Earth's climate in the near and distant future is uncertain. As the CO_2 concentration in the Earth's atmosphere rises, the greenhouse effect must lead to an increase in the atmosphere's temperature and, after a time lag, to a further ocean temperature increase. The IPCC-2007 report projected that the rate of climate warming will increase. This trend is obviously non-sustainable. However, recent data, especially from the period after the 1998 El Niño, revealed a slowdown of the 20th century warming rate as the world entered the 21st century. In some regions, this slowdown has turned into cooling. For example, surface layers of the East China Sea and Taiwan Strait have cooled by 1°C since 1998 (Belkin and Lee, 2014). Clearly, re-assessment of the current climate trends based on the most recent data is needed.

LME-based management can be significantly improved through a better understanding of oceanic and atmospheric circulation and physical-biological interactions at the LME scale (Sherman *et al.* 2009, 2011, 2013, 2014a and 2014b; Belkin *et al.* 2009; Sherman *et al.*, 2005; Duda and Sherman 2002). It is therefore crucial to make clear the various mechanisms that translate global-scale climate changes into LME-scale changes

Great efforts have been made to document global climate variability (Trenberth *et al.* 2007), but studies of LME-scale climate variations based on a uniform, spatially, and temporally consistent methodology were lacking until recently (Belkin, 2009). This report extends and updates our previous study by adding six years of recent data (2007 to 2012). This addition has turned out to be critically important, as the most recent data has confirmed a slowdown, and even reversal of, late 20th century warming in some regions (Kosaka and Xie 2013; England *et al.* 2014. Our goal is to document these most recent changes and put them in a historical perspective with comparisons with earlier trends.

5.2.2 Main findings, discussion and conclusions

Table 5.2 lists net SST changes from 1957 to 2012 for 66 LMEs plus the WPWP. These changes were estimated from linear regressions of annual mean SST. Plots of annual mean SST and accompanying narratives for each LME are available on the TWAP LME website and data portal (onesharedocean.org) and in the author's report to IOC/UNESCO (Belkin 2014).

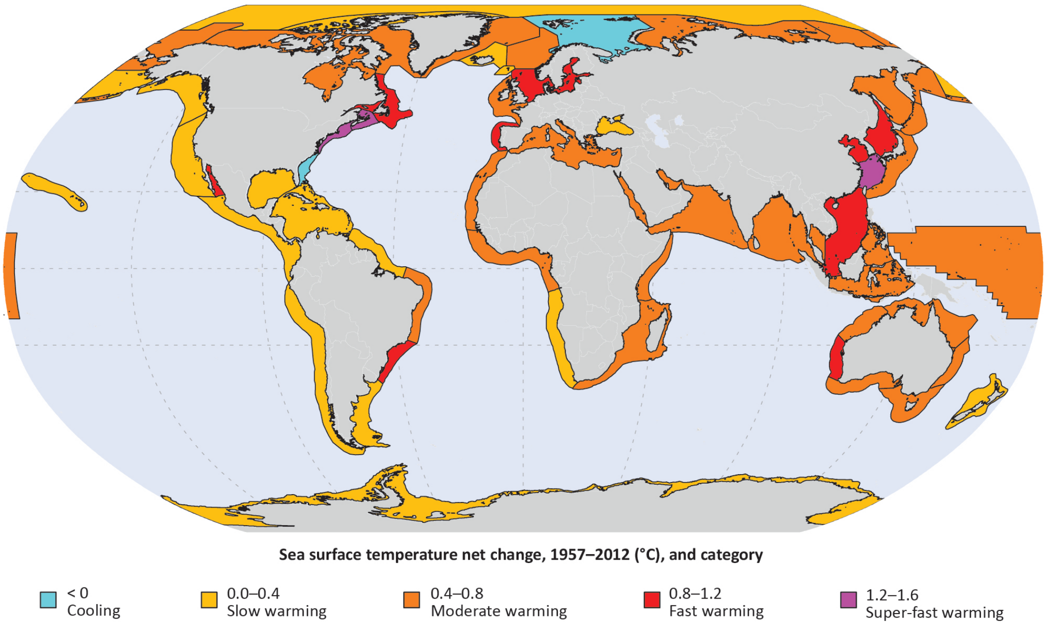
Table 5.2 Net sea surface temperature changes in LMEs and the WPWP, 1957–2012. Colour codes are used to map the distribution of SST change in Figure 5.8.

SST change category and colour code	LME	Change in SST (°C)
Super-fast warming	East China Sea	1.57
	Scotian Shelf	1.46
	Northeast US Continental Shelf	1.40
Fast warming	Gulf of California	1.13
	South Brazil Shelf	1.07
	Sea of Japan	1.05
	Newfoundland-Labrador Shelf	1.04
	West-Central Australian Shelf	0.96
	North Sea	0.93
	Baltic Sea	0.93
	Yellow Sea	0.93
	Iberian Coastal	0.90
	South China Sea	0.80
Moderate warming	Agulhas Current	0.72
	Kuroshio Current	0.70
	Oyashio Current	0.68
	Mediterranean	0.66
	Guinea Current	0.66
	Northern Bering-Chukchi Seas	0.65
	Sulu-Celebes Sea	0.64
	Southeast Australian Shelf	0.61
	Kara Sea	0.60
	Hudson Bay Complex	0.60
	East Brazil Shelf	0.59
	Canary Current	0.59
	East-Central Australian Shelf	0.58
	Sea of Okhotsk	0.57
	Norwegian Sea	0.55
	Somali Coastal Current	0.55
	Indonesian Sea	0.54
	Southwest Australian Shelf	0.54
	Bay of Bengal	0.53
	Northeast Australian Shelf	0.53
	Greenland Sea	0.51
	Celtic-Biscay Shelf	0.51
	Canadian Eastern Arctic-West Greenland	0.50
	Northwest Australian Shelf	0.50
	Arabian Sea	0.48
	West Pacific Warm Pool Province	0.48
	West Bering Sea	0.47
	Beaufort Sea	0.47
	Laptev Sea	0.47
	North Australian Shelf	0.44
	East Siberian Sea	0.44
	Gulf of Thailand	0.42
	Red Sea	0.40
	Aleutian Islands	0.40

SST change category and colour code	LME	Change in SST (°C)
Slow warming	North Brazil Shelf	0.38
	Iceland Shelf and Sea	0.36
	Black Sea	0.31
	Pacific Central-American Coastal	0.27
	Benguela Current	0.27
	East Bering Sea	0.24
	Humboldt Current	0.24
	Gulf of Mexico	0.16
	Caribbean Sea	0.15
	Canadian High Arctic-North Greenland	0.13
	Insular Pacific-Hawaiian	0.12
	Antarctic	0.12
	Faroe Plateau	0.10
	Central Arctic	0.10
	New Zealand Shelf	0.09
	Gulf of Alaska	0.06
	Patagonian Shelf	0.06
	California Current	0.02
Cooling	Barents Sea	-0.06
	Southeast US Continental Shelf	-0.28

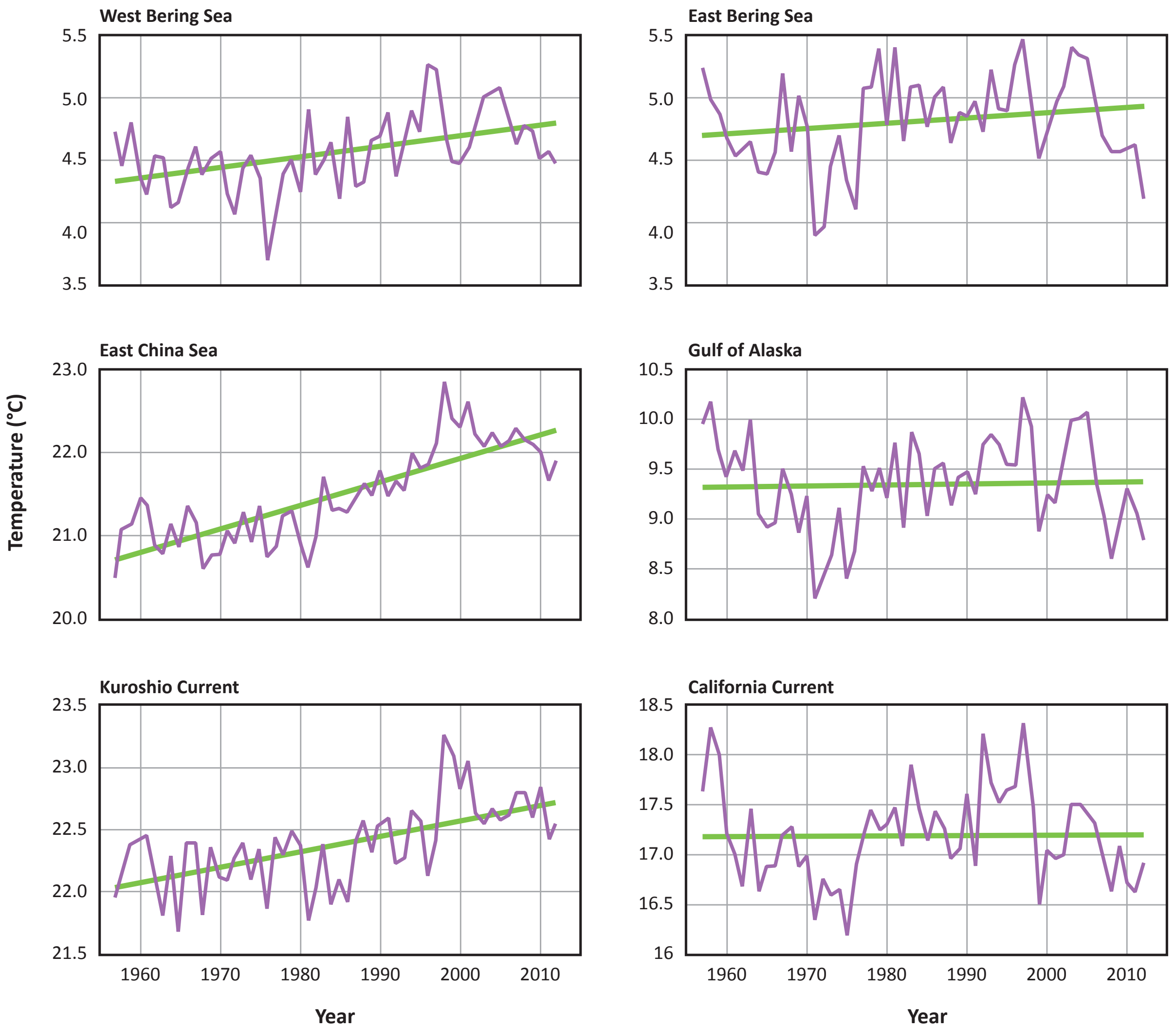
All but two LMEs warmed between 1957 and 2012 (Table 5.2 and Figure 5.8). Temperature change ranged from -0.28°C to 1.57°C over 55 years, varying widely between different regions and even between adjacent LMEs. The long-term warming between 1957 and 2012 was not steady in the great majority of LMEs. Instead, their thermal history consisted of alternating cooling and warming epochs, separated by regime shifts (Figure 5.9 to Figure 5.11). For example, the Southeast US Continental Shelf LME cooled by almost 0.3°C, while the nearby Northeast US Continental

Figure 5.8 Long-term sea surface temperature trends (net changes) in 66 LMEs, 1957–2012. The LMEs with the greatest increases in SST are concentrated in three regions: Northwest Atlantic, Northeast Atlantic, and Western Pacific. Long-term net cooling over this period was observed in two LMEs only: Barents Sea LME and Southeast US Continental Shelf LME. See Table 5.2 for sea surface temperature net change for each LME.



Calculated from linear regressions of annual SSTs for each LME.

Figure 5.9 Sea surface temperature time series in selected LMEs of the North Pacific. The regime shift of 1976–1977 in the Bering Sea, Gulf of Alaska, and California Current marked a transition from cooling to warming. The post-1997/1998 cooling is evident in these LMEs.

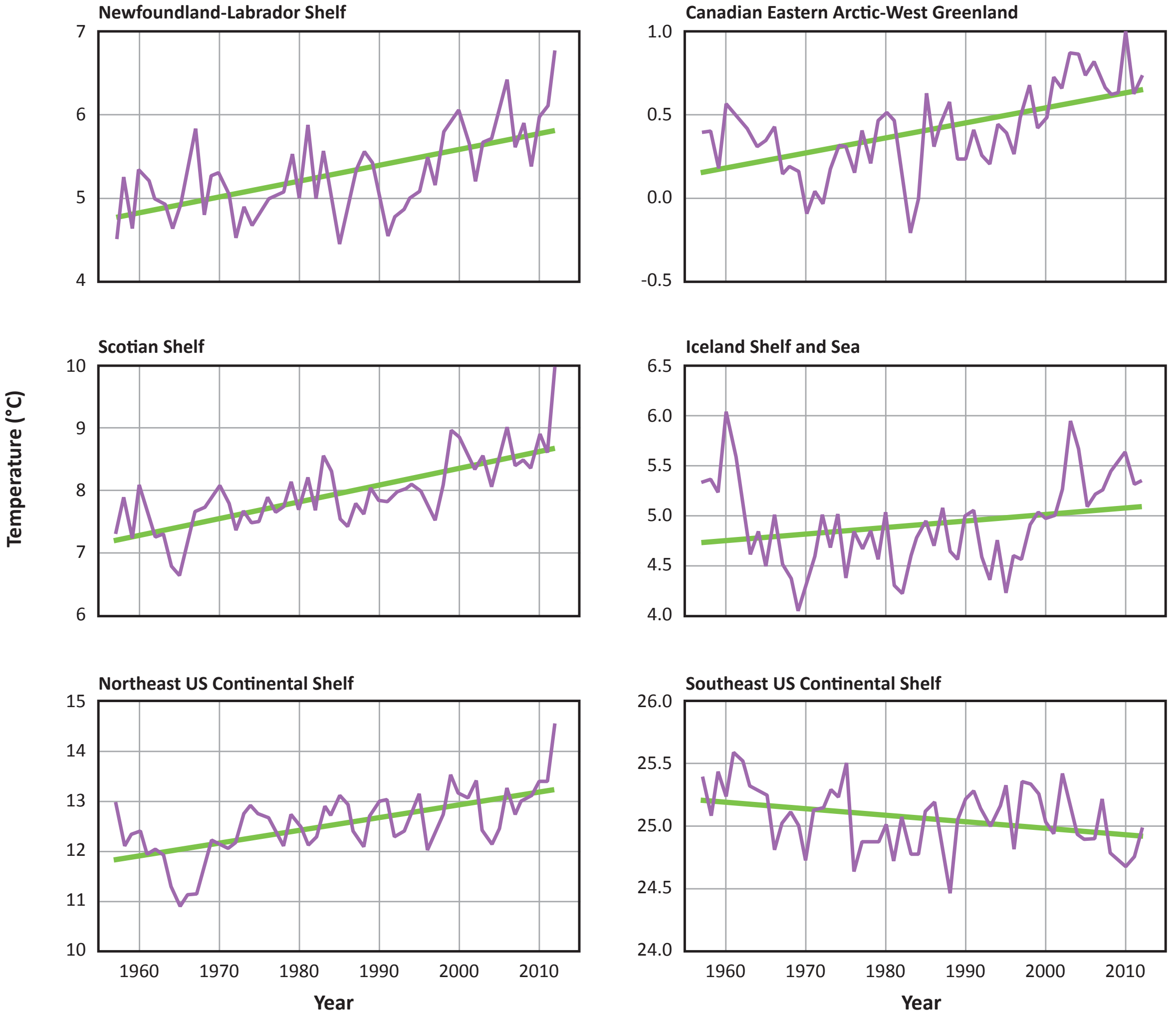


Note the variation in scales for temperature.

Shelf LME was one of the fastest warming LMEs in the world ocean, with a 1.4°C increase in SST over 55 years. In the North Atlantic, the most conspicuous regime shift in the 1970s to 1980s has marked a transition from cooling to warming (Figure 5.10 and Figure 5.11). In the North Pacific, the most conspicuous regime shift in SST occurred around 1976 to 1977, while the regime shift of 1988 to 1989 was not evident in the SST records (Figure 5.9; Hare and Mantua 2000).

The post-1998 data revealed a slowdown, and even a reversal, of the late 20th century warming in many North Pacific LMEs (Figure 5.9**;** Belkin and Lee 2014). Some LMEs in other regions also showed signs of this change. This is a global-scale phenomenon, with the annual mean global temperature showing no increase during the twenty-first century (Kosaka and Xie 2013). This phenomenon has recently become a focus of observational and modelling studies (Chen and Tung 2014; Drijfhout *et al.* 2014; England *et al.* 2014; Kosaka and Xie 2013). As pointed out by Easterling and Wehner (2009), "*…the climate over the 21st century can and likely will produce periods of a decade or two where the globally averaged surface air temperature shows no trend or even slight cooling in the presence of longer-term warming*." The global SST can be expected to exhibit variations similar to global air temperature on the same time scales, approximately 10 to 20 years. Any long-term climate change adaptation and mitigation policies should consider this variability.

Figure 5.10 Sea surface temperature time series in selected LMEs of the Western North Atlantic. The Northwest Atlantic experienced a steady warming, which abruptly accelerated after 2010. In the Canadian Eastern Arctic-West Greenland and off Iceland, cooling episodes in the late 1960s to early 1970s and early 1980s were linked to salinity anomalies accompanied by negative anomalies of SST. The Southeast US Continental Shelf LME is the only LME showing a steady decline of SST over the 1957–2012 period.



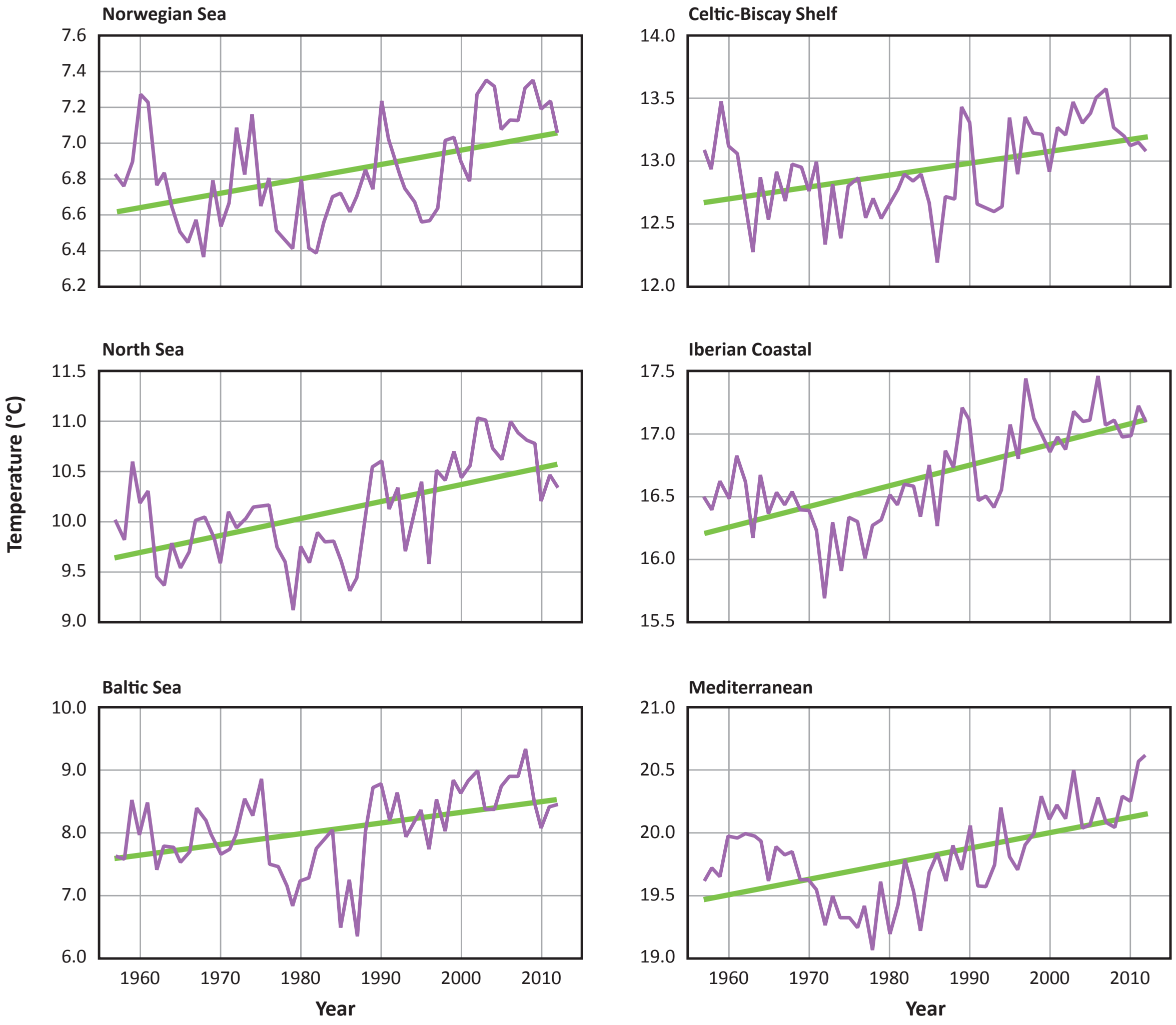
Note the variation in scales for temperature.

The global map of warming rates (Figure 5.8) illustrates regional variations of net changes. The full range of net changes in SST was divided into five intervals or categories (an optimum number for visual rendering of global distribution of net changes), with each interval encompassing a range of 0.4°C and consistent with the terminology introduced by Belkin (2009) (Table 5.3). Colour codes were used to represent the five categories to which the LMEs were assigned based on their net change in SST.

Table 5.3 Classification of LMEs based on net change in sea surface temperature, 1957–2012

Category and colour code		Range of changes in SST (°C)
Super-fast warming	🟪	1.2–1.6
Fast warming	🟥	0.8–1.2
Moderate warming	🟧	0.4–0.8
Slow warming	🟨	0.0–0.4
Cooling	🟦	-0.4–0.0

Figure 5.11 Sea surface temperature time series in selected LMEs of the Eastern North Atlantic (European seas). The fast warming in this region was not a regular progression – it was interrupted by cooling epochs. The most pronounced cooling episodes were linked to the low-temperature, low-salinity, high-sea-ice-cover salinity anomalies in the 1970s, 1980s, and 1990s. The Iberian Coastal and Mediterranean LMEs experienced sharp regime shifts in the 1970s, switching from rapid cooling to rapid long-term warming through the rest of the 1957–2012 period, over which SST has risen by approximately 1.5°C in both LMEs.



Note the variation in scales for temperature.

The above classification does not imply any natural (data-driven) clustering of LMEs. The analysis shows that all 66 LMEs are distributed rather evenly across the SST warming rate variability range and do not form any clusters (classes) of values.

The East China Sea LME warmed the most of all the LMEs (1.57°C between 1957 and 2012). The Southeast US Continental Shelf and the Barents Sea LMEs were the only two to cool during that period (by 0.28°C and 0.06°C respectively). In three large-scale regions, the long-term warming between 1957 and 2012 exceeded 0.8°C: (1) Western North Atlantic off the North American coast (Northeast US Continental Shelf, Scotian Shelf, and Newfoundland-Labrador Shelf LMEs); (2) Western Pacific (South China Sea, East China Sea, Yellow Sea, and Sea of Japan LMEs); and (3) Northeastern Atlantic (North Sea, Baltic Sea, and Mediterranean LMEs) as shown in Figure 5.9 to Figure 5.11. Three additional LMEs (Gulf of California, South Brazil Shelf, and West Australian Shelf) also experienced rapid warming (exceeding 0.8°C) between 1957 and 2012.

The SST time series shows long-term (decadal and multi-decadal) trends, separated by regime shifts between warming and cooling epochs. These trends show different patterns and time lines in different oceans. The North Atlantic's main trend pattern is characterized by cooling from the late 1950s to the early 1970s, continuing into the 1980s in some places, followed by warming up to the present time. Trends are punctuated by cold anomalies associated with the 'great salinity anomalies' that propagated around the North Atlantic Ocean in the 1970s, 1980s, and 1990s (Belkin *et al.* 1998; Belkin 2004). In the North Pacific, the most dramatic regime shift was around 1976 to 1977, followed by another regime shift in 1988/1989 (Hare and Mantua 2000). However, the impact of the 1988 to 1989 regime shift on the thermal state (characterized by SST) of the North Pacific LMEs was significantly less than the impact of the earlier regime shift. Somewhat surprisingly, the Arctic Ocean and its coastal seas, as a whole, have not experienced the accelerated warming that has been observed in air temperature over Arctic landmasses.

5.2.2.1 Impacts on marine ecosystems and services and socio-economic and policy implications

Global warming has already affected marine ecosystems significantly (Cheung *et al.* 2013; Sherman *et al.* 2009, 2011, 2013, 2014a and 2014b; Halpern *et al.* 2008). This impact is projected to increase (Trenberth *et al.* 2007). Warming may affect fish or other biota at a global scale (Klyashtorin and Lyubishin, 2007), although the mechanisms at work are not clear. The global warming signal translates down to ocean-scale, basin-scale, and LME-scale signals that affect ecosystems and marine living organisms through changes in ambient temperature. Long-term consequences of global warming will be LME-specific (Sherman *et al.*, 2009, 2011, 2013, 2014a, 2014b), therefore LME-scale estimates and projections of SST warming and cooling rates are especially important. There is no consistent link between SST trends and environmental risks. Sherman *et al.* (2011 and 2013) have shown that the ongoing warming is beneficial for many LMEs, but detrimental to others. Sherman *et al*. (2009) recommended protecting current and future fisheries yields with a cap-and-sustain strategy in certain LMEs as a precautionary action in the light of the uncertainties around climate warming effects. Climate warming is associated with non-linear changes in fish stock abundance that are difficult to predict.

5.2.2.2 Confidence levels

The overall confidence level of the main results and conclusions is very high. The confidence levels of individual results, which are summarized in the key messages section at the beginning of this chapter, vary from high to very high. Confidence in the conclusion that all but two LMEs have warmed since 1957 is high, while very high confidence is assigned to conclusions about regional and temporal patterns of warming, and about the post-1999 slowdown of warming in most North Pacific LMEs.

5.2.3 Data and methodology

This analysis uses the same data set and methodology as Belkin (2009). The main reason for choosing SST to represent ocean climate is that SST is the only oceanic variable that has been routinely measured worldwide since the 19th century, thereby providing the longest instrumental record of ocean climate change compared to other oceanic observables. Of the few global SST climatologies available, we have chosen the UK Met Office Hadley Centre SST climatology designated as HadISST1 (Rayner *et al.* 2003 and 2006). This includes data as far back as 1870. It has the best spatial and temporal resolution (1°x 1° and monthly, respectively) compared with other data sets. Overall, the Hadley climatology appears to be the best choice and was therefore used in the IPCC-2007 Report (Trenberth *et al.*, 2007).

For each LME, annual mean SST was calculated from monthly SSTs in 1° x 1° cells, area-averaged within the given LME. The square area of each spherical trapezoidal 1° x 1° cell is proportional to the cosine of the middle latitude of the given cell, thus all SSTs were weighted by the cosine of the cell's middle latitude. After integration over the given LME area, the resulting sum of weighted SSTs was normalized by the sum of the weights (cosines). For each LME, long-term LME-averaged SSTs were computed by long-term averaging of annual area-weighted LME-averaged SSTs. Anomalies of annual LME-averaged SST were calculated by subtracting the long-term mean SST from the annual SSTs. Long-term trends based on linear regression were calculated from annual SSTs for each LME. Net SST changes (warming rates) between 1957 and 2012 were calculated based on the linear SST trends.

References

Behrenfeld, M.J., O'Malley, R.T., Siegel, D.A., McClain, C.R. and others (2006). Climate-driven trends in contemporary ocean productivity. *Nature* 444, 752–755

Belkin, I.M. (2004). Propagation of the "Great Salinity Anomaly" of the 1990s around the northern North Atlantic. *Geophysical Research Letters* 31 (8), L08306. doi: 10.1029/2003GL019334

Belkin, I.M., (2009). Rapid warming of Large Marine Ecosystems. *Progress in Oceanography* 81 (1-4), 207-213. doi: 10.1016/j.pocean.2009.04.011

Belkin, I.M. (2014). Long-term variability of sea surface temperature in Large Marine Ecosystems: An update, 1957-2012. Final Report to IOC/UNESCO, University of Rhode Island, Narragansett, USA, Part 1, 10 pp., Part 2, 67 pages

Belkin, I.M. and Lee, M.A. (2014). Long-term variability of sea surface temperature in Taiwan Strait. *Climatic Change* 124 (4), 821-834. doi: 10.1007/s10584-014-1121-4

Belkin, I.M., Levitus, S., Antonov, J. and Malmberg, S-A. (1998). "Great Salinity Anomalies" in the North Atlantic. *Progress in Oceanography* 41 (1), 1-68. doi: 10.1016/S0079-6611(98)00015-9

Boyce, D.G., Lewis, M.R. and Worm, B. (2010). Global phytoplankton decline over the past century. *Nature*, 466, 591–596

Chen, X.Y. and Tung, K.K., (2014). Varying planetary heat sink led to global-warming slowdown and acceleration. *Science* 345 (6199), 897-903. doi: 10.1126/science.1254937

Cheung, W.L., Watson, R. and Pauly, D. (2013). Signature of ocean warming in global fisheries catch. *Nature* 497, 365-369. doi: 10.1038/nature12156

Drijfhout, S.S., Blaker, A.T., Josey, S.A. and others (2014). Surface warming hiatus caused by increased heat uptake across multiple ocean basins. *Geophysical Research Letters* 41 (22), 7868-7874. doi: 10.1002/2014GL061456

Duda, A. and Sherman, K. (2002). A new imperative for improving management of large marine ecosystems. *Ocean and Coastal Management* 45 (11-12), 797-833. doi: 10.1016/S0964-5691(02)00107-2

Easterling, D.R. and Wehner, M.F. (2009). Is the climate warming or cooling? *Geophysical Research Letters* 36, L08706. doi: 10.1029/2009GL037810

England, M.H., McGregor, S., Spence, P. and others (2014). Recent intensification of wind-driven circulation in the Pacific and the ongoing warming hiatus. *Nature Climate Change* 4, 222-227. doi: 10.1038/NCLIMATE2106

Halpern, B.S., Walbridge, S., Selkoe, K.A. and others (2008). A global map of human impact on marine ecosystems. *Science* 319 (5865), 948-952. doi: 10.1126/science.1149345

Hare, S.R. and Mantua, N.J. (2000). Empirical evidence for North Pacific regime shifts in 1977 and 1989. *Progress in Oceanography* 47 (2-4), 103-145. doi: 10.1016/S0079-6611(00)00033-1

Hartmann, D.L., Klein Tank, A.M.G., Rusticucci, M., Alexander, L.V. and others (2013). Observations: Atmosphere and Surface. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (eds. Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Klyashtorin, L.B. and Lyubishin, A.A. (2007). *Cyclic Climate Changes and Fish Productivity*. (ed. Sharp, G.D.). VNIRO Publishing, Moscow, 224 pages

Kosaka, Y. and Xie, S.P. (2013). Recent global-warming hiatus tied to equatorial Pacific surface cooling. *Nature* 501 (7467), 403-407. doi: 10.1038/nature12534

Levitus, S., Antonov, J. and Boyer, T., (2005). Warming of the world ocean, 1955–2003. *Geophysical Research Letters* 32 (2), L02604. doi: 10.1029/2004GL021592

Levitus, S., Antonov, J.I, Boyer, T.P. and others (2012). World Ocean heat content and thermosteric sea level change (0-2000 m), 1955-2010. *Geophysical Research Letters* 39, L10603, doi: 10.1029/2012GL051106

Lewandowska, A.M., Boyce, D.G., Hofmann, M., Matthiessen, B., Sommer, U. and Worm, B. (2014). Effects of sea surface warming on marine plankton. Ecology Letters, doi: 10.1111/ele.12265

Polovina, J. J., Howell, E. A., and Abecassis, M. (2008). The ocean's least productive waters are expanding. *Geophysical Research Letters*, 35: L03618. doi:0.1029/2007GL031745

Polovina, J.J., Dunne, J.P., Woodworth, P.A. and Howell, E.A. (2011). Projected expansion of the subtropical biome and contraction of the temperate and equatorial upwelling biomes in the North Pacific under global warming. ICES Journal of Marine Science 68(6), 986–995, doi:10.1093/icesjms/fsq198

Rayner, N.A., Parker, D.E., Horton, E.B. and others (2003). Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *Journal of Geophysical Research* 108 (D14), 4407. doi: 10.1029/2002JD002670

Rayner, N.A., Brohan, P., Parker, D.E. and others (2006). Improved analyses of changes and uncertainties in sea surface temperature measured *in situ* since the mid-nineteenth century: The HadSST2 dataset. *Journal of Climate* 19 (3), 446-469. doi: 10.1175/JCLI3637.1

Sherman, K., Sissenwine, M., Christensen, V. and others (2005). A global movement toward an ecosystem approach to management of marine resources. *Marine Ecology Progress Series* 300, 275-279

Sherman, K., Belkin, I.M., Friedland, K.D. and others (2009). Accelerated warming and emergent trends in fisheries biomass yields of the World's Large Marine Ecosystems. *AMBIO* 38 (4), 215-224

Sherman, K., O'Reilly, J., Belkin, I.M. and others (2011). The application of satellite remote sensing for assessing productivity in relation to fisheries yields of the world's large marine ecosystems. *ICES Journal of Marine Science* 68 (4), 667-676. doi: 10.1093/icesjms/fsq177

Sherman, K., Belkin, I., Friedland, K.D. and O'Reilly, J. (2013). Changing states of North Atlantic large marine ecosystems. *Environmental Development* 7, 46-58. doi: 10.1016/j.envdev.2013.05.004

Sherman, K. (2014a). Adaptive management institutions at the regional level: The case of Large Marine Ecosystems. *Ocean & Coastal Management 90*, 38-49. doi: 10.1016/j.ocecoaman.2013.06.008

Sherman, K. (2014b). Toward ecosystem-based management (EBM) of the world's large marine ecosystems during climate change. *Environmental Development* 11, 43-66. doi: 10.1016/j.envdev.2014.04.006

Trenberth, K.E., Jones, P.D., Ambenje, P. and others (2007). Observations: Surface and Atmospheric Climate Change (eds. Solomon, S., Qin, D., Manning, M. and others), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom, and New York, NY, USA, 235-336

© L.Heileman

Chapter 6
Fishand Fisheries

© L. Heileman

Chapter 6.1. The Status of fisheries in large marine ecosystems, 1950–2010

Lead Authors

Daniel Pauly, Vicky W.Y. Lam (Sea Around Us, Fisheries Centre, University of British Columbia).
Lead authors contributed equally to this chapter.

Chapter Citation

Pauly, D., Lam, V.W.Y. (2016). Chapter 6.1: The Status of fisheries in large marine ecosystems, 1950–2010. In IOC-UNESCO and UNEP (2016). *Large Marine Ecosystems: Status and Trends*. United Nations Environment Programme, Nairobi, pp 113-137.

Fish and Fisheries

6.1 The Status of fisheries in large marine ecosystems, 1950–2010

SUMMARY

The traditionally local and sectoral focus of fisheries science, monitoring, and management has precluded the development and use of indicators at large spatial scales. With the advent of concepts such as large marine ecosystems (LMEs) it has become evident that such indicators will be needed for better integration of fisheries in ecosystem-based management approaches. Such approaches are particularly important because of the large-scale migrations of some exploited stocks and the increasing role of distant-water fleets. This chapter presents the methods for developing LME-scale fish-catch time series, along with evaluation of a set of derived ecosystem indicators for each LME except the Barents Sea and Norwegian Sea, and the Western Pacific Warm Pool (WPWP).

Global landings data, assembled mainly by the Food and Agriculture Organization (FAO), are mapped by the Sea Around Us (www.seaaroundus.org) on a worldwide grid. Data are then regrouped into LMEs and the WPWP. This data set was used to produce the annual catches for each LME by taxa for 1950 to 2006, with time series extended to 2010 based on reported changes in aggregated landings. The landings were then combined with other parameters, such as primary production, to compute more informative catch-related indicators. The data were used to evaluate nine indicators: 1) ratio of capacity-enhancing subsidies to the value of landed catch; 2) primary production required (PPR) to sustain the landings reported by countries fishing within the LME (a measure of the ecological footprint); 3) Marine Trophic Index (MTI); 4) Fishing-in-Balance (FiB) Index; 5) stock status by number; 6) catch biomass of exploited stocks; 7) catch from bottom-impacting gear types; 8) fishing effort; 9) change in catch potential under projected global climate change by the 2050s. The average indicator values for 2000 to 2010 were used to group the 64 assessed LMEs into five categories according to their relative level of ecological degradation or potential impacts (or risk) from fisheries. The confidence levels for data and indicators are: low for fishing effort data; medium for potential fish catch associated with climate change; ranging from low to medium for the nine indicators.

The total annual landings in all LMEs increased over the 60-year period and peaked at 64 million tonnes in 1994. In the last decade (2000 to 2010), the total annual landings in all LMEs fluctuated between 56 and 62 million tonnes, corresponding to about 73 to 76 per cent of global marine fish landings. Conclusions from evaluation of the nine indicators include:

- Many LMEs have high proportions of exploited stocks in the collapsed and overexploited categories;
- Decreases in the trophic levels of catches (seen in the MTI trends) and spatial expansion of fisheries (seen in the FiB Index trends) are occurring in many LMEs, indicating ecosystem impacts of fishing and the reaction of fisheries, respectively;
- Global fishing effort is still generally increasing. Among the 64 LMEs assessed, the Bay of Bengal and Sulu-Celebes Sea have the highest rates of change in effective fishing effort in the last decade;
- The Antarctic and the Baltic Sea LMEs have the highest levels of capacity-enhancing subsidies (financial assistance from the governments) relative to the landed catch value. The East China Sea is among the LMEs with high ecological footprints (measured as PPR). The largest projected decrease in catch potential

under climate change is in the East Siberian Sea and Indonesian Sea LMEs. The proportion of the catch from bottom-impacting gear to the total catch is highest in the Southeast US Continental Shelf LME;

- The WPWP shows similar trends to the mean LME trends for some indicators, but has experienced greater increases in some indicators of ecosystem degradation or pressure, including effective fishing effort. Under a climate change scenario, the catch potential in 2050 for the WPWP is projected to drop by 7 per cent, compared to an expected mean increase of about 9 per cent in the LMEs.

Key Messages

1. **Sources of pressure and degree of risk to ecosystems from fisheries vary among LMEs, with implications for management.** Management approaches need to be tailored to the dominant sources of pressure. Only the Laptev Sea and Northern Bering-Chukchi Sea LMEs in the Arctic do not have any indicators in the 'high' and 'highest' risk categories, and nearly 80 per cent of LMEs have three or more of the nine indicators in the 'high' or 'highest' risk categories. There were, however, no consistent patterns in the distribution or combinations of indicators with high-risk levels.
2. **Although the number of collapsed stocks in LMEs is increasing, the number of rebuilding stocks is also increasing, an encouraging sign.** Overall, 50 per cent of global stocks within LMEs are deemed overexploited or collapsed, and only 30 per cent fully exploited. However, the fully exploited stocks still provide 50 per cent of the globally reported landings, with the remainder produced by overexploited, collapsed, developing and rebuilding stocks. This appears to confirm the common observation that fisheries tend to affect biodiversity (as reflected in the taxonomic composition of catches) even more strongly than they affect biomass (as reflected in the landed quantities).
3. **The parts of LMEs that are under national jurisdiction should do better, as both domestic and foreign fishing within exclusive economic zones (EEZs) can be regulated by the coastal countries concerned.** The parts of LMEs that are beyond the EEZs of coastal states are subjected to a management regime that is essentially open-access. A few countries are fully using the governance tools available to them to rebuild overfished stocks and mitigate the impact of fishing and competition between local and foreign fleets in their EEZs, and hence in the LMEs that they belong to.
4. **The projected change in the productivity of marine living resources under climate change may have significant implications for the fishing industries, economies, and livelihoods of many countries.** This is because climate change affects marine ecosystems and is expected to affect fisheries and a range of other ecosystem services. The East Siberian Sea and Indonesian Sea LMEs are projected to be the most affected by warming, with the largest decrease in fish catch potential by the 2050s. The projected substantial decrease in the catch potential of certain LMEs due to global warming would cause these regions to become more vulnerable as a result of other synergistic factors such as increasing fishing and socio-economic pressures.
5. **Fisheries and other statistics for LMEs are always uncertain composites and the indicators derived here may not represent any specific country or policy.** This is partly because countries do not report fisheries data at the LME scale. In addition, countries bordering a specific LME may be rebuilding their exploited stocks and have different fisheries policies that affect trends for the LME.
6. **Accurate catch data needed for fisheries assessments are not available because the fisheries statistics supplied by member countries to the FAO usually fail to account for small-scale fisheries.** Catch reconstruction data accounting for small-scale fisheries (artisanal, subsistence, and recreational) at the national level are needed to improve the accuracy of LME catch time series and hence the quality of the indicators.

6.1.1 Introduction

While there is a need for countries to manage fisheries within their Exclusive Economic Zones (EEZs), better integration of fisheries could be achieved at the level of LMEs (Sherman *et al.* 2003; contributions in Sherman and Hempel 2008; Pauly *et al.* 2008, from which this chapter was adapted), given the large-scale migrations of some exploited stocks and the increasing role of distant-water fleets (Pauly *et al.* 2013; Bonfil *et al.* 1998).

Although there have been some efforts to use ecological indicators such as IndiSeas (http://www.indiseas.org/; Shin and Shannon.2010) to compare the ecological states of LMEs, there are still no LME-level national or international jurisdiction reports, catch data sets, or other measures from which fisheries sustainability indicators could be derived. Therefore, the fisheries within LMEs must be documented explicitly for this purpose, mainly by assembling data sets from national and other sources. This was done using an approach developed by Watson *et al.* (2004), which relies on splitting the world oceans into more than 180 000 spatial cells of one-half degree latitude-longitude and mapping all catches that are extracted from the corresponding areas onto these cells, by species and higher taxa. The catches in these spatial cells can then be regrouped into higher spatial aggregates, such as the 66 LMEs that have so far been defined in the world's oceans.

Since these aggregates of spatial cells can then be combined with other data (for example, the ex-vessel price of the fish caught, or their trophic level), one can then easily derive other time series, such as indicators of the degree to which LMEs may be degraded or impacted by fisheries. In this chapter we present the methods of obtaining fish-catch time series, along with a set of derived time series ecosystem indicators for all LMEs and the WPWP (Box 6.1).

Box 6.1 Sea Around Us fisheries indicators: definitions and interpretation

As elsewhere in this report, the chapters dealing with fisheries in LMEs use indicators – devices for providing information on a state or trend of something. Because an indicator is not the 'something' that it is linked to, understanding the definition of the indicator is very important for understanding the state or trend that the indicator illustrates.

Thus, for example, stock-status plots, as defined and used by the Sea Around Us (Kleisner *et al*. 2013) are not based on meta-analyses of the actual stock assessments performed for resource species in an EEZ or LME, as might be expected. Rather, stock-status plots are defined by the specific procedure used to generate them, which is based on:

1. identifying the peak (C_{max}) of a time series of catches for a given species/EEZ or species/LME combination;
2. expressing fisheries status in any given year with reference to C_{max}. For example, where catch is less than 50 per cent of C_{max}, status is 'developing'; where catch is 50 per cent or more of C_{max}, status is 'fully exploited' (Kleisner *et al.* 2013 and section 6.1.4.6); and
3. presenting cumulated fisheries status for (3a) all stocks of an EEZ or LME, or (3b) the biomass caught by the fisheries of different status.

Item 3a tends to cause misunderstandings because readers often expect this indicator to reflect the status of assessed stocks in an EEZ or LME, while instead it refers to all species in the catches reported from the area in question, including species that are not assessed (and are often overfished). Thus, because of different definitions, the TWAP LMEs assessment may show different stock status than other assessments. In such cases it is better to refer to the indicator in 3b because the non-assessed species usually contribute little to overall catches. Note also that the trends of stock status plots are far more important than the percentages of stocks of a given status in a given year. The indicator results are presented here as averages for the period 2000-2010.

Similarly, values of indicators that rely on estimates of subsidies depend on what is considered a 'subsidy', which can vary among countries, and on the years for which subsidy estimates are available. The Sea Around Us definition of subsidies follows the definition of 'financial transfers' of the Organization for Economic Cooperation and Development (OECD), which differs from the definitions used by various countries. Thus, the OECD publishes subsidy estimates for countries which, by their own definitions, do not subsidize their fisheries. In all such cases, we have adopted the approach of the OECD and other providers of internationally available data, such as the United Nations (UN) or Food and Agriculture Organization (FAO), even if their data were less current than the data available nationally.

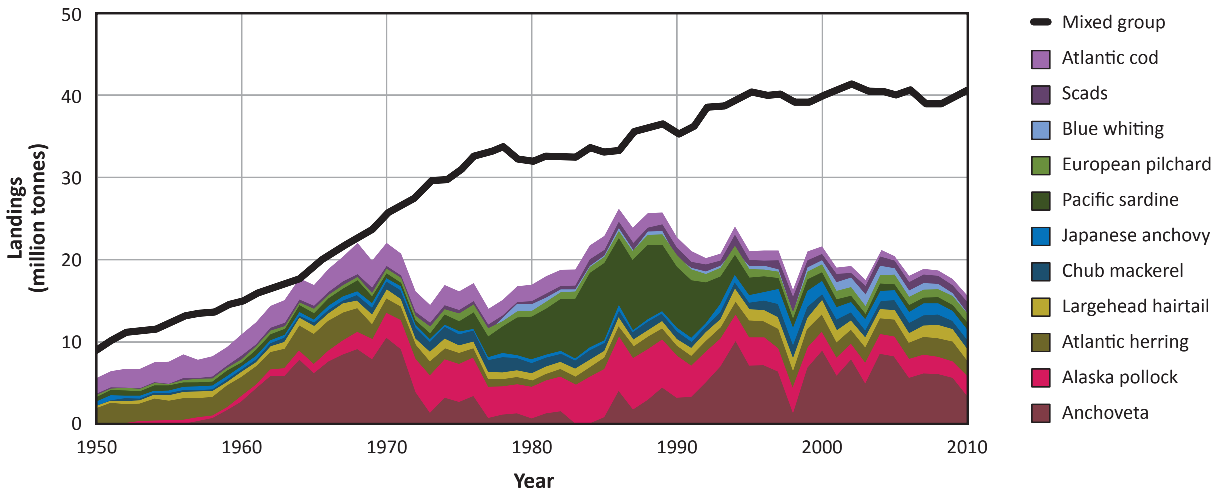
6.1.2 Main findings

6.1.2.1 Fishing pressures in LMEs and human drivers

Annual landings

Figure 6.1 shows landings, by species, for all LMEs. There are some uncertainties associated with the filters and gradients used to allocate the catch spatially to grid cells (Watson 2011). The first source of uncertainty is identification of the landed species or group. Secondly, there are some uncertainties about the reporting countries because, for example, some of the vessels may be reflagged. Thirdly, the statistical area from which the catch originates can be uncertain, mainly because, for the sake of convenience, some countries report their catch as being all from one area, even though they fish in several areas. The uncertainties inherent in the initial database were resolved as far as possible by using information from other databases. Since annual landings are used for providing inputs to several secondary indicators that are included here, such as catch from bottom-impacting gear, value of landings, fish-stock status, and Marine Trophic Index, the uncertainties associated with the landings would also carry forward to these secondary indicators.

Figure 6.1 Time series of landings by species in all LMEs, 1950–2010



Total annual landings generally increased over the period 1950 to 2010, peaking at 64 million tonnes in 1994. In the last decade (2000 to 2010), total annual landings in all LMEs fluctuated between 56 and 62 million tonnes. According to Garibaldi and Limongelli (2003), the total catch of the 867 species classified as distributed in the LMEs represented about 90 per cent of the global marine catches. This is close to a previous estimate (Sherman 1994) of approximately 95 per cent of total world marine fisheries catches. However, estimates from the Sea Around Us (www.seaaroundus.org), because they are based on higher spatial precision and achieve higher precision in dividing the data by species, show a discrepancy in the percentage of catch from these earlier estimates. The average contribution of LMEs to the world catch, based on the Sea Around Us, has declined from around 83 to 87 per cent in the early decades of the 60-year period to around 73 to 76 per cent in recent years.

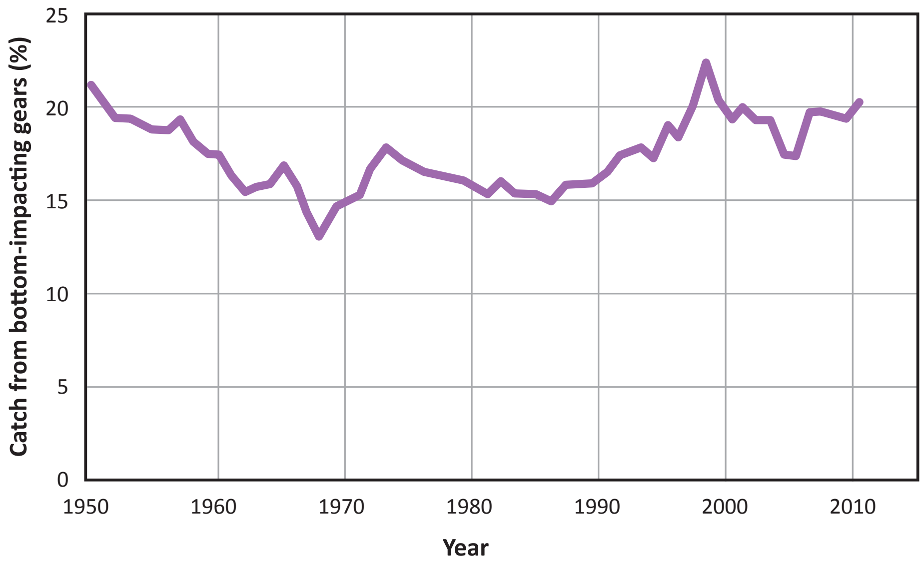
Figure 6.1 shows trends in landings for the 11 most abundant species, with the remainder pooled into a ‘mixed group’. Since not many species are globally important, the chart shows more ‘mixed group’ landings than would typically occur in any one LME. The only major species group not caught mainly in LMEs is large pelagic fishes, mainly tuna (7 per cent of the global catch in the 2000s). The remaining species include both high-seas-only species, such as Antarctic toothfish, and ‘straddling’ groups such as mackerel and squids.

The absolute level of fisheries catch (or landings) in a given LME cannot be used as an indicator of anything (except that fishing occurs). Catch level will vary with the size of the LME and its environmental conditions, as well as with the history and level of exploitation. For catch levels to be informative about, for example, the degree of degradation of an LME from fisheries, the catch levels must be related to primary production of the LME, previous catches (as shown below), changes in management, or other confounding factors, or they must be used to compute catch-related indicators.

Catch from bottom-impacting gear

The relative contribution of the total LME catch that is caught by bottom-impacting gear (mainly trawls, also some dredges; Watson *et al.* 2006a and 2006b) is an indicator of potential ecosystem degradation from fisheries. The trend of the proportion of catch from bottom-impacting gear to the total annual catch in all LMEs is shown in Figure 6.2. The proportion reached its peak in 1998 and then declined slightly, fluctuating around 20 per cent over the past decade. The Southeast US Continental Shelf LME has the highest percentage of catch from bottom-impacting gear.

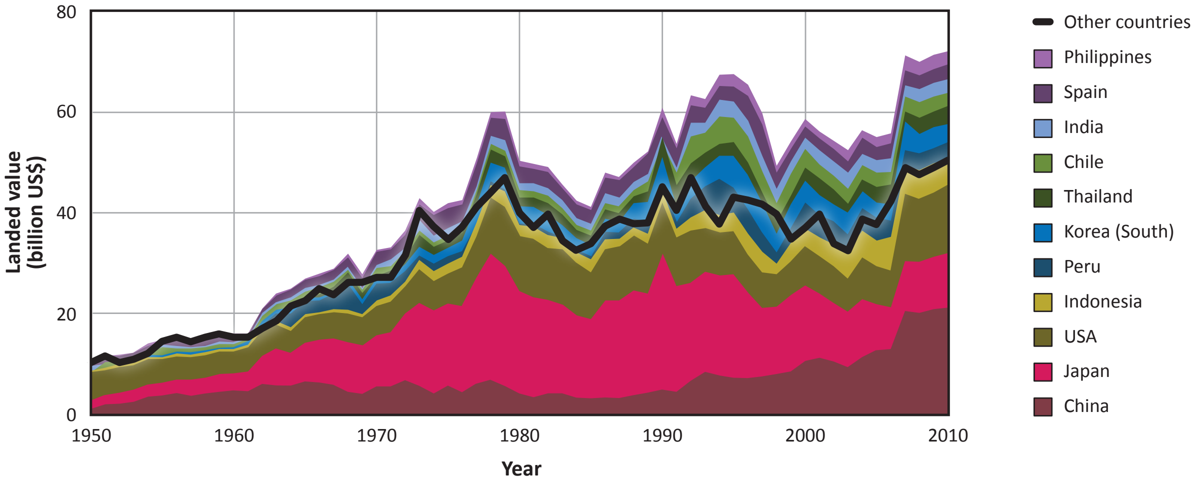
Figure 6.2 Percentage of the total annual catch from bottom-impacting gears in all LMEs, 1950–2010



Value of landings and capacity-enhancing subsidies

Fishing is an economic operation, and the ex-vessel value (Swartz *et al.* 2013; Sumaila *et al.* 2007) of the landings (value of the first sale of the fish) has to cover all fixed and variable costs of fishing and still generate a profit, except when fisheries are subsidized (Sumaila *et al.* 2013). One of the uncertainties around the ex-vessel value is a consequence of overestimation of the average value of the low-trophic, small pelagic fishes, which occurs because the model of Swartz *et al.* (2013) does not distinguish between fish for direct human consumption and low-value fish for fishmeal production. Figure 6.3 shows the annual landed values for the 11 fishing countries with the highest values in all 66 LMEs. China has the highest landed values in the last decade; however, the sharp increase in the mid-2000s is questionable, and may be due to over-reported landings data by China to the FAO. As can be seen, LMEs account for most of the value of the world's marine fisheries catches, with an average of 72 per cent of the value of global landings in the last decade. The total landed value increased overall in the past 60 years, but fluctuated between US$80 billion and US$120 billion over the last two decades.

Figure 6.3 Ex-vessel value of reported landings in all LMEs, by country



Coloured time series are for the top 11 fishing countries; landed values of other countries combined are represented by a black line. All values presented are based on real 2005 prices (deflated prices).

As with amount of fish caught, the absolute value of fisheries catches in a given LME cannot be used as indicator of anything (except that fishing occurs and the catch is sold). However, a useful related indicator is the ratio of capacity-enhancing subsidies to total landed catch value (Sumaila *et al.* 2008 and 2013; Sumaila and Pauly 2006), since such subsidies could contribute to the degradation of marine ecosystems. The value of this indicator ranges from 0 to 0.8 (Table 6.1). The higher the ratio, the greater the potential for ecosystem degradation. The Baltic Sea, Kara Sea, and Greenland Sea LMEs have the highest ratios among the 64 assessed LMEs (Annex Table 6-A).

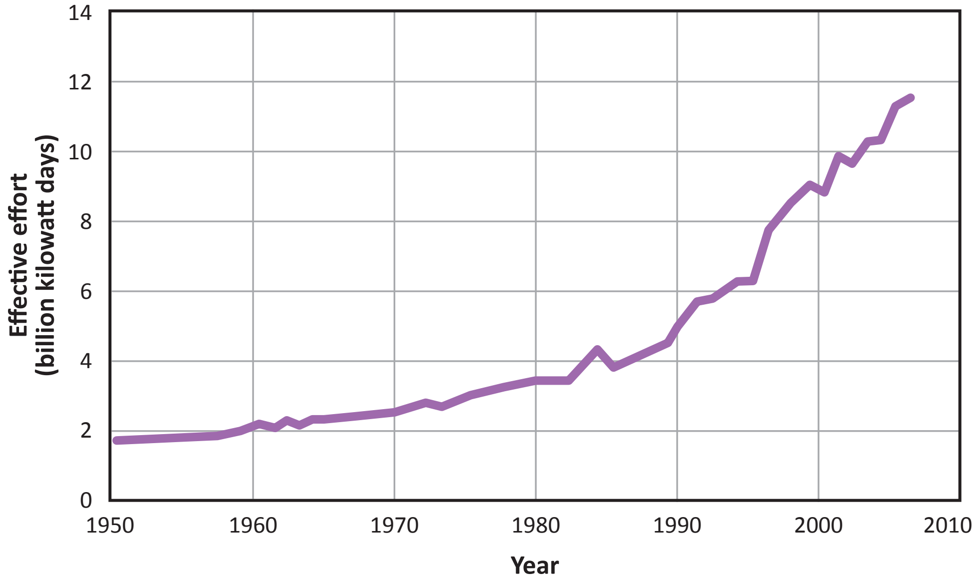
Table 6.1 Five relative risk categories and cut-off points used for grouping the LMEs for each indicator

Risk category colour code	Level of risk/degradation	Subsidy to landed value	Ecological footprint (PPR/PP)	MTI	FiB	Stock status (number) (% of stocks collapsed or overexploited)	Stock status (biomass) (% of stocks collapsed or overexploited)	% catch from bottom-impacting gear	Rate of change of effective fishing effort (million kW days per year)	% change in catch potential in the 2050s
		Range of values								
🟦	Lowest	0 – 0.09	0 – 0.012	0.04 – 0.8	-5 – -0.85	0 – 34	0 – 10	0 – 10.5	-20 – 0.2	14.5 – >100
🟩	Low	0.09 – 0.16	0.012 – 0.06	-0.028 – 0.04	-0.85 – 0.39	34 – 46	10 – 18	10.5 – 15	0.2 – 1.8	3.5 – 14.5
🟨	Medium	0.16 – 0.22	0.06 – 0.14	-0.12 – -0.028	0.39 – 0.9	46 – 51.5	18 – 31.5	15 – 20	1.8 – 5.7	-3.6 – 3.5
🟧	High	0.22 – 0.31	0.14 – 0.25	-0.35 – -0.12	0.9 – 1.8	51.5 – 59	31.5 – 47.8	20 – 32.3	5.7 – 10	-8 – -3.6
🟥	Highest	0.31 – 0.8	0.25 – 1.3	-1.5 – -0.35	1.8 – 4.2	59 – 100	47.8 – 100	32.3 – 100	10 – 130	-28 – -8

Fishing effort

Fishing effort can be defined as the total energy used (for example by a fleet of fishing vessels) to catch fish during a specified period. It can be expressed, for example, for a particular year, by multiplying the total power of all the engines in the vessels in the fleet (in million kilowatts) by the number of days at sea in that year. Global fishing effort was estimated to exceed optimum levels by a factor of two to four in the early 2000s (Pauly *et al.* 2002) and is still generally increasing (Anticamara *et al.* 2011; Watson *et al.* 2013). This 'nominal' effort calculated from the fleet's engine power and days fishing can be adjusted to reflect the gradual technological improvements in fish finding and catching that can result in an increase in the quantity of fish caught per unit of fishing effort. The resulting 'effective' effort is equivalent to an increase of nominal effort of 1 to 3 per cent per year (Pauly and Palomares 2010; Pauly *et al.* 2002). For this report, this technological improvement factor was set at 2.42 per cent per year, based on a prior meta-analysis of published efficiency increases (Pauly and Palomares 2010). A database of the nominal fishing effort deployed by the world's maritime countries was created by Anticamara *et al.* (2011), and spatialized by Watson *et al.* (2013). This database was used to estimate the effective fishing effort by LME from 1950 to 2006, shown aggregated for all LMEs in Figure 6.4.

Figure 6.4 Aggregate effective fishing effort in LMEs, 1950–2006



Many countries have incomplete data sets on fishing effort (for example, including years with no reported effort), while some countries have no statistics on fishing effort (Watson *et al.* 2013; Anticamara *et al.* 2011). Although these gaps were filled by using the method described in Anticamara *et al.* (2011), the fishing effort of global tuna fleets and those fleets fishing in the Antarctic were not estimated. While this previous version of the Sea Around Us global fishing effort database was a good foundation for assessing the pattern of global fishing effort over time, it was not adequate for the details related to reconstructing fishing effort for each EEZ individually. Currently, the global fishing effort database is being updated by Sea Around Us to 2010. However, this updating process was not complete at the time of writing. The LMEs with the rate of change in effective effort greater than 10 million kilowatt days per year were assigned to the highest risk category. The Bay of Bengal and Sulu-Celebes Sea LMEs have the highest rate of change in effective fishing effort in the last decade (Annex Table 6-A).

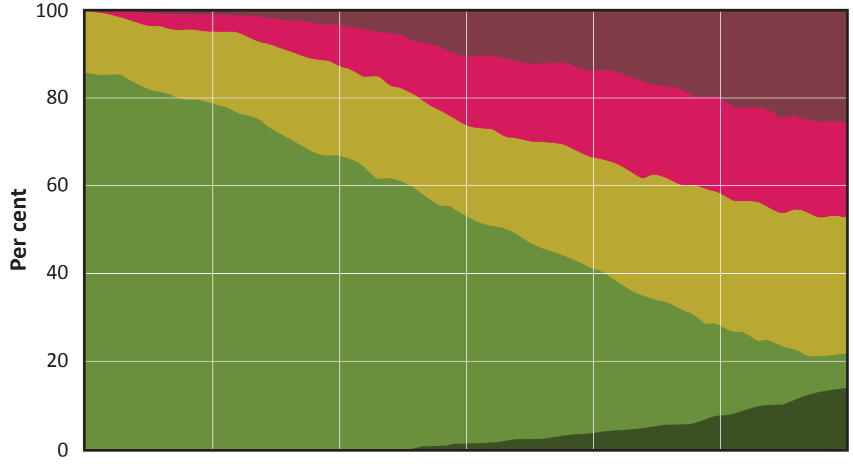
6.1.2.2 Fish stock status

A marine species is usually considered ‘overexploited’ if it produces catches that fall below 50 per cent of its maximum stock size; when catches decline below 10 per cent, a stock is considered ‘collapsed’) (Froese and Kesner-Reyes 2002). As a result of intense exploitation, most fisheries tend to follow predictable stages of development (undeveloped, developing, fully exploited, overexploited, collapsed).

Figure 6.5 Paired stock status plots for the catch of all LMEs, assessing the status of stocks defined as taxa with a time series of landings in an LME

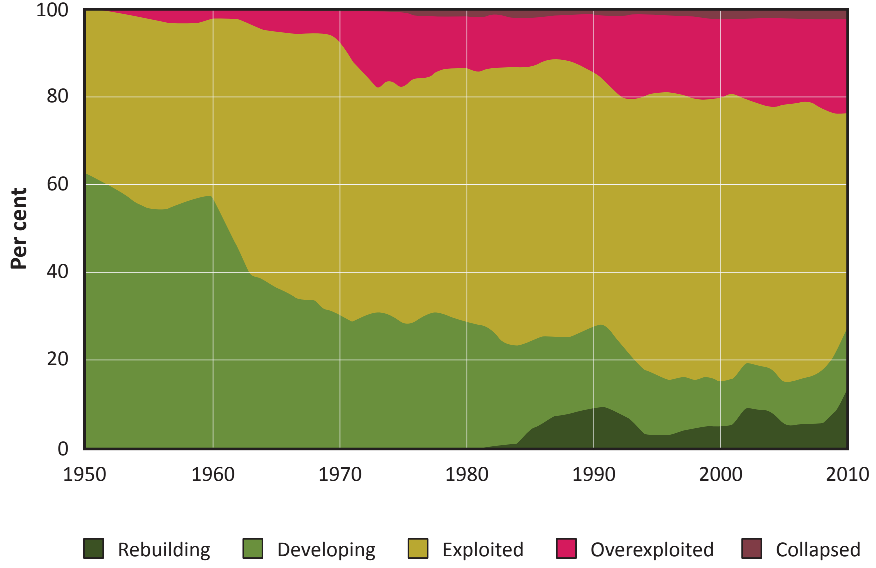
a) Number of stocks by status

Percentage of stocks of a given status, by year, showing a rapid increase of the number of overexploited and collapsed stocks.



b) Catch by stock status

Percentage of catches extracted from stocks of a given status, by year, showing a slower increase of the percentage of catches that originate from overexploited and collapsed stocks.



Source: based on Kleisner et al. 2013; see also text

Stock status plots can be used to generate an indicator of the status of fish stocks in the LMEs: for example, the percentage of catch biomass that originates from overexploited and collapsed stocks, which will be high in degraded LMEs. Stock status plots have their origin in the work of Granger and Garcia (1996), two FAO scientists who fitted time series of landings of the most important species in the FAO database with high-order polynomials and evaluated stock status from the resulting slopes. Based on these evaluations they classified fisheries as being in 'developing', 'fully utilized' or 'senescent' phases. Kleisner *et al.* (2013), based on Froese and Kesner-Reyes (2002) and Pauly *et al* (2008), simplified these graphs by defining, for any time series, five phases relative to the maximum reported catch (or landings) in that time series, representing a 'stock': developing, exploited, overexploited, collapsed, and rebuilding. However, the interpretation of the stock–catch status plots can be problematic, as they are based on catches, but not on population size estimates (Kleisner and Pauly 2011a). Despite this, it is still a useful tool for analysing fisheries resource trends at the global level.

The fisheries in a given area can then be diagnosed by plotting time series of the fraction of 'stocks' in any of these categories (Kleisner *et al.* 2013). This method of diagnosis suggests that the number of collapsed stocks is increasing, although the number of rebuilding stocks is also increasing, an encouraging sign (Figure 6.5). Also shown is a variant of the stock status plots, defined such that it documents, for a series of years, the fraction of the reported catch amount (or biomass) that is derived from stocks in various phases of development (as opposed to the number of such stocks). Figure 6.5 shows that such a plot of relative catch by stock status (b) is quite different from a plot of number of stocks by status (a). This figure illustrates that, overall, 50 per cent of global stocks within LMEs are deemed overexploited or collapsed, and only 30 per cent are fully exploited (Figure 6.5(a)). The fully exploited stocks, however, still provide 50 per cent of the globally reported landings biomass, with the remainder produced by the other development stages. Overexploited and collapsed stocks contribute less than 30 per cent of the overall reported landed biomass (Figure 6.5(b)). These stock status plots suggest that the impact of fishing on the number of stocks is much higher than its impact on total landed biomass. We think that this difference between numbers and biomass confirms the common observation that fisheries tend to affect biodiversity (as reflected in the taxonomic composition of catches) more strongly than they affect biomass (as reflected in the landed quantities).

In the last decade, the Hudson Bay Complex LME had the highest percentages of both the number and biomass of stocks in the collapsed and overexploited categories, out of the total number of stocks among the 64 LMEs assessed. However, it must be appreciated that this implies, in absolute terms, a small number of stocks and limited landings.

6.1.2.3 Ecosystem impacts of fishing

Primary production required

Footprint analysis consists of expressing all human activities in terms of the land area required for generating products that are consumed by humans, or for absorbing the waste generated in the course of supplying these products (Wackernagel and Rees 1996). Extending the footprint concept to LMEs requires taking into account that the productivity of a given area of ocean is determined by the local primary production, which can vary tremendously over small distances, depending on local mixing processes (Longhurst 2010). It is therefore not appropriate to consider the surface area of LMEs, but rather their average primary production, as the reference for footprint analysis. This leads to the concept of primary production required (PPR) (Pauly and Christensen 1995).

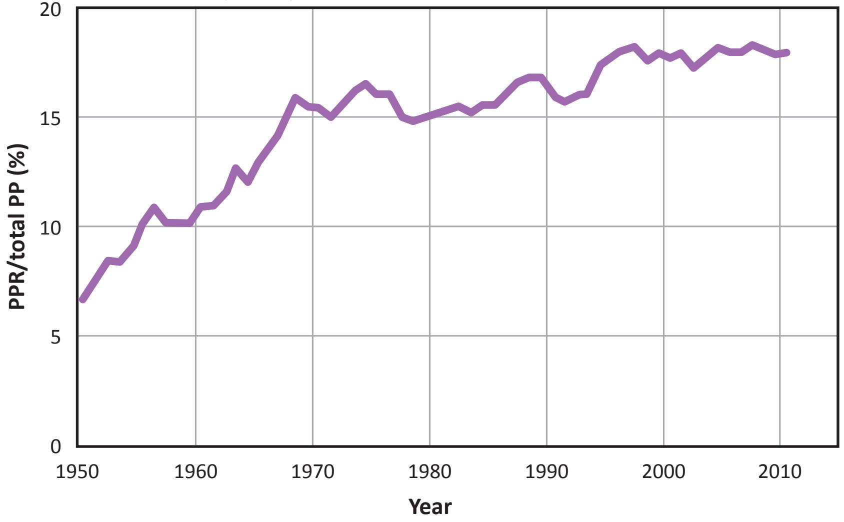
Figure 6.6(a) shows the PPR to sustain the landings reported by countries fishing within the world's LMEs, displayed as fractions of their combined primary production (total PP). As the intensity of fisheries impacts is one of the major factors contributing to the degradation of marine ecosystems, and as these impacts are captured by the PPR of the catch, the fraction PPR/total PP (ecological footprint) can be used directly as an indicator, with high values indicating high levels of degradation (Table 6.1 and Annex Table 6-A). Although this indicator captures trophic extraction and energy-related effects, it will miss habitat and other non-trophic ecosystem service effects.

The fraction (also expressed as a percentage) of PPR/total PP provides an estimate of ecological footprint. It has increased steadily over the years, in line with increasing reported landings, and is approaching 18 per cent. In recent

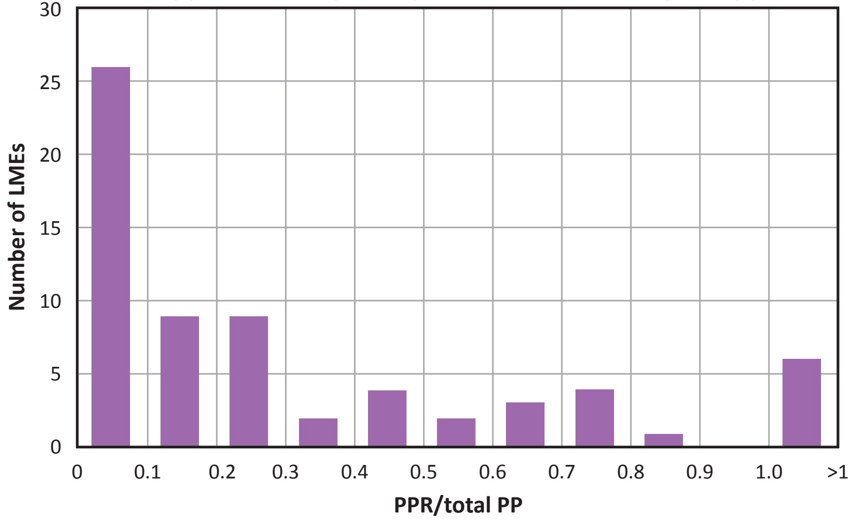
Figure 6.6 Primary production required (PPR) to sustain fisheries in the world's LMEs, an expression of their 'ecological footprint'

a) Trend in the fraction of PPR/total PP

PPR is calculated separately for each species (or group of species) caught by the fleets of all countries operating in an LME.



b) Primary production required by the fisheries/Observed primary production



years, the countries with the largest footprint in all LMEs combined were China, US, and Indonesia, with China outpacing all others (even when corrected for over-reporting of landings, Watson and Pauly 2001). Figure 6.6(b) shows the number of LMEs in each of the ecological footprint categories, and Annex Table 6-A lists the LMEs in the five risk categories. The average PPR to support the fisheries of most of the LMEs (expressed as a percentage of PP) is less than 20 per cent, with 26 LMEs having PPR/total PP below 10 per cent. Only a few LMEs have PPR/total PP values greater than 50 per cent (see Pauly *et al.* 2008).

Marine Trophic Index and Fishing in Balance Index

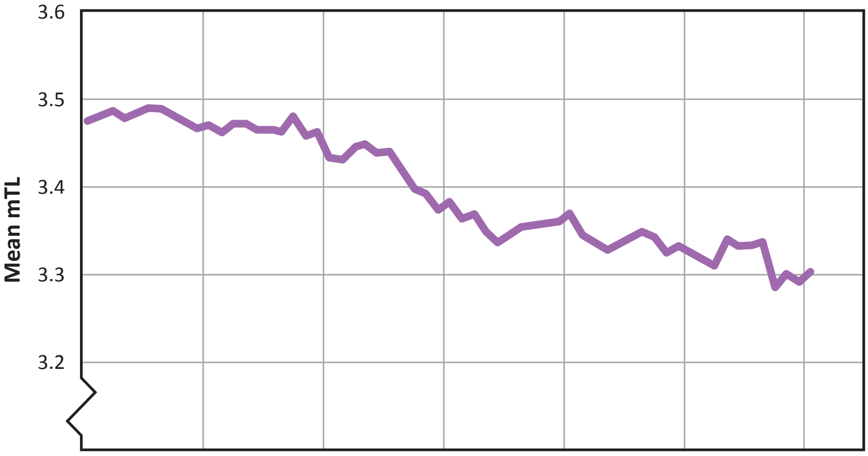
When a fishery begins in a given area, it usually targets the largest among the accessible fish, which are also intrinsically the most vulnerable to fishing (Cheung *et al.* 2007). Once these are depleted, the fisheries then turn to less desirable, smaller fish. This pattern has been repeated countless times in the history of humankind (Jackson *et al.* 2001) and many times since the 1950s, when landing statistics began to be collected systematically and globally by FAO. With a trophic level assigned to each of the species in the FAO landings dataset, Pauly *et al.* (1998) were able to identify a worldwide decline in the trophic level of fish landings, a phenomenon they called 'fishing down marine food webs'.

The mean trophic level is reflected by the Marine Trophic Index (MTI), which is an indicator used by the Convention on Biological Diversity and expresses the mean marine trophic level (MTL) of the fisheries catches in an area. In addition to the uncertainties associated with landings, other uncertainties are associated with the MTI (Kleisner and Pauly 2011b). In particular, the Index is very sensitive to fisheries expansion, which allows tapping into previously unexploited stocks of high trophic-level fishes. A fishery that has overexploited its resource base (for example, on the inner shelf) will tend to move to a new resource base (the outer shelf and beyond) (Watson and Morato 2013; Morato *et al.* 2006). There, it accesses previously unexploited stocks of demersal or pelagic fish, and the MTI calculated for the whole shelf, which may have declined at first, increases again, especially if the 'new' landings are high (Kleisner *et al.* 2014). Diagnosis of whether fishing down the marine food web is or is not occurring therefore depends on whether a geographic expansion of the fishery has taken place, which is more likely than not, given the observed global tendency toward expansion (Swartz *et al.* 2010).

Figure 6.7 Two indicators based on the trophic levels of exploited fish, used to characterize the fisheries in the LMEs

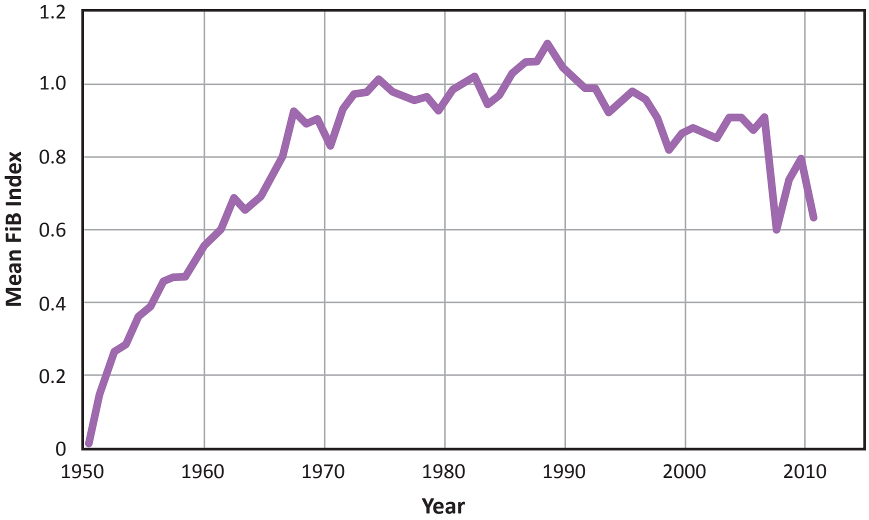
a) Marine trophic level

Trend of mean marine trophic level, indicating "fishing down marine food webs" for the LMEs (masked by offshore expansion of the fisheries for some LMES). Marine trophic level is used to calculate the Marine Trophic Index.



b) Fishing-in-Balance Index

Corresponding trend of the Fishing-in-Balance (FiB) Index



To facilitate the interpretation of MTI trends, an index of Fishing-in-Balance (FiB) was developed by Pauly *et al.* (2000). The Index has the property of increasing if catches increase faster than would be predicted by trophic level declines, and of decreasing if increasing catches fail to compensate for a decrease in trophic level. The Index value remains the same or increases when a downward trend in mean trophic level is compensated for by an increase in the volume of catch, as should happen given the pyramidal nature of ecosystems and an energy transfer efficiency of about 10 per cent between trophic levels. As defined, the FiB index increases if increases in landings more than compensate for a declining MTI. In such cases (and obviously also in the case when landings increase and the MTI is stable or increases), increase in the FiB index indicates that a geographic expansion of the fishery has taken place, that is, that another part of the ecosystem is being exploited (Bhathal and Pauly 2008). In this analysis we have assumed that the increase in FiB is not due to other factors such as bottom-up effects, for example an increase in primary production, which may also be possible given the occurrence of coastal eutrophication in some LMEs.

Figure 6.7 presents the mean trophic level and the FiB index values for all LMEs combined. It indicates a decline in the mean trophic level from a peak in the 1950s to a low in the mid-1980s, attenuated by an offshore expansion of the fisheries (Figure 6.7(b)). In the mid-1980s, the continued offshore expansion, combined with declining inshore catches, led to a slowdown in the declining trend, and even a trend reversal in the mean trophic level of some LMEs. The ‘fishing down’ effect was completely masked.

While the exploitation of a given ecosystem generally starts with the high trophic level (larger organisms) and then moves down (Pauly *et al.* 1998), there is no threshold trophic level that can be used to tell when ecosystem degradation starts. However, a decline in trophic level is generally indicative of massive changes in the structure and composition of the ecosystem. A positive difference between the mean trophic levels in the 1950s and the 2000 to 2010 period is, therefore, indicative of ecosystem degradation (Annex Table 6-A).

The indicators in this and the preceding two sections are interpreted without references to single-species stock assessments, mainly because such assessments are not usually performed at an LME scale. Even if they were, they would only cover a few LMEs, as stock assessments are generally performed only in developed countries. There is, on the other hand, a substantial literature assessing the status of fish at smaller scales (see reviews in, for example, Worm and Branch 2012; Garcia and Rosenberg 2010), which could be used for more nuanced evaluations of the status of the fisheries resources in different areas of some LMEs.

6.1.2.4 Fish catch responses to global warming

LMEs will be increasingly affected by climate change. The impact on fish stocks is explored using a dynamic bioclimate envelope model capable of reproducing and amplifying into the future the observed poleward migration of fishes exploited by fisheries (Cheung *et al.* 2008b and 2009). Since climate change affects marine ecosystems and is expected to affect fisheries and other ecosystem services, the change in projected catch potential allows analyses of the impact of climate change on fish stocks. The projected change in the productivity of marine resources in the ocean under climate change may have large implications for the fishing industries, economies, and livelihoods of many countries. LMEs with a projected decrease in catch potential of more than 8 per cent in the 2050s were assigned to the highest risk category. The largest decrease in projected catch potential under climate change is in the East Siberian Sea and Indonesian Sea LMEs (Annex Table 6-A). The projected substantial decrease in the catch potential in these LMEs due to climate change would cause these regions to become more vulnerable under the effect of other synergistic factors, including increasing fishing and socio-economic pressures. Future studies should include multi-ensemble model comparisons to address the uncertainty of the climate model (Barange *et al.* 2014; Barange and Perry 2009). This, however, is outside the scope of the current assessment.

6.1.2.5 Socio-economic and governance implications

Apart from the indicator of capacity-enhancing subsidies as a fraction of catch value, the indicators do not refer directly to the socio-economic condition and governance arrangements of the countries adjacent to and/or exploiting the fisheries resources of LMEs. Little can therefore be said about the socio-economics and governance of the LMEs. Those parts of LMEs that are beyond the EEZs of coastal states are subjected to a management regime that is essentially open-access, notwithstanding the work of the Regional Fisheries Management Organizations (Cullis-Suzuki and Pauly 2010). The parts of LMEs that are under national jurisdiction should do better, since both domestic and foreign fishing within EEZs can, in principle, be regulated by the coastal countries concerned. A few countries are making full use of the governance tools available to them to rebuild overfished stock and mitigate the impact of fishing and competition between local and foreign fleets in their EEZs, and hence in the LMEs that they belong to.

6.1.3 Discussion

Traditionally, the local and sectoral focus of fisheries science, monitoring, and management has precluded the development and use of indicators at large spatial scales. With the advent of ecosystem-based concerns and concepts such as large marine ecosystems (Sherman *et al.* 2003), it has become evident that such indicators will be needed for better integration of fisheries in ecosystem-based management approaches.

Existing national and international institutions, due to their historic sectoral, local, and national focus, are often not in a position to report fisheries information, (catches, values, and associated indicators) at an ecosystem scale such as LMEs. In contrast, the Sea Around Us was specifically established to assess the impacts of fisheries at an ecosystem level. The Sea Around Us has therefore developed tools and concepts to present available fisheries data via half-degree spatial cells, which allows interpretation of the data at various spatial scales, including that of LMEs. It is this place-based, rather than sector-based, approach that allows us to document fisheries impacts at the scale of LMEs. The authors have also derived a standard set of indicators and graphical representations, presented here on a global scale (for all currently defined LMEs combined). Although there are no scientifically defined thresholds for most of the indicators in this study, the ranking system can be improved by taking into account the approaches for selecting reference points (for example, by taking expert opinions) and inter-system comparisons that were used in other studies (Shin *et al.* 2010).

The different indicators and graphs presented here allow comprehensive overviews of the general status of fisheries and ecosystems of each LME, since they account for the characteristics of fisheries, biology, and ecology of the exploited species and ecosystem. The global status of fisheries in each LME is mixed and no indicator or group of indicators give a consistent message on LME status. The indicators of pressure or ecosystem degradation from fisheries have high values or high risk levels in all the LMEs except the Laptev and Northern Bering-Chukchi Seas LMEs in the Arctic, as well as in the WPWP. Although the number of collapsed stocks in LMEs is increasing, the number of rebuilding stocks is also increasing, for example in the USA, an encouraging sign. Overall, 50 per cent of global stocks within LMEs are deemed overexploited or collapsed, and only 30 per cent fully exploited. However, the fully exploited stocks still provide 50 per cent of the globally reported landings, with the remainder produced by overexploited and collapsed stocks.

All these indicators require accurate catch data rather than incomplete landings. Such data, however, are not available for LMEs or for country EEZs, because, among other constraints, the fisheries statistics supplied from member countries to the FAO usually fail to account for small-scale fisheries (artisanal, subsistence, and recreational). The methods we use for re-expressing the FAO's global reported landings data set on a spatial basis, here through LMEs, cannot compensate for these limitations. Rather, it makes the limitations visible and emphasizes the need for catch reconstruction at the national level (in the sense of Belhabib *et al.* 2014; Zeller *et al.* 2006, 2007, and 2011), from which accurate LME catch time series can then be derived. Reconstructed catches by LME will be available from mid-2015 from the Sea Around Us*,* and we hope that they will lead to a renewed phase of fisheries research at the LME scale.

Even with these limitations, the LME framework, populated with relevant and current catch and related fisheries data, as has been done in this chapter, can provide the information needed to develop policies for ecosystem-based fisheries management. It can, for example, provide data for identifying areas where management and/or mitigation measures are particularly needed (Annex Table 6-A). The LME framework also provides a neutral platform for jurisdictions (national and sub-national) to come together to discuss resource management issues within a single ecological unit and evaluate the consequences of policies, irrespective of political boundaries.

Although the LME framework is useful for research purposes and policy discussion, the responsibility for managing the resources exploited by two or more states still resides with Regional Fisheries Bodies, according to the UN Fish Stock Agreement and the FAO Code of Conduct. This LME-scale information and indicator evaluation can also provide guidance on information gaps (for example, gaps in spatial effort data) and areas for research (for example on large-scale fisheries-independent biomass estimation), so that ecosystem-based management of fisheries and marine areas in many of the world's coastal regions can be strengthened. The indicators presented in this chapter can also be integrated with the policy guidance on ocean issues provided by Goal 14 of the UN Open Working Group on Sustainable Development Goals to "*conserve and sustainably use the oceans, seas and marine resources for sustainable development*" (United Nations Open Working Group 2014).

6.1.3.1 Confidence levels

The confidence levels for the indicators range from low to medium. As discussed in the main findings section, uncertainty arises from different sources associated with the collection of catch data. These sources originate from the identification of reported taxa, reporting countries, and the spatial locations of the catch. Since annual landings are used as the primary data for most of the secondary indicators presented (including catch from bottom-impacting gear, value of landings, fish stock status, MTI and FiB Index), the uncertainties associated with the landings would be inherited by these secondary indicators.

The confidence level of the fishing effort data used in this chapter is low, since the current fishing effort database used surrogates for data-poor EEZs. The confidence level of the potential fish catch associated with climate change is medium because of the climate model uncertainty. Future studies should include multi-ensemble model comparisons to address the uncertainty of the climate models.

6.1.4 Methodology and analysis

6.1.4.1 Reported catches (or landings) by species

Annual catch data were extracted from the Sea Around Us database from 1950 to 2006. The Sea Around Us developed an algorithm using a rule-based approach that disaggregated reported catch data from 1950 to 2006 into 180 000, 30' latitude x 30' longitude spatial cells of the world ocean (Watson *et al.* 2004). The main sources of catch data were fisheries statistics from the FAO (FAO 2014), which were replaced only where more appropriate data were available, for example, for the Antarctic LME by Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) data. This allocation process produced spatial time series of landings data from 1950 to 2006 that could be aggregated by the EEZs of maritime countries, or by LME, and that distinguished between landings by foreign and domestic fleets.

Since the last allocation of data (to 2006), there has not been an update on global spatial landings from FAO. However, the Sea Around Us has extended the catch series for the present study based on FAO catch data from 2007 to 2010. This was first performed by comparing the complete list of taxa in the Sea Around Us catch database with a list of all taxa occurring in the FAO data from 2007 to 2011. Next the proportions of each species in the Sea Around Us catch database in LMEs were calculated. Finally, these proportions were used to allocate each taxon in the FAO catch to LMEs within an FAO statistical area in which that taxon was caught. The results are catch time series for most species that run from 2007 to 2010.

The cell-based catches and their surrogates for 2007 to 2010 were regrouped into LMEs and the WPWP, and the resulting catch times series were then used to derive the nine indicators described here. Each indicator was used to group the 64 assessed LMEs into five relative risk categories according to the relative level of potential degradation or impacts of fisheries (Table 6.1). Ideally, the cut-off points for the five relative risk categories should be based on set targets or reference points, but, in many cases, these do not exist. Since references on the cut-off points for each category were not available, the 64 LMEs were divided evenly across the five risk categories, with each category including either 13 or 14 LMEs. For most indicators, the LMEs were ranked from the lowest to highest value of the indicator. For the MTI and change in catch potential under climate change, LMEs were arranged from the highest to the lowest value. The LMEs were then grouped into five categories according to the indicator values, with each category represented by a risk level (from 'lowest' to 'highest' risk levels) (Table 6.1). Annex Table 6-A shows the indicator values and corresponding risk category for each LME in the last decade (2000 to 2010).

6.1.4.2 Indicator 1. Ratio of capacity-enhancing subsidies to value of landed catch

The annual landed value by each fishing country in each LME is the sum of annual landed values for all taxa or species groups caught by each fishing country. The landed values were estimated by multiplying the ex-vessel prices (by fishing country and year) of each species in 2005 US$ (adjusted for inflation to year 2005 using consumer price index data from the World Bank) (Swartz *et al.* 2013; Sumaila *et al.* 2007) by the average annual catch from the Sea Around Us global catch database (Watson *et al.* 2004). Details on how the ex-vessel price database was developed are presented in Sumaila *et al.* (2007 and Swartz *et al.* 2013). The subsidies derived from the studies described in Sumaila *et al.* (2013 and 2010) (available on a per-country basis at www.seaaroundus.org) were used, together with the catch values, to estimate the ratio of capacity-enhancing subsidies to landed values in the last decade (years 2000 to 2010). The value of this indicator ranges from 0 to 0.8, with higher values corresponding to greater potential degradation (Table 6.1 and Annex Table 6-A).

6.1.4.3 Indicator 2. Primary production required

Since the degradation of marine ecosystems is determined mainly by the intensity of fisheries impacts, and since these are captured by the PPR of the catch (expressed as a fraction of the observed primary production in the area where the catch was taken), PPR/total PP (ecological footprint) can be used directly as an indicator, with high values indicating a relatively high level of degradation (Table 6.1). PPR is measured as the ratio between the human consumption or appropriation from that ecosystem and the ecological productivity of the ecosystem (Wackernagel and Rees 1996). The landings data used to estimate ecological footprints (PPR/total PP) are those presented above. PPR was calculated separately for each species (or group of species) for the fleets of all countries operating in the LME in question, and expressed in terms of the primary production in that LME.

The ecological footprint of fisheries is estimated by calculating the PPR to sustain the 'pyramid' from which the species that make up fisheries resources obtain their food. The PPR of fisheries thus depends on the catch of various species and on their trophic level. The PPR to produce a given amount of a high trophic level fish (such as tuna) is much higher than that required for the same amount of a low trophic level fish (such as sardines) because the transfer efficiency from one trophic level to the next is low, usually 10 per cent (Ware 2000; Pauly and Christensen 1995). To compute the PPR for a given tonnage of fish catch, the catch and the mean trophic level (TL) of each taxon in the catch, and an estimate of transfer efficiency (TE) were combined using the equation (Pauly and Christensen 1995):

$$PPR = Catch \cdot \left(\frac{1}{TE}\right)^{TL-1}$$

Since we used a TE of 10 per cent, the equation becomes:

$$PPR = Catch \cdot 10^{TL-1}$$

Global estimates of primary production were derived from remotely-sensed SeaWiFS data. The PPR of all species (or groups of species) in each LME were then summed. The ecological footprint was then estimated by dividing the total primary production required by the total observed primary production in each LME, with both catches and primary production expressed in the same weight units.

6.1.4.4 Indicator 3. Marine Trophic Index

The MTI is an indicator used by the Convention on Biological Diversity. It expresses the mean trophic level (mTL) of the fisheries catches in an area. The indicator is linked to 'fishing down the food web' (Pauly *et al.* 1998; Christensen 1995; Christensen and Pauly 1993; Pauly and Christensen 1995). Its calculation requires careful examination of specific conditions in LMEs. It is generally expected that a decline in MTI may indicate a decline in the biodiversity of the top predators (linked to overexploitation). The MTI tracks changes in mTL, defined for year *k* as:

$$MTI = mTL_k = \frac{\sum(Y_{ik} \,.\, TL_i)}{\sum(Y_{ik})}$$

where Y_{ik} is the catch of species *i* in year *k*, and TL_i the trophic level of species (or group) *i*, the latter usually obtained from diet composition studies documented in FishBase (www.fishbase.org). The mean trophic level, and the MTI, for all fisheries landings in each LME has been calculated.

The change in the value of MTI in the 2000s from that in the 1950s is used as the indicator. Its value ranges from -1.5 to 0.7 (Table 6.1 and Annex Table 6-A). Negative values represent a decrease in the mean trophic level in an LME. Therefore, the lower the value of this indicator, the higher the risk category the LME is placed in, thus the LMEs with the lowest MTI values are assigned to the 'highest' risk category, and those with the highest MTI values are assigned to the 'lowest' risk category.

6.1.4.5 Indicator 4. Fishing-in-Balance Index

The effect of geographic expansion on the trophic level of catch was first analysed with an index called Fishing-in-Balance (FiB) (Bhathal and Pauly 2008). This index was developed to capture the fact that as the abundance of top predators declines, predation pressure on prey groups (notably forage fishes) is lowered and the biomass of those groups may decline, which in turn can lead to increased catches at lower trophic levels (Pauly *et al.* 2000). If the process is in balance, the FiB index will be constant, that is, the reduction of high Trophic Levels (TL) is balanced (when TLs are considered) by a corresponding increase at low TLs (Pauly *et al.* 2000). The FiB Index is defined for any year *k*:

$$\mathrm{FiB} = \mathrm{Log}\,(\mathrm{Y}_k * (1/\mathrm{TE})^{\mathrm{TL}_k}) - \log(\mathrm{Y}_0 * (1/\mathrm{TE})^{\mathrm{TL}_0})$$

where *Y* is the catch, TL is the mTL in the catch, TE is the transfer efficiency between trophic levels, and 0 refers to the year used as a baseline. The FiB is calculated from the geometric mean of each of the terms, thereby preserving the relationship between ecologically equivalent amounts of fish at different trophic levels. This index may: 1) remain constant (equal 0) if the fishery is 'balanced', that is, all trophic level changes are matched by 'ecological equivalent' changes in catch tonnage; 2) increase (positive index value) if there are (a) bottom-up effects (for example, increase in primary productivity) or (b) geographic expansion of the fishery to new waters which, in effect, expands the ecosystem exploited by the fishery; or 3) decrease (negative index value) if discarding occurs that is not represented in the catch, or if the ecosystem functioning is impaired by the removal of excessive levels of biomass (Kleisner *et al.* 2011b).

The LMEs are categorized by the positive difference between the mean TL in the 2000 to 2010 period and the 1950s, a larger difference being indicative of greater potential for ecosystem degradation (Table 6.1 and Annex Table 6-A). Larger differences in this value imply that the fisheries expanded offshore in the LME in question.

6.1.4.6 Indicators 5 and 6. Stock status by number and catch biomass of exploited stocks

Stock status plots (SSPs) use catch time series to assign individual stocks to different development stages, based on catch levels in relation to the maximum or peak catch of the time series (Pauly *et al.* 2008; Froese and Kesner-Reyes 2002). For example, the 'overexploited' stage occurs after the time series peak and for catch levels that are between 10 and 50 per cent of the peak catch, in contrast to the 'collapsed' stage, which also occurs after the peak of the time series, but at catch levels lower than 10 per cent of the peak catch.

The algorithm can be applied to numbers of stocks (species) and to catch tonnage per species to highlight the annual proportions of stocks and total catch in a particular stage. Stocks that are classified as ‘overexploited’ or ‘collapsed’ are indicative of a lack of sustainability, especially when the bulk of the catch tonnage is from taxa with these designations. Here, the percentage of the number of stocks in the collapsed and overexploited stages (based on the total number of stocks), and the percentage of the catch biomass of stocks in the collapsed and overexploited stages (based on the total catch biomass in the last decade) are used as indicators.

We defined a stock to be a taxon (at either species, genus, or family level of taxonomic assignment) that occurs in the catch records for at least five consecutive years, over a minimum of a ten-year time span, and that has a total catch in an area of at least 1 000 tonnes over the time span analysed. The number of stocks by status in a particular LME in a given year can be estimated and presented as percentages.

6.1.4.7 Indicator 7. Catch from bottom-impacting gear types

Annual landings by bottom-impacting gear types, including dredges and bottom trawls, were extracted from the Sea Around Us database for the period 1950 to 2006. The catch from bottom-impacting gear types is considered as a proxy for habitat status. Since the Sea Around Us extended catch data from 2007 to 2010 are not aggregated by gear type, the catch of bottom-impacting gear types (trawling and dredging gears) was estimated by calculating the proportions of these gear types to the total catch by each fishing country and LME combination in 2006. These proportions were then used to estimate the catch by bottom-impacting gear types from 2007 to 2010. The fraction of catch from bottom-trawling gear to the total catch (obtained by pooling data from the countries involved) was calculated for each LME. A ten-year average of the proportions was used to provide a single indicator value per LME (Annex Table 6-A). The percentage of the catch from the bottom-impacting gear to the total catch (from 2000) is used as an indicator.

6.1.4.8 Indicator 8. Fishing effort

Fishing effort data for the period 1950 to 2006 were obtained from the FAO, the European Union, the Regional Fisheries Management Organizations managing tuna stocks, and CCAMLR (Watson *et al.* 2013; Anticamara *et al.* 2011). Data from these different sources were standardized based on engine power (watts) and fishing days. Fishing effort was then estimated by country, vessel gross registered tonnage class, and vessel/gear types from the sources mentioned above. Non-fishing vessels such as patrol ships, research vessels, and mother-ships/carrier vessels were excluded from the analysis. Gaps in the database, which involved mainly countries with small catches and fleets, were filled by using effort data from EEZs with similar catch profiles, which acted as surrogates for data-poor EEZs (Anticamara *et al* 2011).

This global fishing effort database is being updated and improved in terms of data quality and transparency. In addition, the fishing effort data in the updated version are assigned to different fisheries sectors and made independent of catch data. In order to implement these changes and generate a database of global fishing effort, the raw data originally collected by Anticamara *et al.* (2011) have been improved by deepening the literature search by country and estimating effort (in kilowatt days) for individual fleets. However, since this work was not completed at the time of writing, the updated database was not used for this chapter.

An indicator of ecosystem degradation can be computed as the rate of change in effort from the mean of the 1980s to the mean of the 2000s, with higher rates of change implying greater potential for degradation of natural living resources or ecosystems. The rate of change in the total effective effort in the last decade is used as the indicator. Values range from -1 600 000 to 129 000 000 kilowatt days per year (Annex Table 6-A).

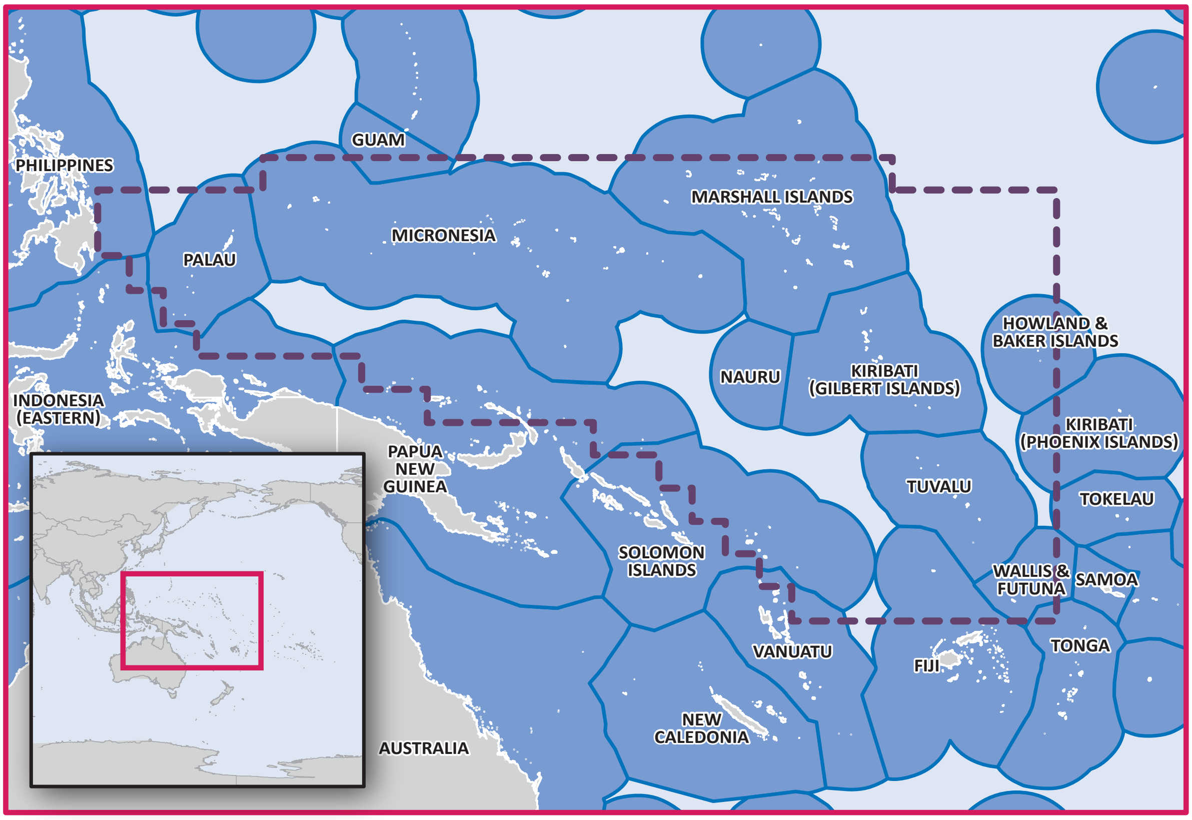
6.1.4.9 Indicator 9. Change in catch potential under global climate change

The catch potential of all pelagic and demersal species in the LME was projected using the Dynamic Bioclimate Envelope Model (DBEM) under the Intergovernmental Panel on Climate Change (IPCC) Special Report Emission Scenario (SRES) A2 scenario (Nakicenovic and Swart 2000). We used a combination of models to project future fisheries catch potential and landings in each LME. Basically, there are two major steps in projecting future maximum catch potential of species: 1) projecting future species distribution ranges under a climate change scenario using a simulation model approach; 2) calculating maximum catch potential using an empirical model. The final result is the projected change in catch potential (in percentage) in each of the half-degree by half-degree grid cells in the ocean in the 2050s. The percentage change (in each LME) in catch potential under climate change in the 2050s from the current status is used as an indicator (Table 6.1 and Annex Table 6-A). LMEs with the greatest negative change in catch potential may have the highest risk, those with the most positive change in catch potential may have the lowest risk. For details on the method used to project the change in catch potential under climate change see Cheung *et al* (2008a, 2008b, and 2010).

6.1.5 The Western Pacific Warm Pool

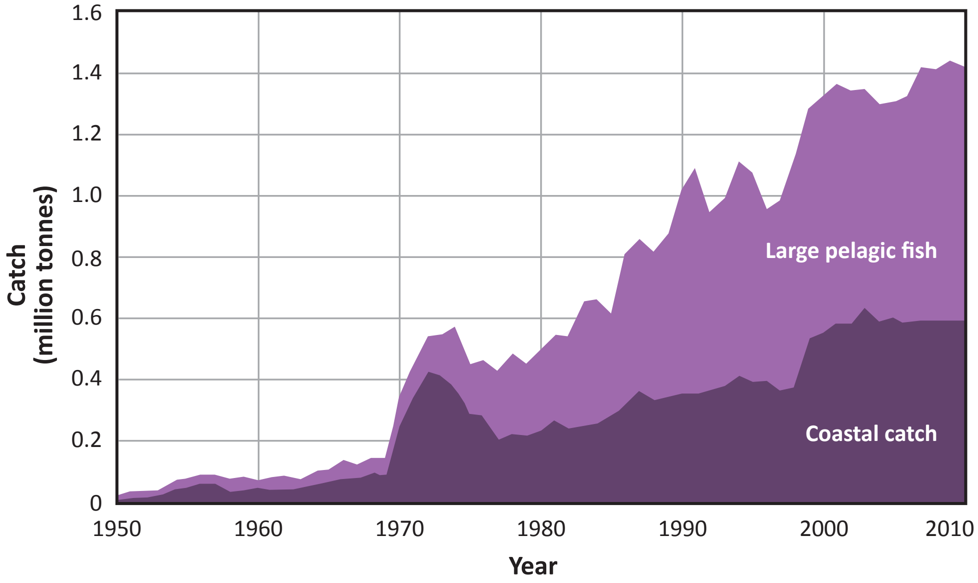
Longhurst's system of oceanographic provinces (Longhurst 1998 and 2010) is an alternative system for partitioning the oceans. Like the system of LMEs, it is based on ecological considerations (Watson *et al.* 2003; Pauly *et al.* 2000; Pauly 1999). Thus, some of these provinces can replace LMEs in parts of the oceans where no LME has been defined. This applies particularly to the Western Pacific Warm Pool province, which covers an area of 12.8 million km^2 in the Central Western Pacific (Figure 6.8). The WPWP fisheries consist of two radically different sets of activities: 1) coastal, mainly coral-reef-based small-scale fisheries around the volcanic islands and the atolls that characterize the region; 2) industrial-scale fisheries for tuna and other large pelagic fishes in the deep waters between these islands and atolls.

Figure 6.8 The Western Pacific Warm Pool and the EEZs of the countries that it includes



The WPWP overlaps with the EEZ of 17 island states (or territories). Three of these (Papua New Guinea, Indonesia, and the Philippines) are relatively large states, but have only small areas that overlap with the WPWP. The others are 12 small island states and one US territory. Of these states and territory, only seven have their main islands included in the WPWP and have domestic fisheries based on these islands. Thus, coastal (coral-reef) fisheries catches are included for only these seven island groups. The rest of WPWP fisheries are for large pelagic fish. Both the coastal catches within the EEZs and the catch of the large pelagic fish shown in Figure 6.9 were extracted from the half-degree cells comprising the WPWP, as described in the main text for LMEs. These catch data are from FAO.

Figure 6.9 Reported landings in the WPWP from 1950 to 2010, based on FAO data spatially allocated. The catches from 2007 to 2010 are estimated using the average values from 2005 and 2006, while the catches of large pelagic fish species are estimated based on changes in aggregated catch reported by the FAO for 2007 to 2010, using the methods described in the text.



Source: based on approach in Watson et al. 2004

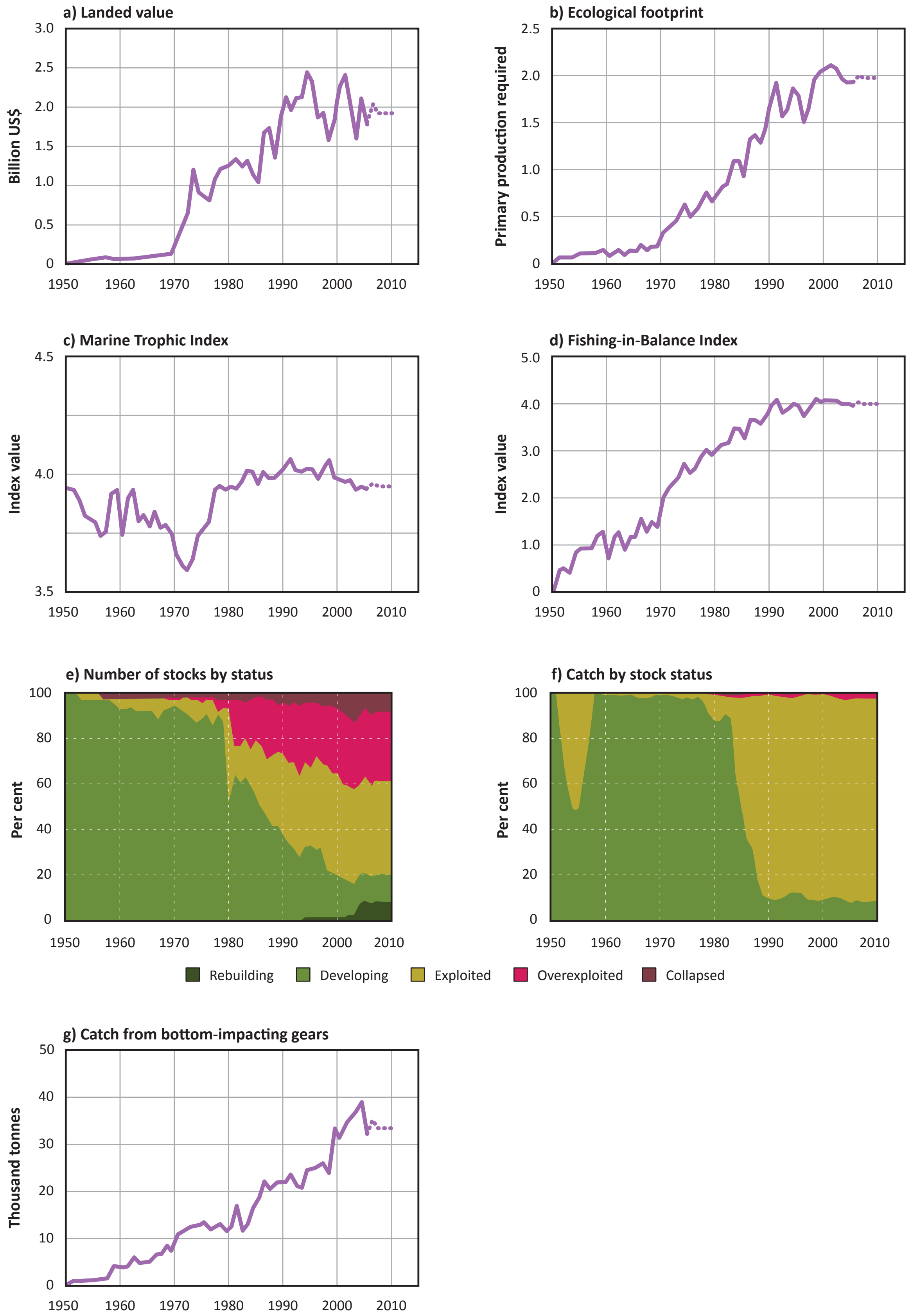
The indicators derived from the catch in Figure 6.9 are presented in Table 6.2, and the trends for each indicator are shown in Figure 6.10.

Table 6.2 Fisheries-based indicators of the WPWP compared to those of the LMEs

Indicators	WPWP	LME (mean value of each indicator)
1. Ratio of capacity-enhancing subsidy to the total landed value	*	0.22
2. Primary production required (PPR) as fraction of primary productivity (PP) for 2000 to 2010	0.2	0.2
3. Difference in Marine Trophic Index (MTI) in the 2000s from that in the 1950s	0.10	-0.16
4. Difference in Fishing-in-Balance (FiB) Index in the 2000s from that in the 1950s	3.25	0.39
5. Stock status (percentage of number of collapsed and overexploited status stocks in the 2000s)	39%	48%
6. Stock status (percentage of catch of collapsed and overexploited status stocks) in the 2000s	1.6%	29%
7. Percentage of catch from bottom-impacting gear in the 2000s	2.6%	22%
8. Slope of effective effort (million kW days per year)	154	9.4
9. Percentage change in catch potential under climate change in the 2050s	-7.0%	9.3%

**Subsidies cannot be computed for the WPWP because the bulk of the catch (tuna and other large pelagic fishes) is caught by distant-water fleets subsidized by their home countries.*

Figure 6.10 Fisheries-related indicators for the WPWP, 1950–2010. The catch and values of all the indicators from 2007 to 2010 are estimated using the average values of 2005 and 2006.



The above fisheries-related indicators can be used to compare the WPWP with the LMEs.

The fraction of primary production required to sustain the landings reported by countries within the WPWP is 0.2; the mean ecological footprint of all other LMEs is also 0.2. Both the MTI and FiB Index of the WPWP show increasing trends from the 1950s to the 2000s. This indicates that ecosystem degradation is increasing and the fisheries are expanding geographically in this region. The number and catch biomass of overexploited and collapsed stocks are 39 per cent and 1.6 per cent of total stock numbers and biomass, respectively. From Figure 6.10 (e) and (f), we can see that the impact of fisheries on the biodiversity of the catch is greater than that on the magnitude of the catch, and that this effect is also found in many LMEs. Finally, the percentage of catch from bottom-impacting gear types is only 2.6 per cent, which is low compared with the average value for all LMEs (22 per cent). The effective fishing effort in the WPWP increased at a rate of 154 million kilowatt days per year from the 1990s to the 2000s. This value is much higher than the mean change in effective effort of LMEs (9.4 million kW days). Under a climate change scenario, the total catch potential in this region is projected to fall by 7 per cent, and the projected average catch potential in all LMEs is projected to increase by 9.3 per cent by the 2050s.

ACKNOWLEDGEMENTS

The work presented here is a product of the Sea Around Us, a scientific collaboration between the University of British Columbia and the Pew Charitable Trusts.

References

Anticamara, J.A., Watson, R., Gelchu, A., and Pauly, D. (2011). Global fishing effort (1950-2010): Trends, gaps, and implications. *Fisheries Research* 107, 131-136

Barange, M. and Perry, R.I. (2009). Physical and ecological impacts of climate change relevant to marine and inland capture fisheries and aquaculture, In *Climate change implications for fisheries and aquaculture: overview of current scientific knowledge* (eds. Cochrane, K., De Young, C., Soto, D. and Bahri, T.). FAO Fisheries and Aquaculture Technical Paper 530. Rome, FAO, 7-106

Barange, M., Merino, G., Blanchard, J.L. and others (2014). Impacts of climate change on marine ecosystem production in societies dependent on fisheries. *Nature Climate Change* 4, 211-216

Belhabib, D., Koutob, V., Lam, V. and others (2014). Fisheries catch misreporting and its implications: the case of Senegal. *Fisheries Research* 151, 1-11

Bhathal, B. and Pauly, D. (2008). Fishing down marine food webs' and spatial expansion of coastal fisheries in India, 1950-2000. *Fisheries Research* 91, 26-34

Bonfil, R., Munro, G., Sumaila, U.R. and others (1998). *Impacts of distant water fleets: an ecological, economic and social assessment*. Fisheries Centre Research Reports 6(6), 111 pages

CBD (2004). Annex I, decision VII/30. The 2020 biodiversity target: a framework for implementation, 351. Decisions from the Seventh Meeting of the Conference of the Parties of the Convention on Biological Diversity, Kuala Lumpur. Montreal: Secretariat of the CBD

Cheung, W., Watson, R., Morato, T. and others (2007). Change of intrinsic vulnerability in the global fish catch. *Marine Ecology Progress Series* 333, 1-12

Cheung, W.W.L., Close, C., Lam V.W.Y. and others (2008a). Application of macroecological theory to predict effects of climate change on global fisheries potential. *Marine Ecology Progress Series* 365, 187-197

Cheung, W.W.L., Lam, V.W.Y. and Pauly, D. (2008b). Dynamic bioclimate envelope model to predict climate-induced changes in distribution of marine fishes and invertebrates. In *Modelling Present and Climate-Shifted Distributions of Marine Fishes and Invertebrates* (eds. Cheung, W.W.L., Lam, V.W.Y. and Pauly, D.). University of British Columbia, Vancouver. Fisheries Centre Research Reports 16(3), 5-50

Cheung, W.W.L., Lam, V.W.Y., Sarmiento, J.L. and others (2009). Projecting global marine biodiversity impacts under climate change scenarios. *Fish and Fisheries,* 10(3), 235-251. doi: 10.1111/j.1467-2979.2008.00315.x

Cheung, W.W.L., Lam, V.W.Y., Sarmiento, J.L. and others (2010). Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. *Global Change Biology*, 16(1), 24-35

Christensen, V. (1995). A model of trophic interaction in the North Sea in 1981, the year of the stomach, *Dana* 11(1), 1-28

Christensen, V. and Pauly, D. (1993). Trophic models of aquatic ecosystems. ICLARM Conference Proceedings 26, Manila, 390 pages

Cullis-Suzuki, S. and Pauly, D. (2010). Failing the high seas: a global evaluation of regional fisheries management organizations. *Marine Policy* 34(5), 1036-1042

FAO (2014). *The State of World Fisheries and Aquaculture 2014*. Rome. 223 pages

Froese, R. and Kesner-Reyes, K. (2002). *Impact of fishing on the abundance of marine species*. ICES CM 2002/L:12, 15

Garcia1, S.M. and Rosenberg, A.A. (2010). Food security and marine capture fisheries: characteristics, trends, drivers and future perspectives. *Philosophical Transactions of the Royal Society B*. 365, 2869–2880, doi:10.1098/rstb.2010.0171

Garibaldi, L. and Limongelli, L. (2003). *Trends in oceanic captures and clustering of large marine ecosystems: two studies based on the FAO capture database*. Food and Agriculture Organization of the United Nations. 71 pages

Grainger, R.J.R. and Garcia, S. (1996). *Chronicles of marine fisheries landings (1950-1994): trend analysis and fisheries potential*. FAO Fisheries Technical Paper 359, 51

Jackson, J.B.C., Kirby, M.X., Berger, W.H. and others (2001). Historical overfishing and the recent collapse of coastal ecosystems. *Science* 293, 629-638

Kleisner, K., Froese, R., Zeller, D. and Pauly, D. (2013). Using global catch data for inferences on the world's marine fisheries. *Fish and Fisheries* 14, 293-311

Kleisner, K. and Pauly, D. (2011a). Stock-status plots of fisheries for Regional Seas. In *The state of biodiversity and fisheries in Regional Seas* (eds. Christensen, V., Lai, S., Palomares, M.L.D. and others). Fisheries Centre Research Reports 19(3), 37-40. Fisheries Centre, University of British Columbia [ISSN 1198-6727]

Kleisner, K. and Pauly, D. (2011b). The Marine Trophic Index (MTI), the Fishing in Balance (FiB) Index and the spatial expansion of fisheries. In *The state of biodiversity and fisheries in Regional Seas* (eds. Christensen, V., Lai, S., Palomares, M.L.D. and others). Fisheries Centre Research Reports 19(3), 41-44. Fisheries Centre, University of British Columbia [ISSN 1198-6727]

Kleisner, K., Mansour, H. and Pauly, D. (2014). Region-based MTI: resolving geographic expansion in the Marine Trophic Index. *Marine Ecology Progress Ser*ies 512,185-199

Longhurst, A.R. (1998). *Ecological Geography of the Sea*. Academic Press, San Diego, 398 pages

Longhurst, A.R. (2010). *Ecological Geography of the Sea* (2nd edition). Academic Press, Amsterdam, 560 pages

Morato, T., Watson, R., Pitcher, T.J. and Pauly, D. (2006). Fishing down the deep. *Fish and Fisheries* 7(1), 24-34

Nakicenovic, N. and Swart, R. (2000). *Emissions Scenarios*. Cambridge University Press, Cambridge, UK

OECD (2004). *Review of fisheries in OECD countries: Country statistics 2000-2002.* Organization for Economic Cooperation and Development, Paris

Pauly, D. (1999). Review of A. Longhurst's Ecological Geography of the Sea. *Trends in Ecology and Evolution* 14(3), 118

Pauly, D. and Christensen, V. (1993). Stratified models of large marine ecosystem: a general approach and an application to the South China Sea. In *Large Marine Ecosystems: Stress, Mitigation and Sustainability* (eds. Sherman, K., Alexander, L. M. and Gold, B. D.), AAAS Press, Washington, DC. 148-174

Pauly, D. and Christensen, V. (1995). Primary production required to sustain global fisheries. *Nature* 374, 255-257

Pauly, D., Christensen, V., Dalsgaard, J. and others (1998). Fishing down marine food webs. *Science* 279, 860-863

Pauly, D., Christensen, V. and Walters, C. (2000). Ecopath, Ecosim and Ecospace as tools for evaluating ecosystem impact of fisheries. *ICES Journal of Marine Science* 57, 697-706

Pauly, D., Christensen, V., Guénette, S. and others (2002). Towards sustainability in world fisheries. *Nature* 418, 689-695

Pauly, D., Alder, J., Booth, S. and others (2008). Fisheries in large marine ecosystems: Descriptions and diagnoses. In *The UNEP Large Marine Ecosystem Report: A perspective on changing conditions in LMEs of the world's Regional Seas*. UNEP Regional Seas Report and Studies 182. United Nations Environment Programme, Nairobi, Kenya, 852 pages

Pauly, D. and Palomares, M.L.D. (2010). An empirical equation to predict annual increases in fishing efficiency. Fisheries Centre University of British Columbia, Working Paper Series

Pauly, D., Belhabib, D., Blomeyer, R. and others (2013). China's distant-water fisheries in the 21st century. *Fish and Fisheries*. www.doi: 10.1111/faf.12032

Sherman, K. (1994). Sustainability, biomass yields and health of coastal ecosystems: An ecological perspective. *Marine Ecology Progress Series* 112, 277-301

Sherman, K. and. Hempel, G. (2008). *Perspectives on regional seas and the Large Marine Ecosystem Approach*. In *The UNEP Large Marine Ecosystem Report: A perspective on changing conditions in LMEs of the world's Regional Seas*. UNEP Regional Seas Report and Studies 182. United Nations Environment Programme, Nairobi, Kenya, 852 pages

Sherman, K., Ajayi, T., Anang, E. and others (2003). Suitability of the Large Marine Ecosystem concept. *Fisheries Research* 64, 197-204

Shin, Y-J. and Shannon, L.J. (2010). Using indicators for evaluating, comparing and communicating the ecological status of exploited marine ecosystems. 1. The IndiSeas project. *ICES Journal of Marine Science* 67 (4), 686-691

Shin, Y-J., Shannon, L. J., Bundy, A., Coll, M. and others (2010). Using indicators for evaluating, comparing, and communicating the ecological status of exploited marine ecosystems. 2. Setting the scene. *ICES Journal of Marine Science* 67 (4), 692-716

Sumaila, U.R., Marsden, A.D., Watson, R. and Pauly, D. (2007). A global ex-vessel fish price database: construction and applications. *Journal of Bioeconomics* 9(1), 39-51

Sumaila, U.R., Teh, L., Watson, R. and others (2008). Fuel price increase, subsidies, overcapacity, and resource sustainability. *ICES Journal of Marine Science* 65, 832-840

Sumaila, U.R. and Pauly, D. (eds.) (2006*). Catching more bait: a bottom-up re-estimation of global fisheries subsidies*. Fisheries Centre Research Reports 14(6), 114

Sumaila, U.R., Khan, A.S., Dyck, A.J. and others (2010). A bottom-up re-estimation of global fisheries subsidies. *Journal of Bioeconomics* 12(3), 201-225

Sumaila, U.R., Lam, V., Le Manach, F. and others (2013). Global fisheries subsidies. European Parliament, Directorate General for Internal Policies. Policy Department B: Structural and Cohesion Policies – Fisheries. Brussels, 44. http://bookshop.europa.eu/en/global-fisheries-subsidies-pbBA0213410/ (accessed 13 May 2015)

Swartz W., Sumaila, U.R. and Watson, R. (2013). Global ex-vessel fish price database revisited: A new approach for estimating 'missing' prices. *Environmental Resource Economics* 56, 467-480

Swartz, W., Sala, E., Tracey, S. (and others) (2010). The spatial expansion and ecological footprint of fisheries (1950 to present). *PloS One* 5(12), e15143

United Nations Open Working Group (2014). Outcome Document– Open Working Group on Sustainable Development Goals

Wackernagel, M. and Rees, W. (1996). *Our ecological footprint: reducing human impact on the Earth*. New Society Publishers, Gabriola Islands, B.C., Canada

Ware, D.M. (2000). *Aquatic ecosystems: properties and models. Fisheries oceanography: integrative approach to fisheries ecology and management*. (eds. Harrison, P.J. and Parsons, T.R.), Blackwell Science, Oxford, 267-295

Watson, R. (2011). *Fisheries landings from Regional Seas*. In *The State of Biodiversity and Fisheries in Regional Seas (eds.* Christensen, V., Lai, S., Palomares, M.L.D. and others). Fisheries Centre Research Reports 19(3), 32-34. Fisheries Centre, University of British Columbia [ISSN 1198-6727]

Watson, R. and Pauly, D. (2001). Systematic distortions in world fisheries catch trends*. Nature* 414, 534-536

Watson, R. and Morato, T. (2013). Fishing down the deep: Accounting for within-species changes in depth of fishing. *Fisheries Research* 140, 63-65

Watson, R., Cheung, W.W.L., Anticamara, J. and others (2013). Global marine yield halved as fishing intensity redoubles. *Fish and Fisheries* 14, 493-503

Watson, R., Kitchingman, A., Gelchu, A. and Pauly, D. (2004). Mapping global fisheries: sharpening our focus. *Fish and Fisheries* 5, 168-177

Watson, R.D., Pauly, V., Christensen, R. and others (2003). Mapping fisheries onto marine ecosystems for regional, oceanic and global integrations. In *Large Marine Ecosystems of the World: Trends in exploitation, Protection, and Research* (eds. Hempel, G. and Sherman, K.), 375-395. Elsevier

Watson, R., Revenga, C. and Kura, Y. (2006a). Fishing gear associated with global marine catches: I Database development*. Fisheries Research* 79, 97-102

Watson, R., Revenga, C. and Kura, Y. (2006b). Fishing gear associated with global marine catches: II Trends in trawling and dredging. *Fisheries Research* 79, 103-111

Worm, B. and Branch, T.A. (2012). The future of fish. *Trends in ecology and evolution* 27(11), 594-599

Zeller, D., Booth, S., Craig, P. and Pauly, D. (2006). Reconstruction of coral reef fisheries catches in American Samoa, 1950-2002. *Coral Reefs* 25, 144-152

Zeller, D., Booth, S., Davis, G., and Pauly, D. (2007). Re-estimation of small-scale for U.S. flag- associated islands in the western Pacific: the last 50 years. *U.S. Fisheries Bulletin* 105, 266-277

Zeller, D., Booth, S., Pakhomov, E. and others (2011). Arctic fisheries catches in Russia, USA and Canada: Baselines for neglected ecosystems. *Polar Biology* 34(7), 955-973

6.1.6 Annex

Annex Table 6-A Classifying the 64 assessed LMEs into 5 relative risk categories for each fisheries-related indicator

LME number	LME name	Subsidy to landed value	Ecological footprint (PPR/PP)	MTI	FiB Index	Stock status (number) in percentage	Stock status (biomass) in percentage	Per cent catch from bottom-impacting gear	Rate of change of effective fishing effort (kW days per year)	Per cent change in catch potential in the 2050s
1	East Bering Sea	0.27	0.17	-0.13	1.17	46.25	29.33	11.15	1 743 026	36.81
2	Gulf of Alaska	0.15	0.14	0.07	1.16	47.87	28.03	14.46	8 381 743	-15.32
3	California Current	0.12	0.13	0.13	1.64	52.39	11.49	7.50	9 799 772	-13.66
4	Gulf of California	0.14	0.04	-0.05	1.93	46.15	6.95	10.38	803 921	-8.34
5	Gulf of Mexico	0.11	0.06	0.06	0.67	50.59	44.21	27.46	9 651 794	-5.09
6	Southeast US Continental Shelf	0.08	0.03	-0.07	-0.25	52.32	31.12	69.98	861 407	-14.51
7	Northeast US Continental Shelf	0.10	0.18	-0.11	-0.32	70.60	47.86	50.67	15 978 532	-15.56
8	Scotian Shelf	0.29	0.07	-1.07	-2.33	64.44	47.33	20.04	15 755 009	1.55
9	Newfoundland-Labrador Shelf	0.17	0.09	-1.26	-3.41	59.55	28.04	53.33	1 319 182	19.50
10	Insular Pacific-Hawaiian	0.16	0.01	-0.48	-2.36	73.93	68.56	12.57	3 060 644	19.86
11	Pacific Central-American Coastal	0.09	0.05	-0.14	2.46	51.31	34.03	6.45	5 609 491	-3.57
12	Caribbean Sea	0.09	0.03	-0.37	0.38	53.97	25.27	19.56	8 419 253	-1.45
13	Humboldt Current	0.03	0.19	-0.58	1.87	56.68	9.67	1.79	8 218 267	-6.44
14	Patagonian Shelf	0.25	0.20	0.28	3.40	49.26	21.99	62.25	6 315 226	-5.63
15	South Brazil Shelf	0.29	0.05	0.24	1.80	37.15	31.89	47.60	3 782 796	-4.55
16	East Brazil Shelf	0.31	0.06	0.19	1.40	36.82	18.17	19.99	2 414 615	3.58
17	North Brazil Shelf	0.24	0.04	-0.02	1.48	37.80	14.39	43.12	4 244 746	-10.67
18	Canadian Eastern Arctic-West Greenland	0.06	0.11	-1.18	-2.66	60.11	12.10	65.72	5 690 151	10.87
19	Greenland Sea	0.57	0.92	-0.46	-0.85	60.85	51.64	17.16	-310 126	41.78
22	North Sea	0.19	0.41	-0.06	-0.18	61.11	39.06	37.56	10 816 970	7.55
23	Baltic Sea	0.75	0.17	-0.41	-0.20	56.92	3.88	2.34	22 776 902	11.40
24	Celtic-Biscay Shelf	0.17	0.31	-0.13	0.58	54.47	48.42	32.21	44 691 104	-0.92
25	Iberian Coastal	0.24	0.31	-0.01	-0.35	60.20	59.42	17.44	6 738 559	-6.59
26	Mediterranean	0.14	0.14	-0.04	0.68	32.28	10.89	18.20	33 725 342	-14.53
27	Canary Current	0.17	0.18	-0.02	2.41	49.50	18.23	9.15	6 033 983	-4.30
28	Guinea Current	0.10	0.06	-0.03	1.72	40.83	17.98	15.63	15 474 117	-4.38
29	Benguela Current	0.19	0.13	0.43	1.81	51.88	60.05	11.00	-1 557 565	-0.01
30	Agulhas Current	0.11	0.06	0.58	1.81	50.77	15.01	13.24	10 971 939	11.64
31	Somali Coastal Current	0.08	0.01	0.07	0.92	52.81	22.94	4.13	3 756 822	14.60
32	Arabian Sea	0.31	0.17	0.03	1.78	32.06	10.50	17.11	24 329 676	-4.99
33	Red Sea	0.20	0.11	0.26	2.29	32.52	17.67	22.80	3 982 575	-7.65
34	Bay of Bengal	0.14	0.25	-0.03	2.13	23.53	7.04	11.63	128 945 675	2.43
35	Gulf of Thailand	0.17	0.46	0.41	2.55	23.54	7.68	25.51	7 759 858	-12.72
36	South China Sea	0.22	0.69	-0.02	1.65	35.80	9.04	22.22	10 415 054	-12.09
37	Sulu-Celebes Sea	0.31	0.44	-0.12	1.90	27.32	4.21	17.09	61 822 343	-6.11

LME number	LME name	Subsidy to landed value	Ecological footprint (PPR/PP)	MTI	FiB Index	Stock status (number) in percentage	Stock status (biomass) in percentage	Per cent catch from bottom-impacting gear	Rate of change of effective fishing effort (kW days per year)	Per cent change in catch potential in the 2050s
38	Indonesian Sea	0.18	0.23	0.03	2.10	26.87	5.81	17.97	49 883 233	-26.75
39	North Australian Shelf	0.22	0.02	-0.31	0.89	30.17	20.79	36.21	297 907	-6.02
40	Northeast Australian Shelf	0.36	0.02	-0.43	-0.50	51.47	56.97	20.23	624 483	6.04
41	East-Central Australian Shelf	0.22	0.01	-0.01	0.66	60.92	51.68	29.64	-1 404	21.61
42	Southeast Australian Shelf	0.22	0.01	-0.18	1.15	47.69	17.52	36.41	1 861 609	6.53
43	Southwest Australian Shelf	0.22	0.01	-0.43	0.53	36.82	15.81	29.46	1 284 043	15.77
44	West-Central Australian Shelf	0.22	0.01	0.19	1.51	42.82	14.62	17.22	61 366	0.65
45	Northwest Australian Shelf	0.21	0.03	-0.10	1.84	31.01	11.10	25.88	585 995	3.06
46	New Zealand Shelf	0.02	0.26	0.72	4.10	53.63	33.33	58.00	1 507 816	-6.58
47	East China Sea	0.31	1.24	-0.08	0.86	48.56	15.26	33.51	5 848 689	-15.90
48	Yellow Sea	0.26	0.95	-0.14	0.89	46.29	8.43	32.18	2 005 531	2.97
49	Kuroshio Current	0.48	0.23	-0.12	-0.20	54.15	60.35	24.03	9 498 713	2.32
50	Sea of Japan	0.38	0.35	-0.10	0.18	40.84	43.58	17.63	6 206 344	-5.88
51	Oyashio Current	0.42	0.23	-0.15	0.38	30.29	36.42	11.72	607 927	5.41
52	Sea of Okhotsk	0.42	0.30	-0.14	0.73	30.71	47.78	11.51	2 038 986	21.61
53	West Bering Sea	0.38	0.10	-0.12	0.52	36.97	43.31	9.24	546 502	29.38
54	Northern Bering-Chukchi Seas	0.00	0.00	-0.01	-1.13	41.94	28.89	11.20	1 393 584	292.50
55	Beaufort Sea	0.03	0.00	0.02	-1.84	37.50	20.38	9.38	0	-20.75
56	East Siberian Sea	0.00	0.00	-0.03	0.43	33.33	22.61	2.50	0	-27.42
57	Laptev Sea	0.00	0.00	-0.02	-0.10	0.00	5.34	4.42	0	14.71
58	Kara Sea	0.73	0.00	-0.33	-3.45	60.94	54.64	36.37	77	14.64
59	Iceland Shelf and Sea	0.44	0.07	-0.49	-0.88	71.32	52.08	13.48	4 317 762	14.34
60	Faroe Plateau	0.09	1.28	-0.06	0.76	44.39	8.33	19.80	2 904	4.50
61	Antarctic	0.22	0.00	-1.20	1.18	65.52	0.08	0.99	119 245	7.24
62	Black Sea	0.12	0.06	-0.14	0.17	48.43	36.27	11.37	17 186 030	-0.10
63	Hudson Bay Complex	0.29	0.00	-0.12	-1.71	100.00	100.00	8.76	-76	-2.15
64	Central Arctic	0.00	0.00	-0.20	-1.82	87.50	62.57	32.19	1 036	0.12
65	Aleutian Islands	0.00	0.00	-0.99	-4.59	45.16	31.69	10.77	448 593	-8.63
66	Canadian High Arctic-North Greenland	0.00	0.02	-1.48	-4.96	58.33	61.56	32.59	305	4.73

Chapter 6.2. Fishery production potential of large marine ecosystems: a prototype analysis

Lead Author

Michael Fogarty (US National Oceanic and Atmospheric Administration)

Contributing Authors

A.Rosenberg; A.Cooper; M. Dickey-Collas; B. Fulton; N. Gutiérrez; K.Hyde; K.Kleisner; T. Kristiansen; C. Longo; C. Minte-Vera; C. Minto; I. Mosqueira; G.Osio; D. Ovando; E.Selig; J. Thorson; Y.Ye

Chapter Citation

Fogarty, M., Rosenberg, A., Cooper, A., Dickey-Collas, M., Fulton, B., Gutiérrez, N., Hyde, K., Kleisner, K., Kristiansen, T., Longo, C., Minte-Vera, C., Minto, C., Mosqueira, I., Osio, G., Ovando, D., Selig, E., Thorson, J.,Ye, Y. (2016). Chapter 6.2: Fishery production potential of large marine ecosystems: a prototype analysis. In IOC-UNESCO and UNEP (2016). *Large Marine Ecosystems: Status and Trends*. United Nations Environment Programme, Nairobi, pp 139–149.

6.2 Fishery production potential of large marine ecosystems: a prototype analysis

SUMMARY

Global consumption of aquatic food products has increased steadily in recent years, but regional differences in availability and utilization of marine resources between developed and developing countries signal an important issue in global food security. Understanding the prospects for sustainable production potential from the seas is particularly important, given the likelihood of increasing demands for animal protein to meet the needs of a burgeoning human population. In this chapter, updated estimates of global fishery production potential from marine fisheries are provided to place the prospects for meeting human needs for protein and essential micronutrients into context.

Satellite-based estimates of primary productivity by plankton size classes, and a more complete food web than in earlier approaches, were used to estimate marine ecosystem productivity. LMEs were designated as strata for the analyses. Inland seas and high-latitude LMEs were excluded from the study. Production estimates for the major functional groups that are important for current or potential fisheries are provided for each LME.

Results showed an overall fishery production potential of 180 million tonnes per year and an additional 50 million tonnes per year of benthos for the LMEs included in the analysis. This prototype analysis is illustrative and further work is needed to refine these figures.

Key Messages

1. **As a rule of thumb based on our preliminary analysis and the literature, fisheries exploitation rates should not exceed 25 per cent of available production in order to be sustainable, and in some systems even lower rates are warranted.** The determination of a harvest reference level is critical for estimating fishery production potential. In the past, assumptions that 50 to 70 per cent of production at a defined mean trophic level could be extracted led to risk-prone decisions. Standard reference points have not been fully established to guide overall policies for marine ecosystems.
2. **Ecosystem exploitation rates vary among functional groups and are highest for fish at high trophic levels.** Exploitation rates for benthos (bottom-dwelling organisms) are uniformly low. This reflects the generally low level of landings reported for benthos relative to other ecosystem components. Species that prey on benthos and those that eat plankton exhibit generally low to moderate exploitation rates, typically less than 20 per cent of estimated production. Relatively high exploitation rates were observed for species that prey on fish, in some cases exceeding the estimated level of available production.
3. **Great caution is needed in interpreting figures for fishery production potential as exploitable biomass.** Increased exploitation of large components of this production is likely to have serious ecosystem-wide negative consequences and other problems.

6.2.1 Introduction

Attempts to define the fishery production potential of marine systems based on energy transfer through the marine food web have an extensive history (Moiseev 1994; Gulland 1970 and 1971; Moiseev 1969; Ricker 1969; Ryther 1969; Schaefer 1965; Graham and Edwards 1962; Kestevan and Holt 1955). Bottom-up control of fish production has now been demonstrated in many regions of the world ocean (Ware 2000), supporting the general approach of tracing pathways involved in the translation of primary production to fishery yields. Our ability to estimate primary production was revolutionized by Steeman-Nielsen's (1951) development and application of the carbon-14 method, which measures the rate at which inorganic carbon is taken up by phytoplankton and uses this to estimate the rate of photosynthetic production of organic matter. Introduction of this method paved the way for elaboration of simple models of transfer of energy from the base of the food web through fish production.

Earlier estimates of fishery production potential based on energy transfer were based on estimates of primary production over all phytoplankton size classes, inferred ecological transfer efficiencies from laboratory experiments and other observations, and observed or assumed levels of the mean trophic level of the catch. The general strategy was laid out by Kestevan and Holt (1955). Graham and Edwards (1962) provided an estimate of potential global fish yield of 115 million tonnes per year for bony (teleost) fish supporting 'conventional' fisheries, using this method. In contrast, their estimate of potential yield based on extrapolations of catch histories in space and time was less than half this value, at 55 million tonnes per year. Schaefer (1965), applying somewhat higher estimates of transfer efficiencies, estimated the annual potential yield to be on the order of 200 million tonnes. Ricker (1969) followed with a projection of approximately 150 million tonnes. In a widely cited evaluation, Ryther (1969) estimated the annual world fish production potential to be of the order of 100 million tonnes, and was the first to apply a partitioning of fishery production potential among different oceanic domains, including coastal, offshore, upwelling, and open ocean systems. Ryther (1969) further applied different estimates of food chain length in these different system types to reflect fundamental differences in ecosystem structure and patterns of energy flow. An overall reliance on key elements of the analysis, such as transfer efficiencies and mean trophic level of the catch, characterized by high levels of uncertainty in food-web-based analyses, led Pauly (1996) to infer that the agreement of Ryther's estimates (1969) with current observations may mainly reflect countervailing errors, meaning that the answers may be 'right', for the wrong reasons (Pauly 1996).

Here we describe elements of a prototype fishery production analysis for large marine ecosystems around the world, developed as part of a study commissioned by the Fisheries and Aquaculture Department of the FAO. This project, Developing New Approaches to Global Stock Status Assessment and Fishery Production Potential of the Seas, was designed to explore new approaches to (1) determining single-stock status with particular reference to assessments in data-limited situations, (2) developing estimates of ecosystem-level production potential. To meet the second objective, we have developed a prototype model of energy flow in fishery systems that expands the basic food chain models underlying earlier fishery production potential models to a simple food web architecture.

6.2.2 Methods and data sources

Ecosystem network models have now been applied for all the LMEs considered in this report, using the well-known Ecopath with Ecosim (EwE; Christensen *et al.* 2009 and 2008) formulation based on the original developments by Christensen and Pauly (1992) and Polovina (1984). Here, we seek to complement these analyses using a simple and broadly applicable characterization of fishery production systems.

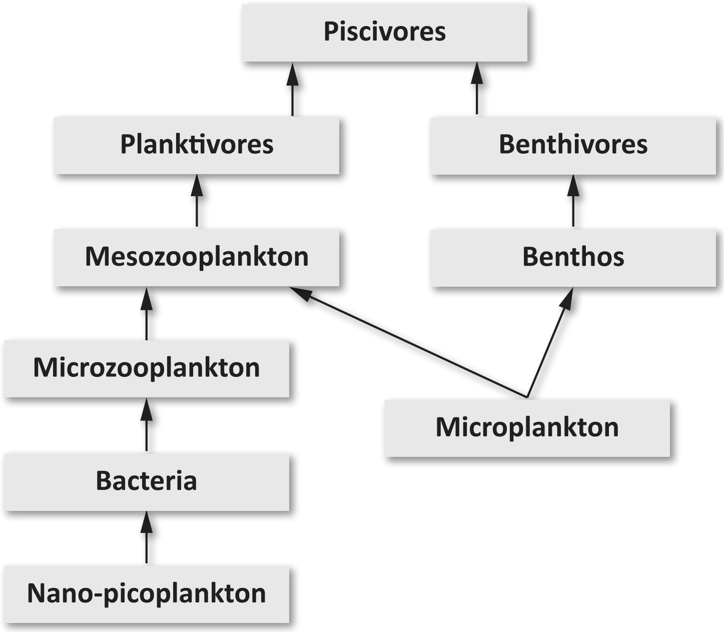
Our approach entails projections of available production at different trophic levels, given information on estimates of primary production. This method is therefore in keeping with the earlier analyses noted above (Ricker 1969; Ryther 1969; Schaefer 1965; Graham and Edwards 1962). We have expanded the implicit food chain approach in these analyses to a very simple, but broadly applicable, food web model. We have specified removals from discrete ecosystem components, including benthos, planktivores, benthivores, and piscivores (Table 6.3), to more fully characterize fishery dynamics directed at different functional groups, often by different fleet sectors. However, we have ignored potential production coming from detrital or demersal primary production, as it was not possible to obtain global estimates of these. Nor have we explicitly accounted for recycling in our estimates of production. We acknowledge that in systems where these elements collectively are a significant proportion of the primary basal resources, our estimates will be conservative.

Table 6.3 Definitions of functional groups for this analysis

Functional group	Definition
Piscivores	Marine organisms that feed on fish
Benthivores	Marine organisms that feed on benthos
Benthos	Organisms living on, in, or near the seabed
Planktivores	Marine organisms that feed on plankton
Mesozooplankton	Plankton that graze on microplankton
Microzooplankton	Plankton cells > 20 micrometres that feed on bacteria
Microplankton	Plankton cells > 20 micrometres: principally diatoms and large dinoflagellates
Bacteria	Bacteria (microscopic one-celled organisms) that feed on nano-picoplankton
Nano-picoplankton	Combined nanoplankton and picoplankton production
Nanoplankton	Plankton cells 2 to 20 micrometres
Picoplankton	Plankton cells 0.2 to < 2 micrometres

In our analysis, we recognize two pathways for transfer of primary production in the system (see Table 6.3 for definitions of functional groups and Figure 6.11 for food web structure): (1) the classical grazing food web tracing the fate of production of microplankton, and (2) production involving transfer through the microbial food web, originating with combined nanoplankton and picoplankton production (nano-picoplankton). The first pathway involves grazing by mesozooplankton and filtering of diatom production by benthic invertebrates, particularly bivalves. The second pathway entails consumption of nano-picoplankton by heterotrophic bacteria (bacteria that rely on organic compounds for carbon and energy) and feeding of microzooplankton on bacteria. In this representation, carnivorous zooplankton (mesozooplankton) prey on microzooplankton. The microbial pathway, therefore, involves two or more trophic transfer steps before reaching mesozooplankton as a bridge to higher trophic levels. We note that the functional groups represented in the upper food web depicted in Figure 6.11 do not strictly correspond to taxonomic groups. Individual taxa may feed at multiple trophic levels, reflecting both ontogenetic shifts in diet (shifts in diet as organisms grow and mature) and generalist feeding strategies with life stages.

Figure 6.11 Food-web structure employed in this analysis. This structure specifically incorporates discrete components of meso, micro, and nano-picoplankton and bacteria. Nano-picoplankton, bacteria, and microzooplankton make up the microbial food web. This differs from classical representations that focus on microplankton. The classical grazing food web is fuelled by microplankton production. Species that shift their diets over an organism's lifespan and species with mixed feeding strategies can occupy multiple compartments in this representation.



For this analysis we have used designated LMEs as strata. LMEs are differentiated by similar physical and ecological features, such as hydrography, productivity, and trophically dependent populations (Sherman 1991; Sherman and Alexander 1986). They were estimated to account for approximately 80 to 90 per cent of the global fisheries catch (Christensen *et al.* 2008), but a more recent estimate from the Sea Around Us is 73 to 76 per cent of global fisheries catch, reflecting improvements in estimation methodology and declines of recent decades (see Chapter 6.1). To account for some of the near-shore versus offshore variability in production within some regions, each LME was subdivided using the 300 m isobaths (depth contours). The sub-areas at depths shallower than 300 m included the characteristically more productive continental shelf areas and the near-shore areas of the upwelling regions. In general, the sub-areas deeper than 300 m were characterized by lower overall levels of production by microplankton. Inland seas and high latitude regions, including Hudson Bay Complex, Black Sea, Arctic Ocean, Kara Sea, Laptev Sea, East Siberian Sea, Beaufort Sea, Northern Bering-Chukchi Seas, and Antarctic LMEs, were not included in this analysis due to the seasonal effects of cloud cover and high solar zenith angles on estimates derived from satellite coverage in these regions.

6.2.2.1 Primary production

Ocean-colour remote sensors provide an unprecedented view of the global ocean and are the only means to obtain basin-scale, synoptic high-frequency measurements of global primary production. Annual estimates of primary production were calculated using data from the Sea-viewing Wide Field-of-View Sensor (SeaWiFS, NASA) and a modified version of the Vertically Generalized Productivity Model (VGPM; Behrenfeld and Falkowski 1997). This modified VGPM model replaces the original temperature-dependent description of photosynthetic efficiencies with the exponential Eppley function (Eppley 1972), which was modified by Morel (1991).

To estimate the proportion of primary production attributed to the microplankton component, we first estimated the microplankton total chlorophyll *a* (biomass) fraction, and then used an empirical relationship to calculate the percentage of microplankton production. Recent advances in ocean-colour remote sensing have led to the development of several Phytoplankton Size Classes (PSC) and Phytoplankton Functional Type (PFT) models. The diatom and dinoflagellate biomasses were combined to represent the microplankton fraction, and the remaining functional groups were combined in the nano-picoplankton group (Vidussi *et al.* 2001).

6.2.2.2 Transfer efficiencies

To objectively assess trophic transfer efficiencies throughout our generic food web, we evaluated estimates of transfer efficiencies derived from 240 published EwE models. Rather than assume or assign trophic transfer efficiencies at different steps in the food web for the models for each LME, we used these model estimates to define probability distributions characterizing transfer probabilities at different steps in the food web. Our characterization of transfer efficiencies between discrete trophic levels based on these Ecopath models followed the approach of Ulanowicz (1993).

6.2.2.3 Ecosystem reference points

As noted earlier, the estimates of fishery production potential described above typically assumed that 50 to 70 per cent of production at a defined mean trophic level could be extracted as catch (Moiseev 1994; Ricker 1969; Ryther 1969; Schaefer 1965; Graham and Edwards 1962). These proposed extraction rates were predicated on prevailing single-species recommendations based on the assumption that fishing mortality rates could equal natural mortality for the stock (Pauly and Christensen 1995). It is now recognized that these earlier target levels for single-species management were too high and led to risk-prone decisions (Pauly and Christensen 1995). Standard reference points have not been fully established to guide overall extraction policies for marine ecosystems. Iverson (1990) proposed that exploitation rates should not exceed the *f*-ratio (the ratio of new primary production to total primary production) in marine systems. This suggestion is based on the underlying recognition that new production (primarily by larger phytoplankton species) is more readily available to fuel production at the higher trophic levels of principal economic interest, while the production derived from the nano-picoplankton is mainly, but not exclusively, consumed within the microbial food web. Although direct estimates of the *f*-ratio are not broadly available for large marine ecosystems throughout the world's oceans, we can take the ratio of microplankton production to total primary production as a first-order approximation.

6.2.3 Results

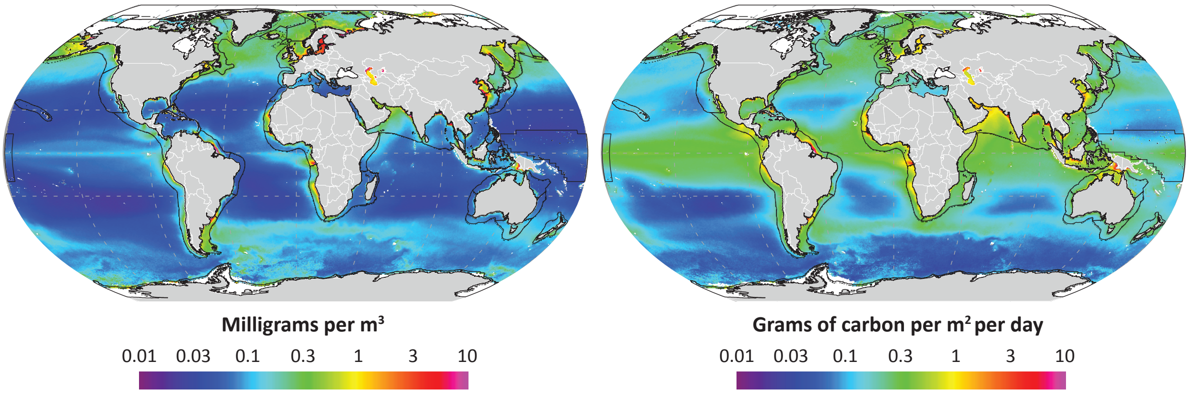
6.2.3.1 Primary production

Chlorophyll concentration and primary production are highest in coastal locations characterized by important inputs of nutrients from land and strong mixing processes driven by winds and tides (Figure 6.12). High levels of chlorophyll and production are concentrated in upwelling regions. Overall, primary production is dominated by

Figure 6.12 Distribution patterns for total chlorophyll *a* and primary production. Chlorophyll *a* and primary production estimates are shown first in total and then broken out into the microplankton and nano-picoplankton production estimates. These estimates of primary production enable estimates of high trophic level production to be modelled as the basis for understanding fishery productivity. High productivity is concentrated in upwelling regions. Primary production is dominated by nano-picoplankton production, especially in the deeper regions.

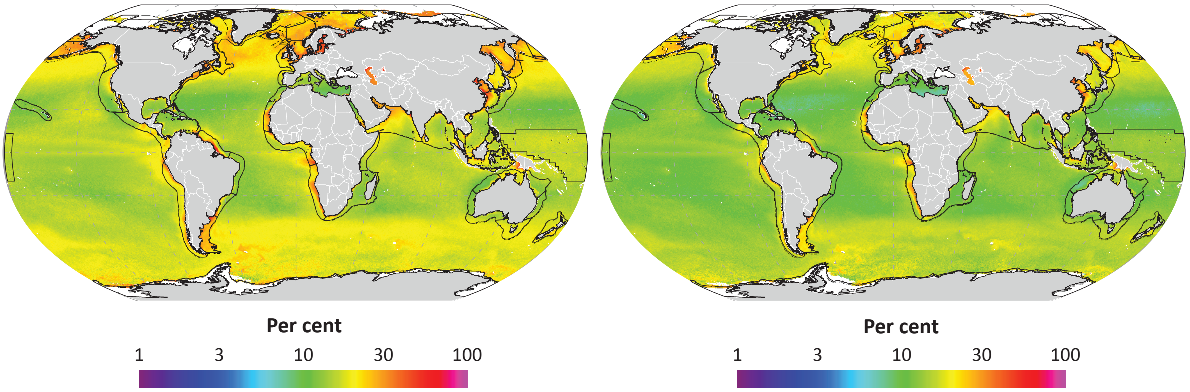
a) Chlorophyll *a*

b) Primary production



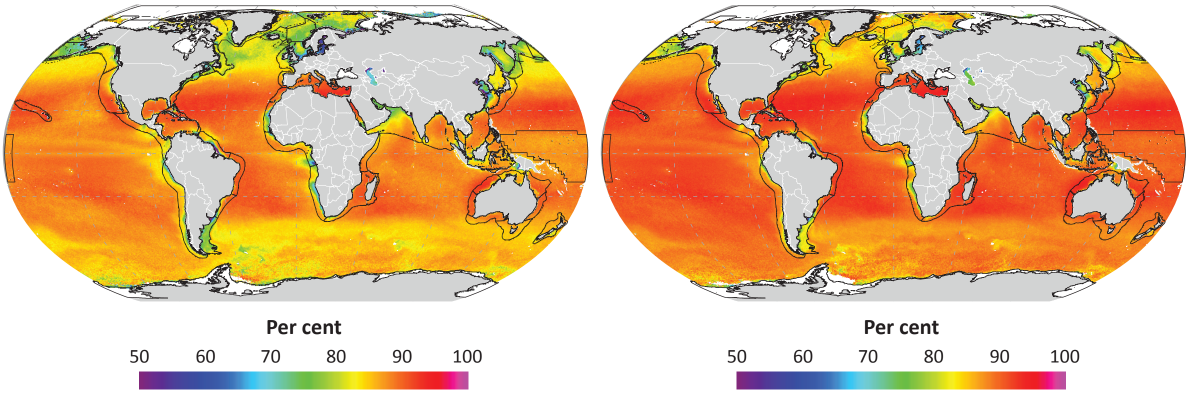
c) Percentage microplankton chlorophyll

d) Percentage microplankton primary production



e) Percentage nano-picoplankton chlorophyll

f) Percentage nano-picoplankton primary production



Values shown are means, based on satellite ocean colour data; LME boundaries are outlined in black.

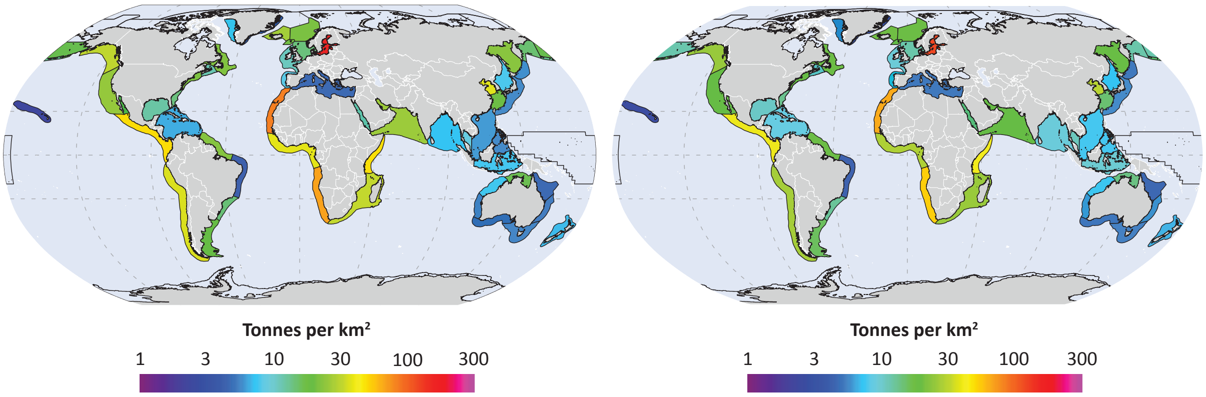
nano-picoplankton production, especially in the deeper coastal locations and the ocean basins. Within the 300 m isobath, microplankton production accounted for 25.1 per cent of the total production, on average. For deeper water components (deeper than 300 m) within individual LMEs, microplankton production accounted for 20.1 per cent of the total production. As expected, the microplankton contribution to production was smallest (14.2 per cent) in the open ocean regions outside LME boundaries.

6.2.3.2 Production by functional group

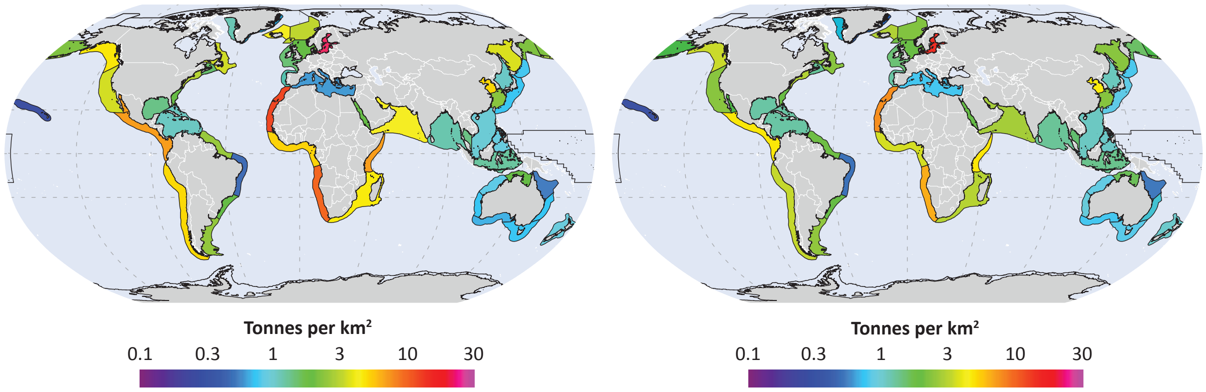
Production estimates for the major functional groups of potential or realized importance to harvesting are provided in Figure 6.13 by LME. Individual species can be represented in more than one trophic level compartment, reflecting both ontogenetic shifts in diet, and mixed or omnivorous feeding strategies. Characteristically high production levels for these groups are found in the dominant upwelling regions of the world's oceans, and in regions where at least seasonal upwelling patterns are important (for example, the Arabian Sea). Western boundary current regions are characterized by moderately high production levels (for example, Oyashio and Kuroshio Current systems, Northwest Atlantic LMEs, and Agulhas Current region). Intermittent and localized upwelling patterns in these regions, coupled with high nutrient concentrations in several of these systems, contribute to relatively high production levels.

Figure 6.13 Estimated production levels in the absence of exploitation, by functional group, for LMEs represented in this study. These estimates rely on modelled food web and transfer efficiencies as described in this chapter. The production components correspond to the food web to include benthos, planktivores, benthivores, and piscivores. High productivity, particularly for species with omnivorous feeding strategies, are found in the dominant upwelling regions of the ocean.

a) Benthos **b) Planktivores**



c) Benthivores **d) Piscivores**



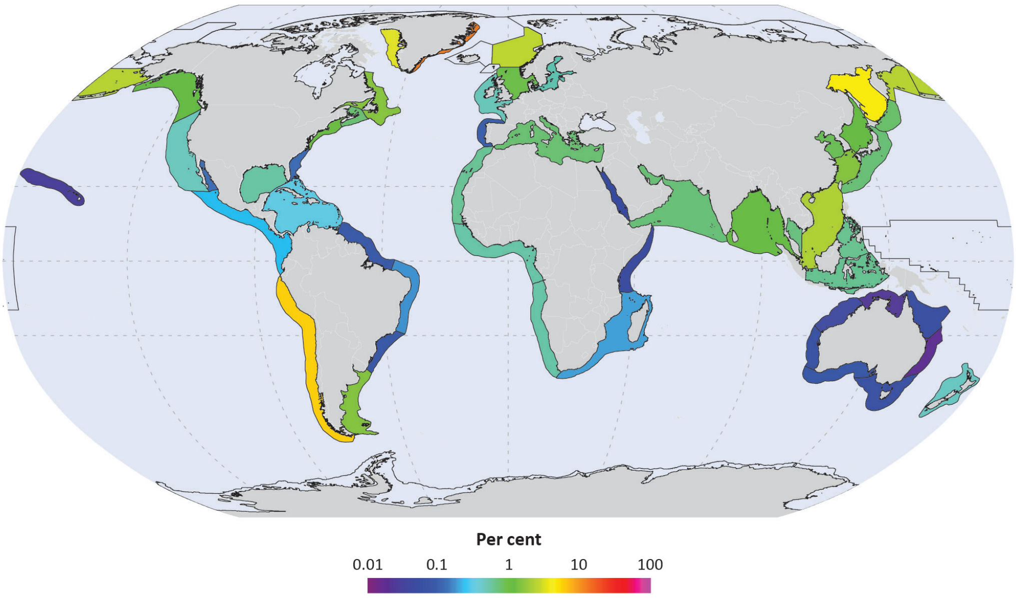
Note the change to logarithmic scale for the benthivore and piscivore functional groups.

6.2.3.3 Fishery production potential

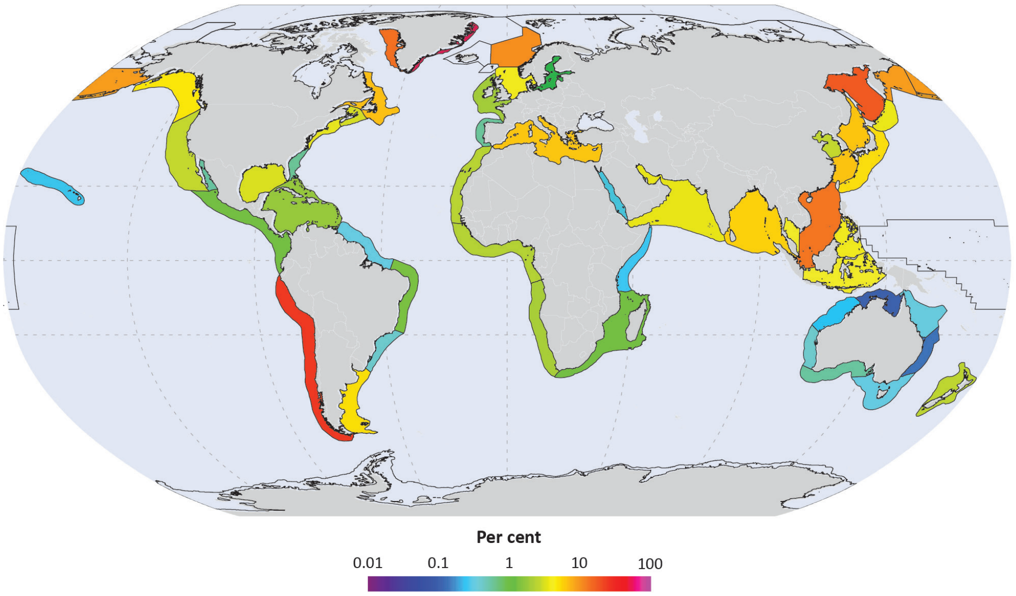
Estimates of fishery production potential depend on the available production at different trophic levels, the proportion of the production comprising species suitable for harvest (including considerations of species composition, marketability, and economic efficiency of harvesting operations), and the determination of sustainable exploitation levels. We have provided estimates of the overall available production by ecotype and functional group for potentially harvestable components of the LMEs considered in this report. In the following discussion, we apply the proposed limiting exploitation level set by the fraction of microplankton production. In Figure 6.14 we show the current landings as a proportion of production of microplankton and microplankton plus picoplankton for reference.

Figure 6.14 Ratio of landings to phytoplankton primary production. Inclusion of nano-picoplankton production adds significantly to overall primary production and gives a better picture of overall production relative to fishery landings. A harvest of up to 10 per cent of production would yield 140–180 million tonnes of benthivore, planktivore, and piscivore production, and an additional 50 million tonnes of benthic organisms. However, much of this productivity is not available or marketable, nor are the ecosystem-level impacts, which are likely to be severe, estimated here.

a) Ratio of landings to total primary production (nano-picoplankton and microplankton)



b) Ratio of landings to microplankton primary production



Under this set of assumptions, we estimate an overall potential annual yield of approximately 140 to 180 million tonnes for the benthivore, planktivore, and piscivore functional groups for the LMEs considered here, and approximately 50 million tonnes of benthic organisms if up to 10 per cent of the benthic production is suitable for harvest. Although this level of benthic fishery yield may not be fully attainable by capture fisheries under current market preferences and economic conditions, we note that the energetic pathways supporting natural benthic production could also potentially support enhanced mariculture production, for molluscs in particular. Aquaculture production has been increasing rapidly (FAO 2012). Although freshwater aquaculture remains dominant, important increases in mariculture are possible, but would, of course, require adequate environmental controls.

6.2.4 Discussion

Understanding the prospects for sustainable production potential from the seas assumes particular importance in the light of the probable demands for animal protein to meet the needs of a burgeoning human population. Currently, 3 billion people obtain nearly 20 per cent of their dietary animal protein needs from aquatic sources, and 4.3 billion obtain approximately 15 per cent of these requirements from fishery and aquaculture products (FAO 2012). Global per capita consumption of aquatic food products has increased steadily in recent years (FAO 2012), but sharp regional differences in availability and utilization between developed and developing countries signal an important issue in global food security. Here, updated earlier estimates of global fishery production potential from marine capture fisheries are provided to put the prospects for meeting human protein and essential micronutrients into context.

We have developed and provided a first application of a new approach to estimating fishery production potential. Earlier fishery production potential analyses (Gulland 1970 and 71; Ricker 1969; Ryther 1969; Schaefer 1965; Graham and Edwards 1962) relied on a combination of methods including temporal and spatial extrapolations of catch trends and simple food-chain models. The latter entailed consideration of overall phytoplankton primary production, ecological transfer efficiencies (typically a single value applied to all trophic levels), and the designation of a single mean trophic level at which catch is extracted. Our approach broadens the consideration of energetic pathways through the classical grazing and microbial food webs. We allow for differential ecological transfer efficiencies for different trophic levels and for extraction of catches at multiple levels in the food web. We attempt to strike a balance between these simple earlier models and more complex ecological network models that often require specification of parameter estimates for a large number of nodes representing different species or species groups. The model involves a projection through this simplified food web, starting with phytoplankton production. It explicitly considers bottom-up forcing of the food web to be the dominant factor in the production dynamics of these systems. We recognize that the interplay between bottom-up and top-down controls can be important in many food webs.

Ryther (1969), in his analysis of simple food-chain models, was the first to partition ocean provinces into fishery production domains. The approach adopted here expands this approach using LMEs as strata (Christensen *et al.* 2009 and 2008). Pauly (1995) suggested that drawing on multiple methods of estimation and spatial domains can help provide more robust overall determinations of fishery production potential. In the absence of other information, we have assumed that the inputs and outflows of energy and organisms within each LME are in balance. We implicitly assume that the overall analysis captures these dynamics when we integrate over LMEs to generate estimates over broader geographical scales.

The determination of a harvest reference level is critical in estimating fishery production potential. We have proposed linking the ecosystem harvest rate to the fraction of microplankton production in the system. This provides estimates centred around 20 per cent. Moiseev (1994) suggested that exploitation rates should not exceed 20 to 25 per cent, although the exact rationale for this level was not specified. However, Moiseev's recommendation is broadly consistent with the microplankton production reference level for the LMEs considered in this report. Direct consideration of the energetic requirements of other ecosystem components must also be made. Cury *et al* (2011) noted that when pelagic prey items of seabirds were reduced to below one-third of their presumed maximum levels, fledging success was significantly impaired. In a consideration of forage-fish management to meet the needs of a

© Bachelier Christian/flickr

broad suite of predators, including mammals and seabirds, Pikitch *et al* (2012) recommended the establishment of precautionary exploitation rates that halve the values assigned under conventional single-species management. Simulations that considered a 25 per cent harvest rate resulted in increased overall economic returns and reduced impacts on upper trophic level predators (Pikitch *et al.* 2012). Christensen (1996) had earlier noted that estimates of the consumption of groundfish are often higher by a factor of three, relative to catches. The early estimates of fishery production potential were based, implicitly or explicitly, on an assumption that the fishing mortality rate and natural mortality rate of the harvested species were equal at the recommended reference point, implying that half the production could be taken as yield. The observations on the actual consumption by natural predators make clear that the harvest rate should be substantially lower. Collectively, these independent recommendations and observations suggest that exploitation rates generally should not exceed 25 per cent of available production, which is consistent with our recommendation for a reference point.

Our first-order estimates of fishery production potential, based on this new approach, suggest a potential annual yield of approximately 140 to 180 million tonnes for planktonic (drifting) and nektonic (swimming) organisms within the LMEs considered here. Our estimate of the annual fishery production potential for benthic organisms is approximately 50 million tonnes, if up to 10 per cent of the benthic production is suitable for harvest. Perhaps a more likely scenario for benthic production would entail a combination of expanded capture fisheries and some form of sustainable mariculture, principally for molluscs.

If these potential yields are to be realized, an overall diversification of the complex of harvested species will have to be achieved, together with a reduction of rates of exploitation of overfished species. It is clear that the best prospect for potential increase in fish yield is for planktivorous species. If this expansion is to occur, it must be undertaken with consideration of the forage needs of other species in the system. It must also be recognized that many of the species that can potentially support such an increase (for example, mesopelagic fish that live mainly at depths below 200 m, often migrating to surface waters at night) will be processed for fish meal and oils and not used for direct human consumption. Such species can contribute to an expansion of mariculture for upper trophic level species and as food supplies for farmed animals.

Moiseev (1994) estimated global annual fishery production potential of 120 to 150 million tonnes for conventionally harvested species, and an additional 60 to 80 million tonnes for lower trophic level species including krill, deep sea squids, and mesopelagic species. Moiseev (1994) departed from previous estimates of potential yield in recommending that ecosystem exploitation rates not exceed 20 to 25 per cent. In this study we have provided first-order estimates with the recognition that inputs to the analysis will be continually refined.

Significant advances in satellite oceanography are being made that will improve our estimates of size-fractionated chlorophyll concentrations. Attempts to correct for potential biases in chlorophyll concentration in near-shore waters due to particulate matter other than phytoplankton in the surface layer are under constant development, resulting in improved estimates. Our estimates of trophic transfer efficiency and energetic pathways through the benthos and mesozooplankton can be re-evaluated with examination of additional food webs constructed for marine systems. A critically important need is to refine the estimation of the harvestable component of the benthic and planktivorous compartments of the food web.

References

Behrenfeld, M.J. and Falkowski, P.G. (1997). Photosynthetic rates derived from satellite-based chlorophyll concentration. *Limnology and Oceanography* 42, 1-20

Christensen, V., Walters, C.J., Ahrens, R. and others (2008). *Models of the world's large marine ecosystems*. IOC Technical Series 80

Christensen, V., Walters, C.J., Ahrens, R. and others (2009). Database-driven models of the world's Large Marine Ecosystems. *Ecological Modelling*, 220 (17), 1984-1996

Christensen, V. (1996). Managing fisheries involving predator and prey species. *Review of Fish Biology and Fisheries* 6, 417-443

Christensen, V. and Pauly, D. (1992). ECOPATH II – a software for balancing steady-state ecosystem models and calculating network characteristics. *Ecological Modelling* 61, 169-185

Cury, P.M., Boyd, I.L., Bonhommeau, S. and others (2011*).* Global seabird response to forage fish depletion-one-third for the birds. *Science* 334 (6063), 1703-1706

Eppley, R.W. (1972). Temperature and phytoplankton growth in the sea. *Fishery Bulletin* 70, 1063-1085

FAO (2012). *The State of World Fisheries and Aquaculture 2012*. Food and Agriculture Organization, Rome

Graham, H.W. and Edwards, R.L. (1962). *The world biomass of marine fishes*. In *Fish in Nutrition* (eds. Heen, E. and Kreuzer, R.). Fishing News Books, London

Gulland, J.A. (1970). *The state of the world resources.* FAO Fisheries Technical Paper 97, 425.

Gulland, J.A. (1971). *The fish resources of the ocean*. Fishing News Books, West Byfleet, Surrey, England

Iverson, R.L. (1990). Control of marine fish production*, Limnology and Oceanography* 35, 1593-1604

Kestevan, G.K. and Holt, S.J. (1955). *A note on the fisheries resources of the Northwest Atlantic.* FAO Fisheries Paper 7

Moiseev, P.A. (1969). *The living resources of the world ocean.* Pishchevaiia prmyshlannost. Moskva, 338 pages. Israel Program for Scientific Translations, Jerusalem

Moiseev, P.A. (1994). Present fish productivity and bioproduction potential of the world aquatic habitats*.* In *The State of the World's Fisheries* (ed. Voigtlander, C.W.). Proceedings of the World Fisheries Congress, Oxford and IBH, New Delhi

Morel, A. (1991). Light and marine photosynthesis: a spectral model with geochemical and climatological implications. *Progress in Oceanography* 96, 263-306

Pauly, D. (1995). Anecdotes and the shifting baseline syndrome of fisheries. *Trends in Ecology and Evolution* 10 (10), 430

Pauly, D. (1996). One hundred million tonnes of fish, and fisheries research. *Fisheries Research* 25, 25-38

Pauly, D. and Christensen, V. (1995). Primary production required to sustain global fisheries, *Nature*, 376 (6537), 279-279

Pikitch, E.K., Rountos, K.J., Essington T.E. and others (2012). The global contribution of forage fish to marine fisheries and ecosystems. *Fish and Fisheries* 15, 43-64

Polovina, J.J. (1984). Model of a coral-reef ecosystem. 1. The Ecopath model and its application to French Frigate Shoals, *Coral Reefs* 3, 1-11

Ricker, W.E. (1969). *Food from the sea.* In: *Resources and Man, U.S. National Academy of Sciences*. W.H. Freeman, San Francisco

Ryther, J.H. (1969). Photosynthesis and fish production from the sea. *Science* 166, 72

Schaefer, M.B. (1965). The potential harvest of the sea. *Transactions of the American Fisheries Society* 94, 123

Sherman, K. (1991). The large marine ecosystem concept – research and management strategy for living marine resources. *Ecological Applications* 1, 349-360

Sherman, K. and Alexander, L. (1986). *Variability and management of large marine ecosystems*. Westview Press, Inc., Boulder, CO, United States

Steeman-Nielsen, E. (1951). Measurement of production of organic matter in sea by means of carbon-14. *Nature* 267, 684-685

Ulanowicz, R.E. (1993). Ecosystem trophic foundation: Lindeman exonerate. In: Complex Ecology (eds. Patten, B.C. and Jorgensen, S.E.). Prentice-Hall, Englewood Cliffs, New Jersey

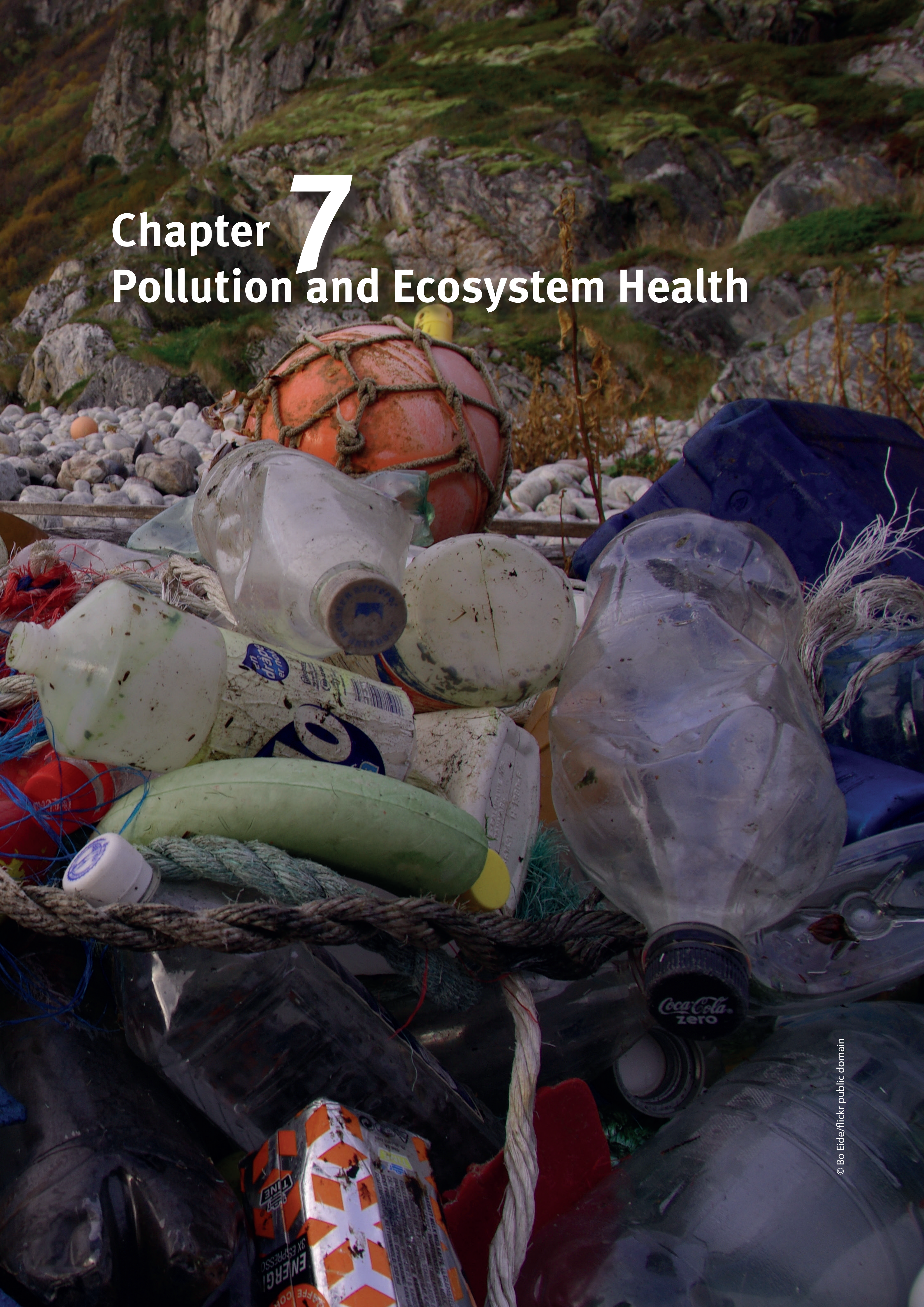
Vidussi, F., Claustre, H., Manca, B.B. and others (2001). Phytoplankton pigment distribution in relation to upper thermocline circulation in the eastern Mediterranean Sea during winter. *Journal of Geophysical Research* 106 (C9), 19939-19956

Ware, D.M. (2000). Aquatic ecosystems: properties and models. In Fisheries Oceanography: An Integrative Approach to Fisheries and Ecology and Management (eds. Harrison, P.J. and Parsons, T.R.). Blackwell Science, Oxford

© Bo Eide/flickr public domain

Chapter 7

Pollution and Ecosystem Health



© Bo Eide/flickr public domain

Chapter 7.1. Floating plastic debris

Lead Authors

Peter Kershaw (Centre for Environment, Fisheries and Aquaculture Science, Lowestoft Laboratory; GESAMP), Laurent Lebreton (Dumpark Ltd., Wellington, New Zealand)

Contributing Authors

Courtney Arthur (Industrial Economics, Incorporated, USA), Marcus Eriksen (5 Gyres Institute, USA), Jésus Gago Piñeiro (Spanish Institute of Oceanography, Spain), Kara Lavender Law (Sea Education Association, USA)

Chapter Citation

Kershaw, P., Lebreton, L. (2016). Chapter 7.1: Floating plastic debris. In IOC-UNESCO and UNEP (2016). *Large Marine Ecosystems: Status and Trends*. United Nations Environment Programme, Nairobi, pp 153-163.

Pollution and Ecosystem Health

7.1 Floating plastic debris

SUMMARY

The use of plastics has been rising almost exponentially since the 1950s and is projected to continue to grow, especially in emerging markets. Plastics enter the marine environment mainly because of poor waste management infrastructure and practices, combined with irresponsible attitudes towards plastic use and disposal. Plastic is durable, much of it floats in seawater, and once it enters the ocean it can be widely dispersed by ocean currents and winds. Floating plastic is now ubiquitous in the global ocean, but highly variable in concentration. Larger items of plastic debris have been shown to have significant detrimental impacts on many species of marine organisms, due mainly to entanglement and ingestion. Very little, however, is known about the effects of micro-plastics on marine organisms. Plastics in the marine environment can also cause significant economic loss and may pose a threat to navigation and human safety.

The relative abundances of floating micro-plastics (less than 4.75 mm in diameter) and macro-plastics (more than 4.75 mm) in each LME were estimated for comparative purposes. Estimates were based on modelling that simulated the movements of floating pieces of plastic in the ocean. Model runs used proxy sources of plastics derived from metrics of coastal population density, shipping density, and the level of urbanization within major watersheds. The modelled estimates of floating plastics are in broad agreement with observational data from shipboard measurements and shoreline surveys. Estimates for each plastic size class were ranked and grouped into five equal categories, with the LMEs with ‘lowest’ abundance of floating plastics forming the ‘lowest’ risk category, and those with the ‘highest’ abundance forming the ‘highest’ risk category.

Many of the LMEs with the ‘high’ to ‘highest’ relative abundances of floating plastics are located in east-southeast Asia, with the Gulf of Thailand having the highest values for both micro- and macro-plastics. LMEs in the ‘highest’ risk category for both size categories of floating plastics are the Southeast US Continental Shelf, Mediterranean, Red Sea, Bay of Bengal, Gulf of Thailand, South China Sea, Sulu-Celebes Sea, Indonesian Sea, Southwest Australian Shelf, East China Sea, and Kuroshio Current.

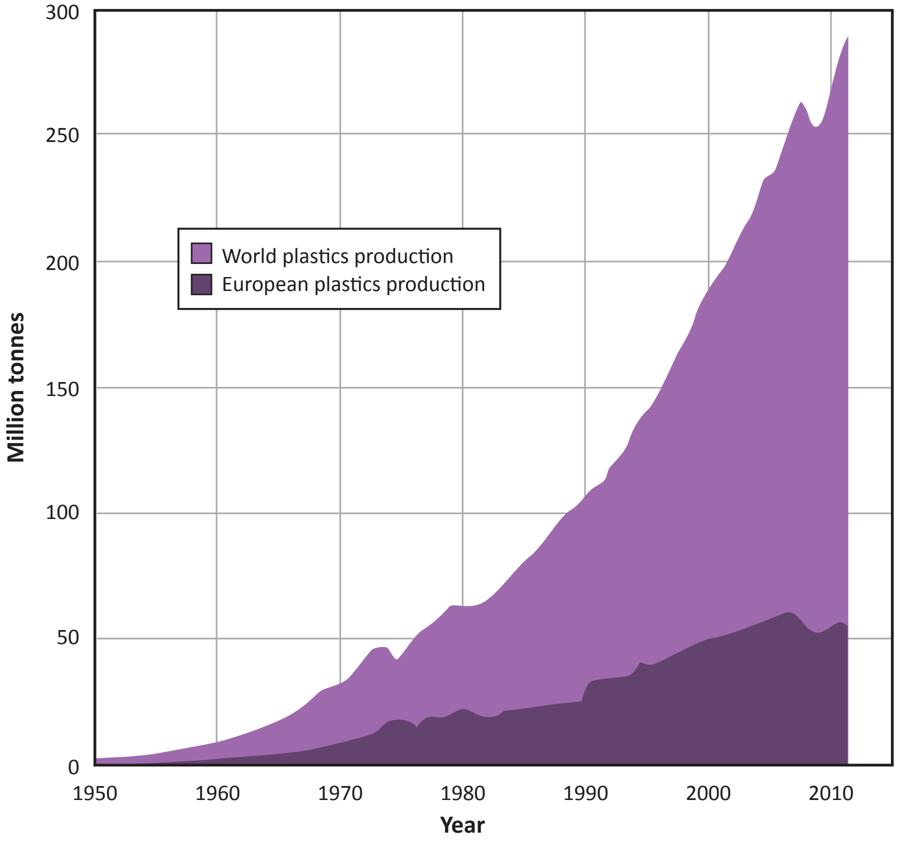
Key Messages

1. **Plastics enter the marine environment from a wide variety of land-based and sea-based activities, and there are few reliable or accurate estimates of the nature and quantities of material involved.** This poses difficulties in designing and implementing cost-effective measures to reduce inputs to LMEs. In most cases, solutions will need to be multi-agency, multi-sector, and trans-national to be effective.
2. **Reliable and consistent observational monitoring data on floating plastics in LMEs are lacking.** This prevents reliable quantitative estimation of the amounts and trends (in space and time) of floating micro- and macro-plastics.
3. **While the estimates of plastic concentrations derived from modelling are imperfect, they provide information for focusing efforts to improve predictive capacity, assess potential socio-economic consequences, and target mitigation measures.** Further improvement to these model estimates should be made if data become available on key sources of plastics (such as fishing, aquaculture, and coastal tourism, which are not accounted for in the current model) and on actual quantities of plastics entering the ocean and how this may be influenced by the level of economic development in different countries.

7.1.1 Introduction

The production and use of petroleum-based polymers on a large scale started in the 1950s (Plastics Europe 2013). Since then there has been an almost exponential increase, as plastics have been used both to replace traditional materials such as metal, glass, and wood, and for completely new products such as computers (Figure 7.1). There are six main polymers in production. Of these, polyethylene, polypropylene, and expanded polystyrene have a specific gravity lower than that of seawater (approximately 1.02) and so will tend to float (Table 7.1). Items composed of the other main polymers will tend to sink once any buoyancy is removed – for example, a PET bottle will sink when it no longer is filled with air. Many plastics contain a range of additives for various purposes, for example to improve UV resistance, plasticity, colour, impact resistance, and fire retardation. These may influence the physical characteristics of the plastics and their potential impact on marine organisms.

Figure 7.1 World plastics production, 1950–2012, showing the rapid increase in production to match demand. The temporally downturn in 2007–2008 reflects the effects of the global economic crisis.



Includes thermoplastics, polyurethanes, thermosets, elastomers, adhesives, coatings and sealants, and PP-fibres; excludes PET-, PA-, and polyacrylic fibres.

Source: Plastics Europe 2013

Table 7.1 Main polymer types, typical applications, and specific gravity. Ultimately, plastics with a specific gravity less than seawater (about 1.02) will tend to float, whereas plastics with a specific gravity greater than seawater will tend to sink.

Polymer type	Typical applications	Specific gravity
Polyethylene (PE)	Plastics bags, containers, fishing gear	0.91–0.95
Polypropylene (PP)	Rope, caps, fishing gear, strapping bands	0.90–0.92
Polystyrene (expanded) (EPS)	Fish boxes, floats, food containers	0.01–1.05
Polystyrene (PS)	Utensils, food containers	1.04–1.09
Polyvinylchloride (PVC)	Film, pipe, containers, boots, window frames	1.16–1.30
Polyethylene terephthalate (PET)	Bottles, strapping gear	1.34–1.39
Polyurethane (PUR)	Wheels, bearings, insulation	1.13–1.26
Polyester resin and glass fibres	Coatings	>1.35
Cellulose acetate	Cigarette filters	1.22–1.24
Seawater		about 1.02

The most characteristic property of plastics is durability. This, combined with lightness and low cost, has led to rapid expansion in use. The economic model prevalent over most of this period has been linear: raw materials → manufacture → use → disposal. This model is unsustainable in the longer term. It also relies on effective systems for dealing with waste and, unfortunately, waste management systems in many parts of the world are inadequate. The main reason why plastic enters the marine environment is poor waste management, combined with inappropriate use, unhelpful public attitudes, and irresponsible behaviour.

The occurrence of plastics in LMEs may result from activities based at sea or on land. Many plastics float. Once in the ocean they are subject to the normal physical processes of ocean circulation and wind-driven transport. A proportion of the plastics entering one LME, either directly (for example, from a ship) or indirectly through river transport, may be transported into an adjoining LME or into the open ocean, depending on the circulation characteristics of the region. This makes tackling plastics pollution a classic transboundary issue – the occurrence of floating plastics in one LME may be the result of inadequate waste management in another.

Plastics have been shown to injure or kill many species of marine organisms (fish, birds, reptiles, mammals and invertebrates), by ingestion or entanglement (CBD 2012). Floating plastics can cause significant loss of income to some social groups, such as fishing communities, pose a hazard to navigation, and endanger the functioning of key infrastructure, for example by blocking cooling water intakes at power stations and desalination plants.

It is becoming increasingly clear that there are also significant quantities of non-floating plastics distributed on the seabed. More data are becoming available as a result of wider acknowledgement of the problem and improvements in sampling methods, including the use of remotely operating vehicles (ROVs) (Pham *et al.* 2014). This issue was outside of the scope of the TWAP study, but requires further attention, as significant effects on ecosystems and on human activities can be anticipated.

7.1.2 Main findings, discussion, and conclusions

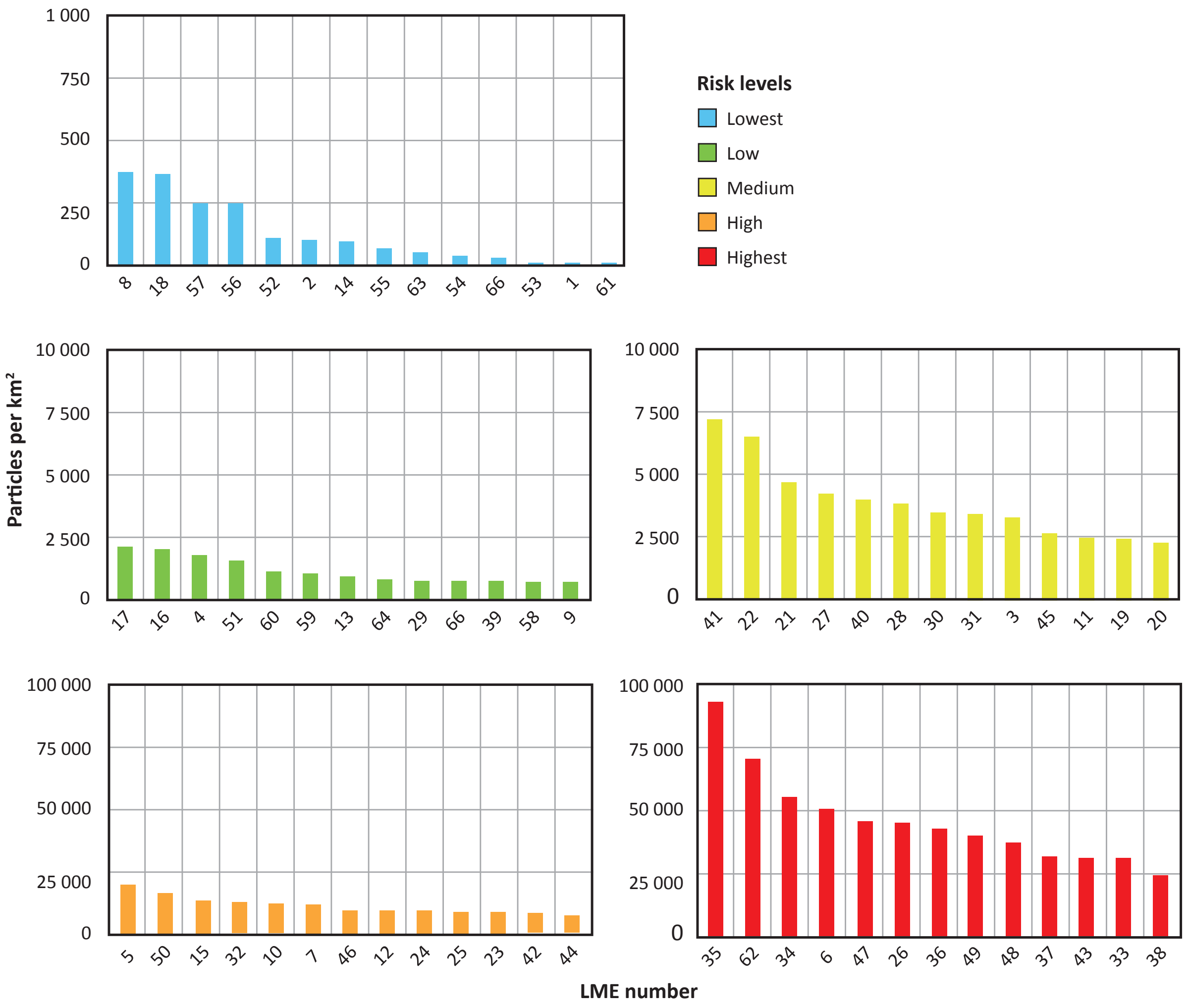
7.1.2.1 Model estimates of floating plastics

Relative quantities of floating plastics were estimated using a combination of hydrodynamic and particle-tracking models (HYCOM/NCODA and Pol3DD). The results of model runs using all three proxies (shipping density, coastal population density, and the level of urbanization within major watersheds) (Eriksen *et al*. 2014; Lebreton *et al*. 2012) were combined. Separate estimates for micro-plastics (smaller than 4.75 mm) and macro-plastics (larger than 4.75 mm) were computed.

Micro-plastics are far more abundant than macro-plastics, but the latter represent a much higher mass. The 66 LMEs were ranked according to the number of micro-plastic particles per km^2 (Figure 7.2) and the mass of macro-plastics per km^2 (Figure 7.3). The estimated abundances vary by four orders of magnitude, with the highest abundance of both micro- and macro-plastics occurring in the Gulf of Thailand LME and lowest in the Antarctic.

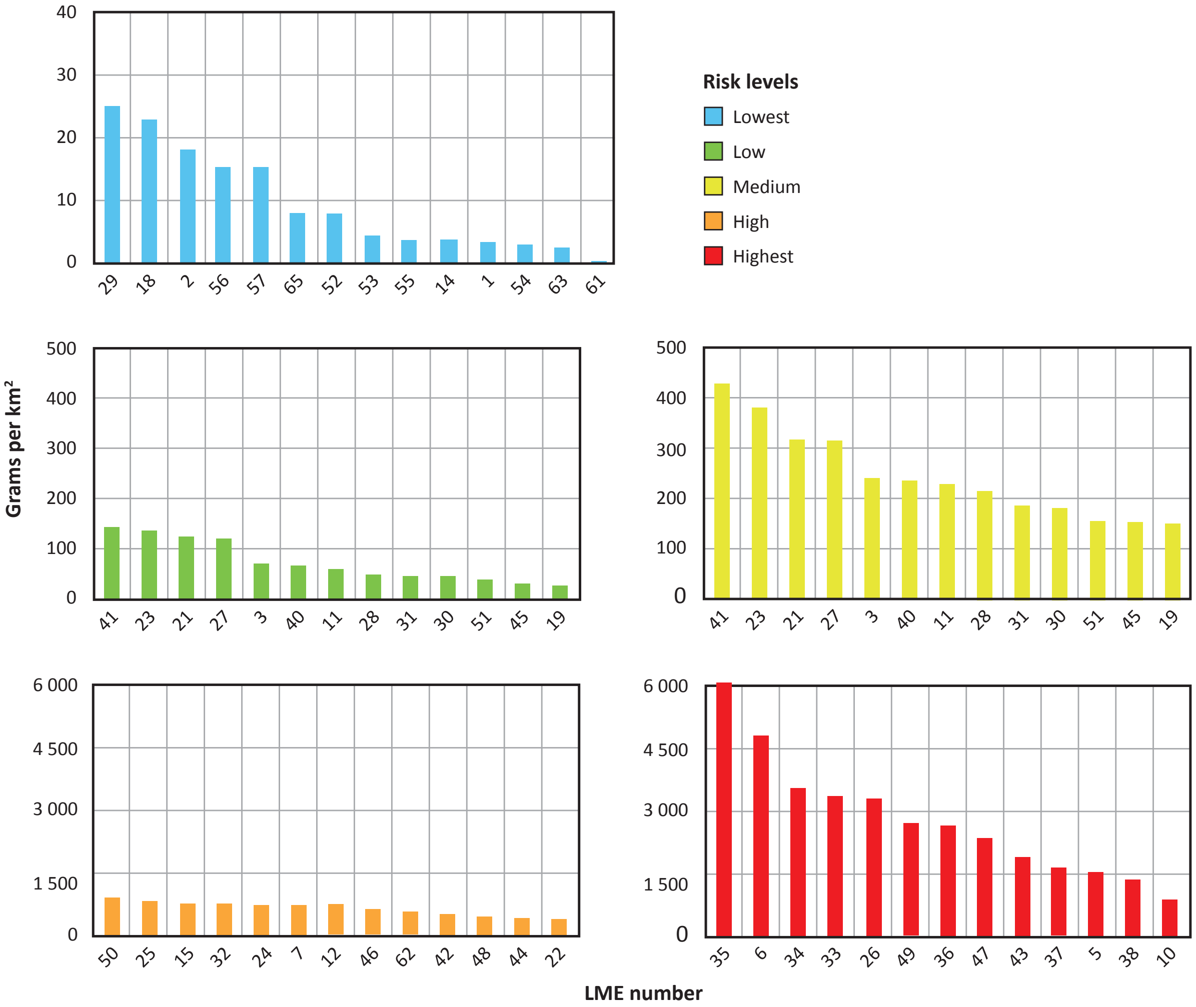
LMEs were divided into five categories for each of two indicators – number of floating micro-plastic particles and mass of floating macro-plastics – based on the rank order from the model estimates (Table 7.2). Approximately equal numbers of LMEs were assigned to each category. Both indicators are estimates from model simulations using proxy sources: 1) shipping density, 2) coastal population density, and 3) level of urbanization within major watersheds, based on Lebreton *et al.* (2012) and Eriksen *et al.* (2014).

Figure 7.2 Relative abundance of floating micro-plastics in 66 LMEs, based on model estimates and placed into five risk categories. The model uses three proxies to represent sources of marine litter: coastal population density, proportion of urbanized catchment (signifying more rapid run-off), and shipping density. Estimates levels are highest in East and Southeast Asia, the Mediterranean, and the Black Sea. LME numbers and names are listed within categories in Table 7.2(a).



LMEs were separated into five categories of relative abundance, based on model estimates using proxy sources; based on Eriksen *et al.* (2014) and Lebreton *et al.* (2012); note scale change on y axis.

Figure 7.3 Relative abundance of floating macro-plastics in 66 LMEs, based on model estimates, and placed into five risk categories. The model uses three proxies to represent sources of marine litter: coastal population density, proportion of urbanized catchment (signifying more rapid run-off), and shipping density. Estimates levels are highest in East and Southeast Asia, the Mediterranean, and the Black Sea. LME numbers and names are listed within categories in Table 7.2(b).



LMEs were separated into five categories of relative abundance, based on model estimates using proxy sources; based on Eriksen *et al.* (2014) and Lebreton *et al.* (2012); note scale change on y axis.

Table 7.2 Grouping of LMEs into five categories on the basis of the relative concentration of (a) micro-plastics and (b) macro-plastics, based on model estimates. The model uses three proxies to represent sources of marine litter: coastal population density, proportion of urbanized catchment (signifying more rapid run-off), and shipping density. For micro-plastics, indicator values for individual LMEs are shown in Figure 7.2 and distribution of risk categories is mapped in Figure 7.4(a). For macro-plastics, indicator values for individual LMEs are shown in Figure 7.3 and distribution of risk categories is mapped in Figure 7.4(b).

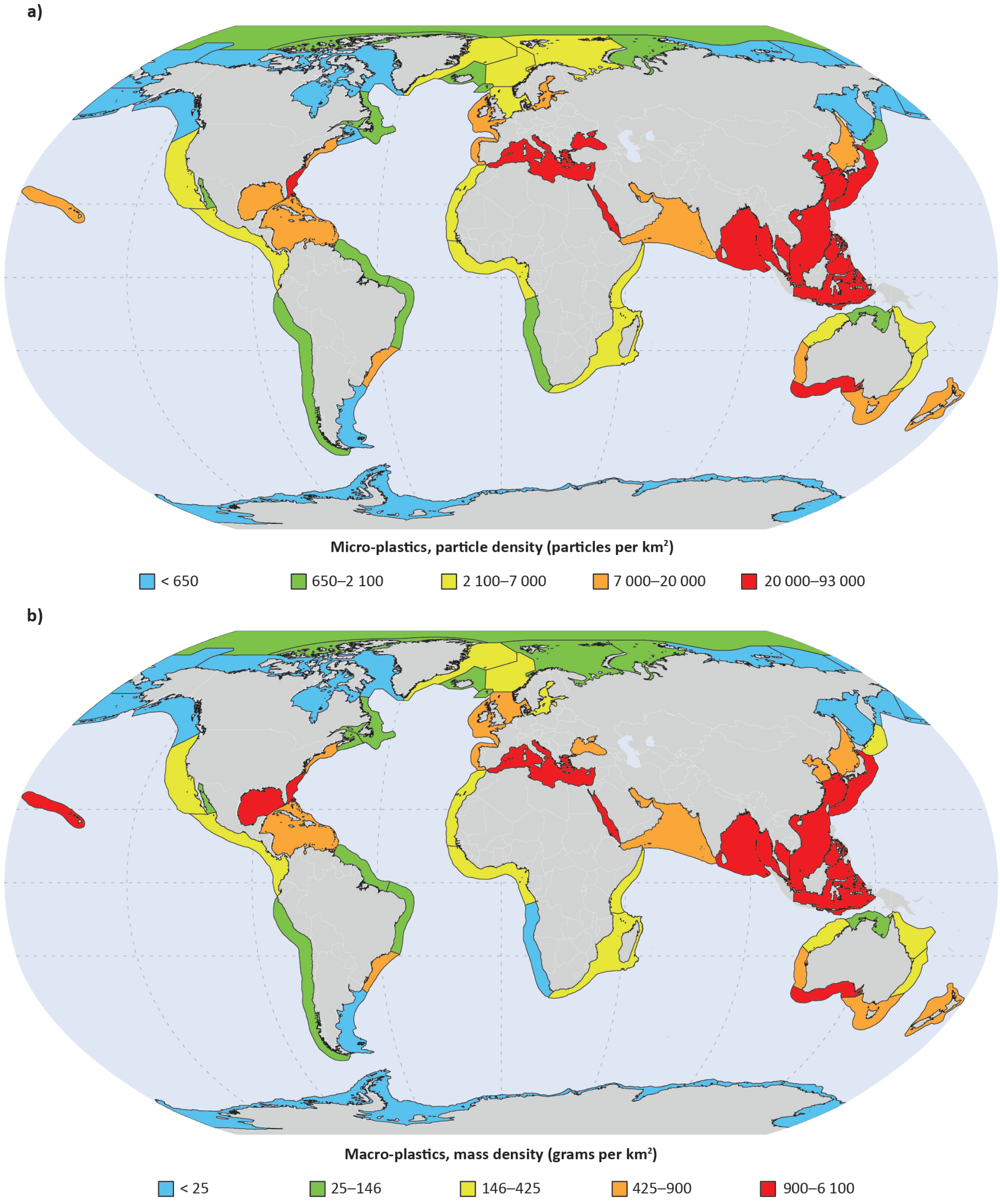
(a) INDICATOR: Number of floating micro-plastics

Risk category	Number of LMEs	LMEs in each category (LME number and name)	Range of values (particles per km^2)
Lowest	14	1. East Bering Sea; 2. Gulf of Alaska; 8. Scotian Shelf; 14. Patagonian Shelf; 18. Canadian Eastern Arctic-West Greenland; 52. Sea of Okhotsk; 53. West Bering Sea; 54. North Bering-Chukchi Seas; 55. Beaufort Sea; 56. East Siberian Sea; 57. Laptev Sea; 61. Antarctic; 63. Hudson Bay Complex; 65. Aleutian Islands	<650
Low	13	4. Gulf of California; 8. Scotian Shelf; 9. Newfoundland-Labrador Shelf; 13. Humboldt Current; 16. East Brazil Shelf; 29. Benguela Current; 39. North Australian Shelf; 51. Oyashio Current; 58. Kara Sea; 59. Iceland Shelf and Sea; 60. Faroe Plateau; 64. Central Arctic Ocean; 66. Canadian High Arctic-North Greenland	650–2 100
Medium	13	3. California Current; 11. Pacific Central-American; 19. Greenland Sea; 20. Barents Sea; 21. Norwegian Sea; 22. North Sea; 27. Canary Current; 28. Guinea Current; 30. Agulhas Current; 31. Somali Coastal Current; 40. Northeast Australian Shelf; 41. East-Central Australian Shelf; 45. Northwest Australian Shelf	2 100–7 000
High	13	5. Gulf of Mexico; 7. Northeast US Continental Shelf; 10. Insular Pacific-Hawaiian; 12. Caribbean Sea; 15. South Brazil Shelf; 23. Baltic Sea; 24. Celtic-Biscay Shelf; 25. Iberian Coastal; 32. Arabian Sea; 42. Southeast Australian Shelf; 44. West-Central Australian Shelf; 46. New Zealand Shelf; 50. Sea of Japan	7 000–20 000
Highest	13	6. Southeast US Continental Shelf; 26. Mediterranean; 33. Red Sea; 34. Bay of Bengal; 35. Gulf of Thailand; 36. South China Sea; 37. Sulu-Celebes Sea; 38. Indonesian Sea; 43. Southwest Australian Shelf; 47. East China Sea; 48. Yellow Sea; 49. Kuroshio Current; 62. Black Sea	20 000–93 000

(b) INDICATOR: Mass of floating macro-plastics

Risk category	Number of LMEs	LMEs in each category (LME number and name)	Range of values (grams per km^2)
Lowest	14	1. East Bering Sea; 2. Gulf of Alaska; 8. Scotian Shelf; 14. Patagonian Shelf; 18. Canadian Eastern Arctic-West Greenland; 29. Benguela Current; 52. Sea of Okhotsk; 53. West Bering Sea; 54. North Bering-Chukchi Seas; 55. Beaufort Sea; 56. East Siberian Sea; 57. Laptev Sea; 61. Antarctic; 63. Hudson Bay Complex	<25
Low	13	4. Gulf of California; 8. Scotian Shelf; 9. Newfoundland-Labrador Shelf; 13. Humboldt Current; 16. East Brazil Shelf; 17. North Brazil Shelf; 20. Barents Sea; 39. North Australian Shelf; 58. Kara Sea; 59. Iceland Shelf and Sea; 60. Faroe Plateau; 64. Central Arctic Ocean; 66. Canadian High Arctic-North Greenland	25–146
Medium	13	3. California Current; 11. Pacific Central-American; 19. Greenland Sea; 21. Norwegian Sea; 23. Baltic Sea; 27. Canary Current; 28. Guinea Current; 30. Agulhas Current; 31. Somali Coastal Current; 40. Northeast Australian Shelf; 41. East-Central Australian Shelf; 45. Northwest Australian Shelf; 51. Oyashio Current	146–425
High	13	7. Northeast US Continental Shelf; 12. Caribbean Sea; 15. South Brazil Shelf; 22. North Sea; 24. Celtic-Biscay Shelf; 25. Iberian Coastal; 32. Arabian Sea; 42. Southeast Australian Shelf; 44. West-Central Australian Shelf; 46. New Zealand Shelf; 48. Yellow Sea; 50. Sea of Japan; 62. Black Sea	425–900
Highest	13	5. Gulf of Mexico; 6. Southeast US Continental Shelf; 10. Insular Pacific-Hawaiian; 26. Mediterranean; 33. Red Sea; 34. Bay of Bengal; 35. Gulf of Thailand; 36. South China Sea; 37. Sulu-Celebes Sea; 38. Indonesian Sea; 43. Southwest Australian Shelf; 47. East China Sea; 49. Kuroshio Current	900–6 100

Figure 7.4 Spatial distribution of the relative abundance of floating (a) micro-plastics and (b) macro-plastics in 66 LMEs, based on model estimates. LMEs have been assigned into one of five risk categories, from 'lowest' to 'highest'. The model uses three proxies to represent sources of marine litter: coastal population density, proportion of urbanized catchment (signifying more rapid run-off), and shipping density. Estimates levels are highest in East and Southeast Asia, the Mediterranean, and the Black Sea.



LMEs were separated into five categories of relative abundance, based on model estimates using proxy sources; based on Eriksen *et al.* (2014) and Lebreton *et al.* (2012).

Figure 7.3 and Figure 7.4(b) show that many of the LMEs with the 'high' to 'highest' relative abundances of floating macro-plastics are in east-southeast Asia, and slightly over half of the LMEs with the 'highest' abundances are in this region. This is consistent with the findings of a recent study that showed that the highest estimates of the mass of land-based plastic waste entering the ocean from 192 coastal countries in 2010 were in this region (Jambeck *et al.* 2015).

The benchmark for floating plastics is zero, since all the types of plastic we are concerned with are synthetic and have been introduced into the ocean in significant quantities relatively recently, from the 1950s onwards. Scientific evidence supports the conclusion that floating plastic is now ubiquitous in the global ocean, including in the remotest parts of the Southern Ocean, as a result of its durability and overall ocean circulation patterns (Cózar *et al.* 2014; Law *et al.* 2014; Barnes *et al.* 2010). Clearly, the input of plastics into the oceans has been taking place for several decades. The rapid increase in production and use that has occurred since the 1950s is predicted to continue, especially in emerging markets. Jambeck *et al.* (2015) predict that, without waste management infrastructure improvements, the cumulative quantity of plastic waste available to enter the ocean from land will increase by an order of magnitude by 2025. It seems certain that the quantity of floating plastic in the marine environment has increased, but it has proved very difficult to quantify this, due partly to an overall lack of reliable data, and partly to the inherent spatial variability that has been observed, which makes representative sampling difficult.

The spatial distribution of LMEs in the five risk categories (Figure 7.4) reflects the relative importance of each of the three proxy sources in each LME (Lebreton *et al.* 2012), large-scale circulation characteristics, and transfer of floating plastic between LMEs. For example, the Mediterranean and Black Sea have extremely limited exchange with the open ocean, so floating plastic will tend to be retained for a long time. It is important to note that this analysis does not include other potentially significant sources, such as aquaculture, fishing, and coastal tourism, and makes no allowance for differences between countries in either per capita use of plastics or the effectiveness of waste management systems.

7.1.2.2 Validation of model estimates from sea-based observations

There are insufficient data from sea-based observations in LMEs for a reliable assessment of the validity of the model estimates. The most comprehensive observations, using towed nets, have been mainly in the open ocean. However, there have been several published studies that support the overall pattern suggested by the model results. For example, ship-based observations of macro-debris show a much lower density in the Southern Ocean (Barnes *et al.* 2010) than in the Straits of Malacca (Ryan 2013; Figure 7.5), reflecting the relative distance from potential sources.

Figure 7.5 Floating macro-plastics in the Straits of Malacca (eastern extremity of Bay of Bengal LME, 'highest' risk category). This is an area with high shipping densities and high coastal populations.

Source: Ryan (2013); images courtesy of Peter Ryan, University of Cape Town

In addition, the identification, through use of the model, of potential hotspots, such as the Mediterranean, Bay of Bengal, and East China Sea LMEs, is in agreement with independent estimates based on observations and known sources (Ryan 2013; UNEP/MAP 2011; Shiomoto and Kameda 2005). The model results also correspond with data from beach surveys and clean-ups that have been conducted in many LMEs. Partial validation is also provided by the results of biological sampling. The most developed biological sampling technique is analysis of the stomach contents of beached seabirds (dead and washed ashore) that feed offshore, such as petrels, fulmars, shearwaters, and albatross (van Franeker and Bell 1988). A long time-series from bird recoveries around the North Sea LME ('high' risk category) shows the relatively high abundance of floating plastic in this region (Figure 7.6) and the change in type of plastics represented, with no overall decrease in total quantity, but a higher proportion of consumer plastics compared with industrial sources.

Figure 7.6 Floating micro- and macro-plastics in the North Sea LME ('high' risk category), retrieved from the stomach of an open-water foraging bird, the northern fulmar (*Fulmarus glacialis*). The North Sea is semi-enclosed (restricting circulation), has a high shipping density, and has a high coastal population.

Images courtesy of Jan van Franeker, IMARES NL

Recommendations for a more harmonized approach to assessment of trends of debris in the marine environment have started to emerge (Lippiat *et al.* 2013), so future assessments should have a more comprehensive data set to analyse. It is already apparent that there can be substantial spatial variability in the observed abundance of floating plastics within an LME, covering several orders of magnitude, due to differences in the type of plastics, distance from the source(s), oceanic circulation, and wind-driven events. An example of spatial variability of floating plastics in the Bay of Bengal LME is described by Ryan (2013).

The scope of this study was limited to an assessment of floating plastics. However, much of our information on the type and relative distribution of plastic debris that has entered the sea comes from beach surveys. The most comprehensive survey is the annual International Coastal Cleanup, organized through the Ocean Conservancy, an NGO (not-for-profit) based in the USA (Ocean Conservancy 2015). This event has expanded steadily in coverage and, in 2013, included 92 countries. The International Coastal Cleanup methodology is not as rigorous as that in many national programmes, but it provides useful information on sources and regional differences.

In contrast, sampling at sea tends to be limited to national monitoring programmes or single transects using vessels of opportunity. Representative sampling of floating plastics at sea with sufficient spatial and temporal extent is very expensive. National efforts have been rather limited to date and methodologies have not been harmonized. Differences in gear type and mesh size for smaller items and lack of a standardized protocol for shipboard observations set a practical limit to compiling comparable data sets. It has also been recognized that conditions at sea, such as the state of winds, waves and swell, can have a significant effect on the apparent abundance of floating plastics. These issues are currently being addressed by the National Oceanic and Atmospheric Administration Marine Debris Program (Lippiat *et al.* 2013), the European Union (EC/JRC 2013), and several Regional Seas Organizations (for example, OSPAR for the North-East Atlantic, and NOWPAP for the Northwest Pacific). Future assessments are likely to be able to use larger and more reliable data sets.

7.1.2.3 Limitations and confidence levels

There are insufficient observations of abundances of floating micro- or macro-plastics for an accurate evaluation of the state of contamination in all LMEs. Simulated distributions were generated using three proxy sources of litter fed into a general ocean circulation model. This provided an internally-consistent data set for estimating the relative, but not absolute, abundance of floating plastics by LME. However, several important potential sources were excluded, including aquaculture and coastal tourism. It has not yet been possible to detect a consistent trend in abundance over time, despite the continuing entry of plastics into the ocean. This appears to be due mainly to the observed high degree of spatial heterogeneity in the distribution of micro- and macro-plastics. Further observations, combined with more sophisticated modelling approaches, are needed to increase the level of confidence in future assessments.

7.1.3 Methodology and analysis

For this assessment, it was concluded that observational data of floating plastic for many LMEs were not sufficient for a reliable comparative analysis to meet the TWAP objectives. Instead, an internally consistent modelling approach was adopted, based on a published study (Lebreton *et al.* 2012). This approach used the ocean circulation modelling system HYCOM/NCODA to create the flow field. HYCOM is computed on a Mercator grid, with 4 500 x 3 298 grid nodes at an average spacing of about 7 km. HYCOM was forced using archived data from the US Navy's Operational Global Atmospheric Prediction System. This system was used to reproduce 30 years of ocean circulation. Particles were then introduced using the particle-tracking model Pol3DD and allowed to disperse passively. Particles were introduced in a spatially explicit way, in proportion to three selected proxies of human activity or development, based on the analysis by Halpern *et al.* (2008): 1) shipping density, representing direct inputs of plastics from commercial shipping; 2) coastal population density, representing plastics used in the retail sector and for consumer goods on a per capita basis; and 3) the level of urbanization within major watersheds (urbanized landscape of buildings, roads, and other hard surfaces), representing areas liable to more rapid run-off of street litter. Two categories of particles were introduced: micro-plastics (less than 4.75 mm in diameter) and macro-plastics (more than 4.75 mm). Full details of the model and model runs were published in Eriksen *et al.* (2014) and Lebreton *et al.* (2012).

The model results provide an internally consistent data set based on several assumptions, but the results should not be used to infer actual quantities. The approach, however, provides a means of identifying potential hotspots of marine plastics that can then become the focus of more specific investigation, leading to the identification and introduction of measures to control existing sources. The analysis used three proxy sources of plastics; a future analytical development would be to include additional sources, such as fisheries, aquaculture, and coastal tourism, which are all known to be significant in many LMEs. Fisheries, for example, is a source of plastic waste in the North Australian Shelf LME, aquaculture is a source in the East China Sea LME, and coastal tourism is known to be a source of floating plastics in the Mediterranean Sea LME. There are other types of uncertainty associated with the analysis. For example, per capita use of plastics tends to correlate with Gross Domestic Product (GDP), but higher-GDP countries may have more effective waste management systems. Modelling approaches can be fine-tuned and improved as more data become available on sources of plastics, and with the introduction of more comprehensive and extensive environmental monitoring programmes.

References

Barnes, D.K.A., Walters, A. and Gonçalves, L. (2010). Macroplastics at sea around Antarctica. *Marine Environmental Research* 70, 250-252

CBD (2012). *Impacts of Marine Debris on Biodiversity: Current Status and Potential Solutions*, *Technical Series* 67, 61 pages. Secretariat of the Convention on Biological Diversity and the Scientific and Technical Advisory Panel – GEF, Montreal

Cózar, A., Echevarría, F., González-Gordillo, J.I. and others (2014). *Plastic debris in the open ocean.* Proceedings of the National Academy of Sciences

EC/JRC (2013). Guidance on monitoring of marine litter in European Seas. MSFD Technical Support Group on marine litter. Joint Research Centre Scientific and Policy Report, European Commission

Eriksen, M., Lebreton, L.C.M., Carson, H.S. and others (2014). Plastic pollution in the world's oceans: more than 5 trillion plastic pieces weighing over 250,000 tons afloat at sea. PLoS ONE 9(12), e111913. doi: 10.1371/journal.pone.0111913

Halpern, B.S., Walbridge, S., Selkoe, K.A. and others (2008). A global map of human impact on marine ecosystems. *Science* 319, 948-952

Jambeck, J.R, Geyer, R. Wilcox, C. and others (2015). Plastic waste inputs from land into the ocean. *Science* 347, 768-771

Law, K.L., Morét-Ferguson, S.E., Goodwin, D.S. and others (2014). Distribution of surface plastic debris in the eastern Pacific Ocean from an 11-year data set. *Environmental Science and Technology* 48(9), 4732-4738

Lebreton, L.C-M., Greer, S.D. and Borrero, J.C. (2012). Numerical modelling of floating debris in the world's oceans. *Marine Pollution Bulletin* 64, 653-661

Lippiat, S., Opfer, S. and Arthur, C. (2013). *Recommendations for Monitoring Debris Trends in the Marine Environment*. NOAA

Ocean Conservancy (2015). International Coastal Cleanup. http://www.oceanconservancy.org/our-work/international-coastal-cleanup/ (accessed 26 May 2015)

Pham, C.K., Ramirez-Llodra, E., Alt, C.H.S. and others (2014). Marine litter distribution and density in European seas, from the shelves to deep basins. *PloS one* 9(4), e95839-e95839

Plastics Europe (2013). *Plastics the Facts*. http://www.plasticseurope.org/Document/plastics-the-facts-2013.aspx?FolID=2

Ryan, P.G. (2013). A simple technique for counting marine debris at sea reveals steep litter gradients between the Straits of Malacca and the Bay of Bengal. *Marine Pollution Bulletin* 69, 128-136

Shiomoto, A. and Kameda, T. (2005). Distribution of floating marine debris in near-shore areas around Japan. *Marine Pollution Bulletin* 50, 1430-1432

UNEP/MAP (2011). *Assessment of the status of marine litter in the Mediterranean*. UNEP (DEPI), Mediterranean Action Plan

Van Franeker, J.A. and Bell, P.J. (1988). Plastic ingestion by petrels breeding in Antarctica. *Marine Pollution Bulletin* 19, 672-674

Chapter 7.2. Pollution status of persistent organic pollutants

Lead Author

Hideshige Takada (Laboratory of Organic Geochemistry, Tokyo University of Agriculture and Technology)

Contributing Author

Rei Yamashita (Laboratory of Organic Geochemistry, Tokyo University of Agriculture and Technology)

Chapter Citation

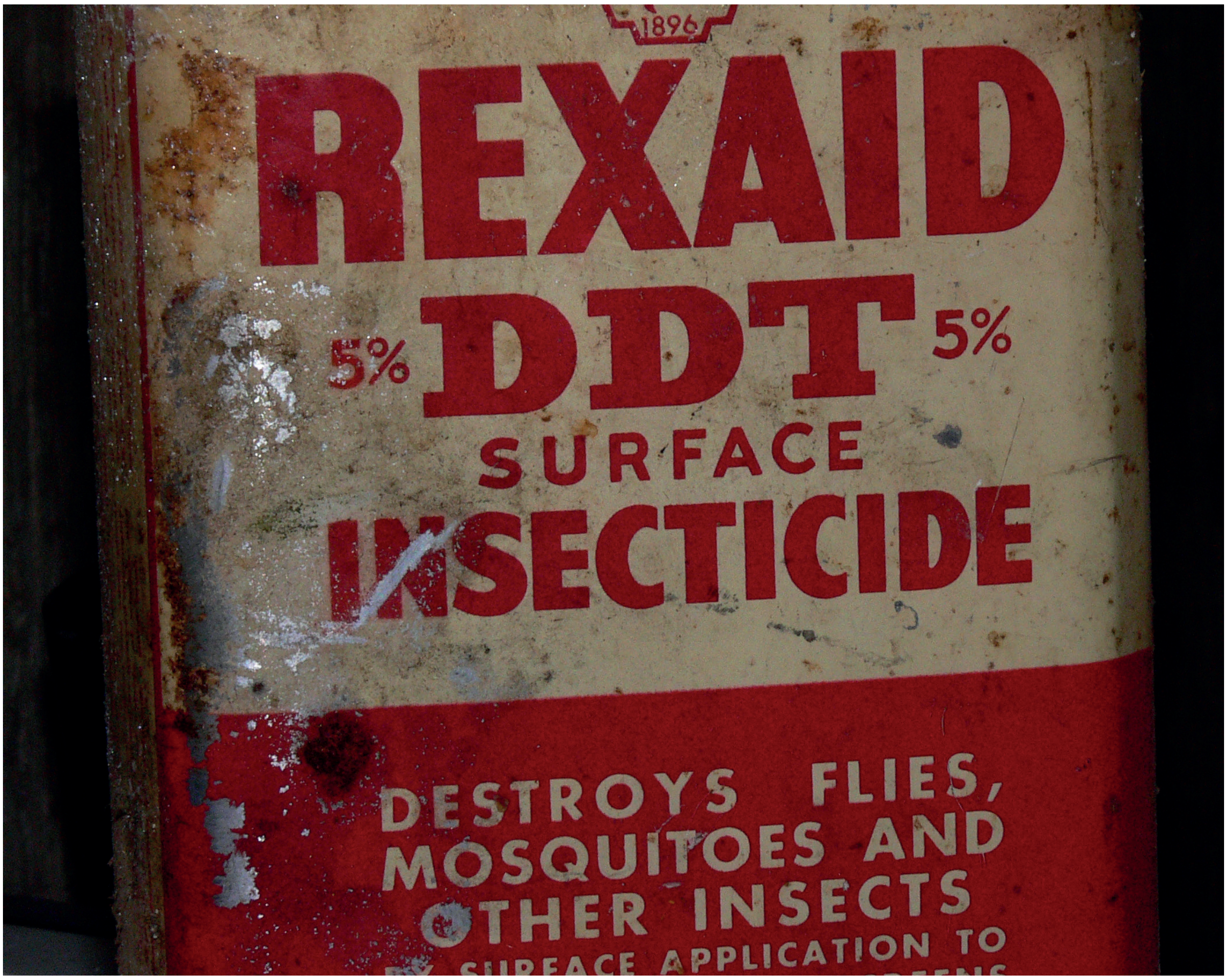
Takada, H., Yamashita, R. (2016). Chapter 7.2: Pollution status of persistent organic pollutants. In IOC-UNESCO and UNEP (2016). *Large Marine Ecosystems: Status and Trends*. United Nations Environment Programme, Nairobi, pp 165-176.

7.2 Pollution status of persistent organic pollutants

SUMMARY

Persistent organic pollutants (POPs) are man-made chemicals used in industrial and agricultural applications; they are widely distributed throughout marine ecosystems. They accumulate in living tissues, become more concentrated through the food chain, and are toxic. POPs pose a health risk to marine biota at higher trophic levels and to human consumers of some sea foods, and have been regulated through the Stockholm Convention on Persistent Organic Pollutants since 2004. Understanding the status, trends, and distribution of POPs in LMEs, and identifying pollutant sources, are important for assessing and maintaining marine ecosystem health, as well as for evaluating the effectiveness of regulation.

This assessment used plastic resin pellets as passive samplers of POPs in LMEs. The pellets, which are used in the manufacturing of plastic products, are found washed up on beaches all over the world. The pellets sorb and concentrate POPs from the surrounding seawater. Pellets from 193 locations in 37 LMEs were collected by volunteers through the International Pellet Watch (IPW) programme between 2005 and 2014 and sent to laboratories to be analysed for three classes of POPs: PCBs (polychlorinated biphenyls), DDTs (dichlorodiphenyltrichloroethane and related chemicals), and HCHs (hexachlorocyclohexane isomers). LMEs were placed into five risk categories, based on the average levels of these three classes of POPs in each LME. The evaluation of risk for individual LMEs is assessed as having medium certainty.



© Brad Smith/flickr

POPs were detected in all the samples, including those from remote islands. Within each LME, POPs levels are highly variable, sometimes by several orders of magnitude. Several LMEs (South Brazil Shelf, California Current, Mediterranean, and Kuroshio Current) have relatively high average levels of more than one class of POPs, and a number of hotspots were identified from sample locations within LMEs.

Key Messages

1. **Several POPs hotspots were identified, indicating a need for follow-up action.** For example, remedial action such as dredging and/or capping of bottom sediment should be considered where hotspots of PCBs and DDTs have been identified and attributed to contamination of the water column through release of POPs from contaminated bottom sediments.
    - PCB hotspots: in five LMEs of Western Europe, in two LMEs along US coasts, and in one LME along the coast of Japan. While these may be legacies of past PCB use, increasing levels were also observed in LMEs along the coasts of more recently industrialized countries, including Brazil, Chile, and South Africa.
    - DDT hotspots: in the California Current LME, Durres (Albania) in the Mediterranean LME, and Ghana in the Guinea Current LME. Moderate to high levels of DDTs are found in 20 widely distributed LMEs, probably due to widespread application of DDT before it was banned in the 1980s.
2. **Results from some LMEs indicate current or recent use or release of banned POPs.** This is indicated by levels of:
    - PCBs in some developing countries (Ghana in the Guinea Current LME and the Philippines in the Sulu-Celebes Sea LME). These findings point to a need for better source control, such as improved management and regulation of electronic waste.
    - DDTs in the South China Sea, Brazil, Ghana, Athens and Sydney. DDT use in malaria control may account for the elevated levels in some tropical and subtropical regions, whereas illegal application of DDT pesticides and antifouling agents may be the cause in other regions.
    - HCHs, with further analyses of the isomers present indicating that illegal use of lindane, a pesticide that is banned for agricultural use, may be responsible for elevated HCHs in pellets from some Southern Hemisphere sample sites, including in Mozambique and South Africa (Agulhas Current LME) and in the New Zealand Shelf LME, as well as along the French coast in the Celtic-Biscay Shelf LME.
3. **The International Pellet Watch programme serves as a sentinel to assess the status of POPs in coastal waters and identify pollution hotspots – but other POPs monitoring is also needed.** The IPW data set would be improved by additional spatial coverage, as data are sparse for some LMEs and missing for others. Time-series sampling of POPs in LMEs is needed to detect trends, evaluate the effectiveness of regulation, and identify emerging pollution sources. Conventional monitoring of POPs in sediments, water, and biota should be conducted in hotspots to confirm the pollution levels and identify the types and sources of pollution so that mitigation actions can be undertaken.

7.2.1 Introduction

Pollution status was assessed for three typical classes of POPs:

1. PCBs, used for a variety of industrial applications from the 1950s to the early 1970s;
2. DDT and its metabolites (degradation products), DDD and DDE; DDT was used as an insecticide to increase agricultural production, mainly from the 1950s to the early 1970s. Although its application in agriculture is prohibited, use of DDT to combat malaria-carrying mosquitoes is still recommended by the World Health Organization, and DDT is in use for this purpose in some tropical countries;
3. HCHs, organochlorine insecticides used from the 1950s to the 1970s in many countries and as late as the 2000s in some countries.

All these compounds are toxic, accumulate in marine biota, and are magnified through the food web, posing a variety of threats to animals at higher trophic levels (including carcinogenicity, mutagenicity, and endocrine disruption). Increasing concern and understanding of the adverse properties of these compounds resulted in the Stockholm Convention on Persistent Organic Pollutants, which entered into force in 2004 and contains provisions for eliminating or regulating production of POPs and for managing POPs wastes. Understanding the pollution status and the temporal and spatial distribution of POPs, and identifying their potential sources, are important, including for evaluating the effectiveness of the Stockholm Convention and detecting emerging pollutants (Ryan *et al.* 2012).

Samples of POPs were obtained from polyethylene resin pellets (2 to 4 mm diameter) that are used in the production of plastic products. Some pellets are unintentionally released into the environment during handling and transport and are carried by surface run-off, streams, and rivers to the ocean. As a result of the increasing global production of plastics and their environmental persistence, plastic pellets are distributed widely in the ocean and are washing up on beaches all over the world. The pellets sorb and concentrate hydrophobic organic contaminants, including POPs, from surrounding seawater (Rochman *et al.* 2013; Mato *et al.* 2001). The concentration factor of PCBs, for example, is more than 1 million. Because they accumulate POPs from the surrounding water so readily, plastic resin pellets are a useful passive sampler for monitoring POPs in coastal waters.

Beached plastic resin pellets from 193 locations in 37 LMEs were collected between 2005 and 2014 and analysed for PCBs, DDT and its metabolites, and HCHs, according to the protocol described below. Pellets were collected through the International Pellet Watch programme, which was established in 2005 (Takada 2006). In IPW, volunteers around the world collect plastic resin pellets on beaches and mail them to the Laboratory of Organic Geochemistry of the Tokyo University of Agriculture and Technology, Japan. The advantage of IPW is the extremely low cost of sampling and shipping compared to conventional monitoring. Further, as sampling does not require any special instruments or technical training, it can be undertaken by members of the public and can cover wide areas of coastal zones.

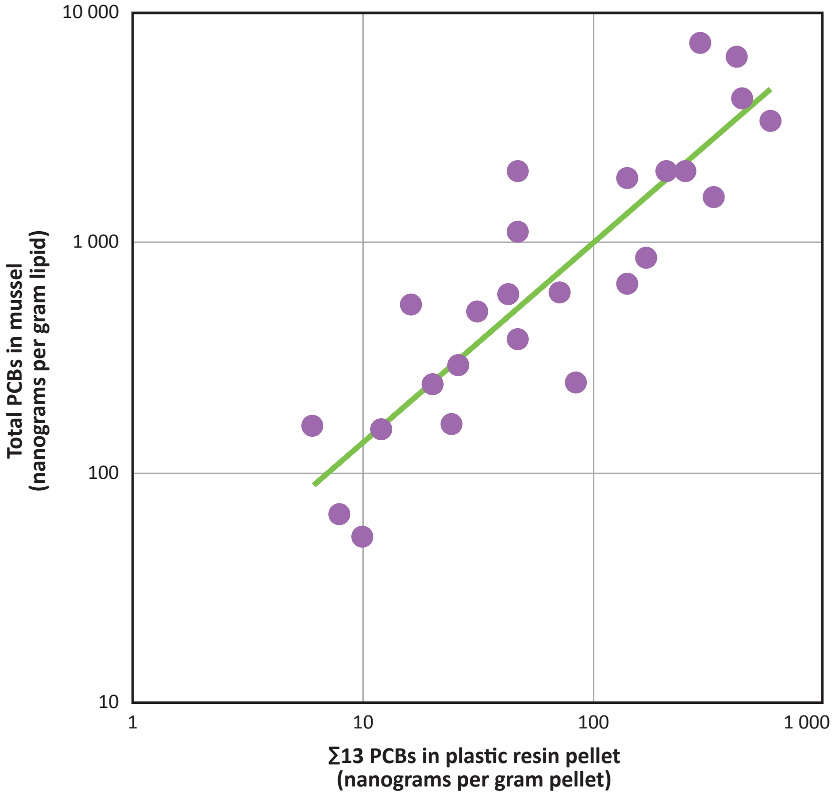
7.2.2 Findings, discussion, and conclusions

To confirm the reliability of IPW as a POPs monitoring tool, comparison with Mussel Watch was conducted. Mussel Watch, a programme that uses a traditional monitoring protocol to track contaminant levels in bivalves, was established in the 1970s and has been used for local and international monitoring of POPs over four decades (Farrington *et al.* 1983; Goldberg, 1975). Data from Mussel Watch were available for some of the locations where pellets were collected. Concentrations of PCBs in pellets showed good correlation with those in mussels collected from the same locations (Figure 7.7), indicating that pellets collected by IPW can be used to sample POPs.

LMEs were placed into five risk categories based on the mean level of POPs in each LME. Concentrations of POPs in pellet samples from all locations are mapped in Figure 7.8, Figure 7.9, and Figure 7.10. These show that POPs are widespread. The target POPs were detected in all samples, including pellets from remote islands. The dispersion of POPs to remote areas is thought to be mainly through atmospheric transport.

POPs in pellets from remote islands are at trace levels, several orders of magnitude lower than the concentrations found in urban coastal zones. Background levels of POPs were established on the basis of analysis of plastic resin pellets collected from remote islands: Canary Islands, Saint Helena, Cocos Islands, Island of Hawaii, Island of Oahu, and Barbados (Heskett *et al.* 2012). Concentrations of POPs in the pellets from these remote islands are 0.1 to 9.9 nanograms per gram for PCBs, 0.8 to 4.1 nanograms per gram for DDTs, and 0.6 to 1.7 nanograms per gram for HCHs (with the exception of St. Helena, where the HCH concentration was measured at 19.3 nanograms per gram). The background levels of PCBs, DDTs, and HCHs were set at 10, 4, and 2 nanograms per gram, respectively. Concentrations of POPs higher than the background levels suggest local or regional inputs. These background levels are set as cut-off concentrations for the lowest risk category.

Figure 7.7 Correlation between median PCB concentrations in plastic resin pellets and in mussels. Plastic resin pellets are unintentionally introduced to marine environments and distributed globally. Due to the hydrophobic nature of the plastics, pellets can be utilized as passive samplers of POPs in coastal waters. The correlation shown in this figure demonstrates that POPs in plastic resin pellets reflect POP contamination levels in coastal waters.



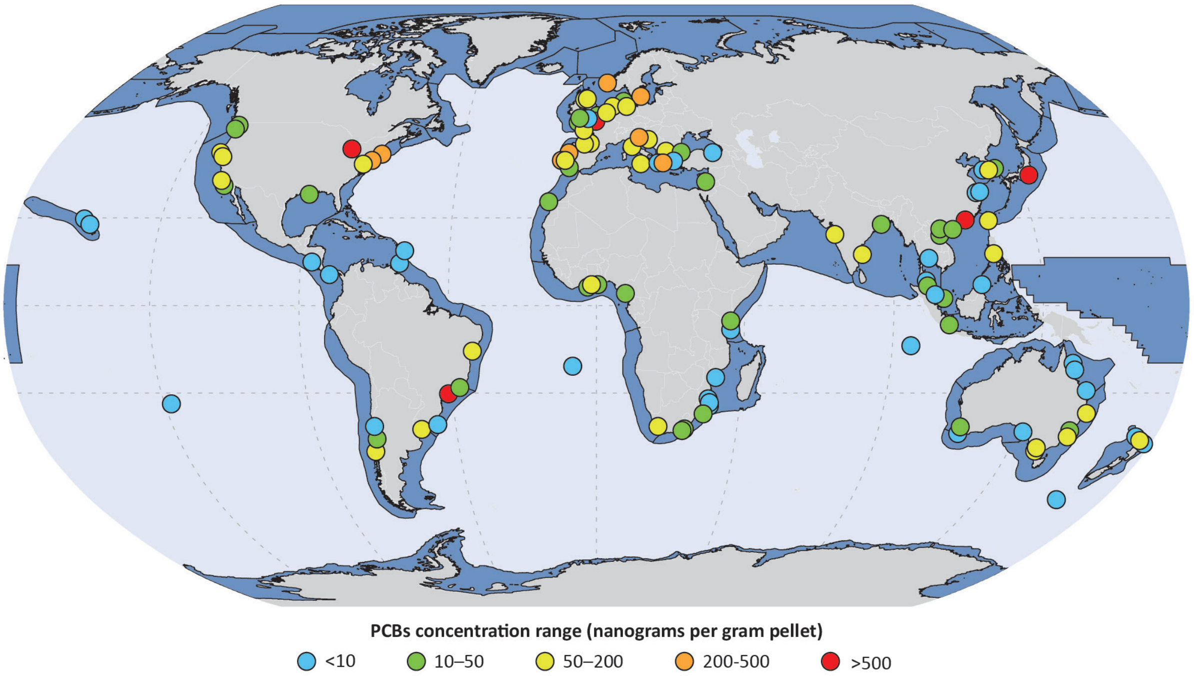
Σ13 PCBs = sum of concentrations of 13 congeners (listed in the text); total PCBs = sum of concentrations of individually resolved peaks of PCB congeners on chromatograms; $r^2=0.77$; n=25; $p < 0.0002$.

7.2.2.1 PCBs

PCB hotspots (‘high’ and ‘highest’ risk categories) were identified in a number of LMEs where PCBs were used for a variety of industrial applications during a period of rapid economic growth from the 1950s to the early 1970s (including the North Sea, Baltic Sea, Celtic-Biscay Shelf, Iberian Coastal, California Current, Northeast U.S. Continental Shelf, and Kuroshio Current LMEs). These hotspots are shown as orange and red dots in Figure 7.8. A considerable portion of the PCBs introduced to coastal zones during that period remains accumulated in bottom sediments, which act as secondary sources of PCBs to the water column. PCBs can be released through desorption (the reverse of adsorption) and/or resuspension of the sediments (Farrington and Takada 2014). Release of contaminants from sediments is a major source of PCBs in seawater and biota in developed countries (Mizukawa *et al.* 2013; Ogata *et al.* 2009). Other PCB hotspots identified are Melbourne (Southeast Australian Shelf LME), Sydney (East Central Australian Shelf LME), Hong Kong (South China Sea LME), and Sao Paulo (South Brazil Shelf LME).

Further studies that combined pellet sampling with analysis of sediment and air samples confirm that bottom sediments act as a major source of PCBs to the coastal waters in Tokyo Bay (Kuroshio Current LME) and Athens (Mediterranean LME). Pellet samples were collected in hotspots at the same sites at five or ten year intervals. The results suggest a decreasing trend in PCB levels on the California coast (California Current LME) from 2006 to 2010 (40 to 80 per cent reduction), whereas no decrease was observed in Tokyo Bay from 2002 to 2012. A possible

Figure 7.8 Concentrations of PCBs in beached plastic pellets within LMEs. Legacy pollution, where bottom sediments act as secondary sources of contamination, is observed in urban coastal waters in Western Europe, the US east and west coasts, and Japan. Results suggest current or recent inputs of PCBs for some developing countries such as Ghana and the Philippines.



Dots are sample locations; measurements are Σ13 PCBs (sum of 13 PCB congeners, listed in the text).

explanation for this difference is geographical setting. The California coast faces the open ocean and is exposed to offshore transport. Dispersion of contaminated sediments could be active enough to reduce PCB pollution levels. Tokyo Bay, by contrast, is semi-enclosed, and contaminants tend to stay longer in the bottom sediments. Differences in regulatory and remedial actions (such as dredging) may also contribute to this difference in trends. Decreasing trends in PCB levels were also observed in the Netherlands (North Sea LME), while locations in the Greek Saronic Gulf in the Mediterranean Sea LME show no such trend, which may be related to the LME's semi-enclosed configuration which allows contaminated sediments to be retained. Continued monitoring is important for understanding the rate of decrease of legacy pollutants and the controlling factors.

In addition to the hotspots in industrially developed countries, increasing levels of PCBs were observed in recently developing countries such as Brazil (Sao Paulo, in the South Brazil Shelf LME), South Africa (Durban and Yzerfontein, in the Agulhas Current LME), and Chile (Conception, in the Humboldt Current LME). Current releases of PCBs to terrestrial environments, and subsequent run-off to the coastal zones, could be contributing to the high concentrations. Current sources include leakages or spills of PCBs from old electronic instruments. Pollution levels of PCBs along the Sao Paulo coast increased rapidly from around 300 nanograms per gram in 2010 to up to 4 000 nanograms per gram in pellets collected in 2012, which is the highest concentration of all locations sampled. This suggests that the South Brazil Shelf LME could be the most heavily impacted by PCBs. In South Africa and Chile, PCB concentrations are not as high (up to 150 nanograms per gram) as in Sao Paulo, but time-series samples at these locations show increasing trends in PCB levels from 2007/2008 to 2014. Continued monitoring and identification of the sources of PCBs are necessary in these rapidly developing countries.

Among the hotspots, Tokyo Bay (Kuroshio Current LME), Hong Kong (South China Sea LME), and Le Havre (Celtic-Biscay Shelf LME), as well as Sao Paulo (South Brazil Shelf LME) and Jakarta Bay (Indonesian Sea LME), have the highest levels of PCBs (over 500 nanograms per gram, which places them in the 'highest' risk category). No regulatory guidelines for PCB concentrations in pellets have been established. Instead, PCB concentrations in pellets can be related to PCB concentrations in lipid (fat) in mussels by using the following equation, which is derived from the correlation between PCB concentrations in mussels and in pellets, as shown in Figure 7.7:

$$\log(\text{PCBs in mussel lipid [nanograms per gram]}) = 0.87 \times \log(\text{PCBs in pellets [nanograms per gram]}) + 1.26$$

Using this equation, 500 nanograms of PCBs per gram of pellets corresponds to 4 000 nanograms of PCBs per gram of lipid in mussels. By using commonly-observed lipid content (100 milligrams of lipid per gram of dry tissue) and moisture content (80 per cent) of the mussel tissue, 4 000 nanograms per gram PCBs in mussel lipid is converted to 400 nanograms per gram PCBs in dry tissue, or 80 nanograms per gram in wet tissue. This latter value is similar to the European Union (EU) limit established for PCBs in muscle meat of fish and fishery products (75 nanograms per gram in tissue; Commission Regulation (EU) No., 1259/2011). The above calculation also indicates that 500 nanograms of PCBs per gram of pellets correspond to 400 nanograms per gram of PCBs in dry mussel tissue. This is similar to the cut-off concentration of PCBs for the 'high' risk category (479 nanograms per gram in dry tissue) when PCB concentrations in mussel obtained from the US Mussel Watch programme are ranked (Farrington and Takada 2014). Thus, using greater than 500 nanograms per gram as the cut-off for the 'highest' risk category in this assessment is considered reasonable. Due to biomagnification, fishery products have higher concentrations of PCBs than mussels, although toxicity is also affected by PCB congeners being metabolized at different rates. The risk based on PCBs in mussel tissue may be a conservative estimate. Locations with PCB concentration in pellets higher than 500 nanograms per gram can be considered as areas where fishery products may exceed the European Union limit and where regulation and remedial actions should be considered.

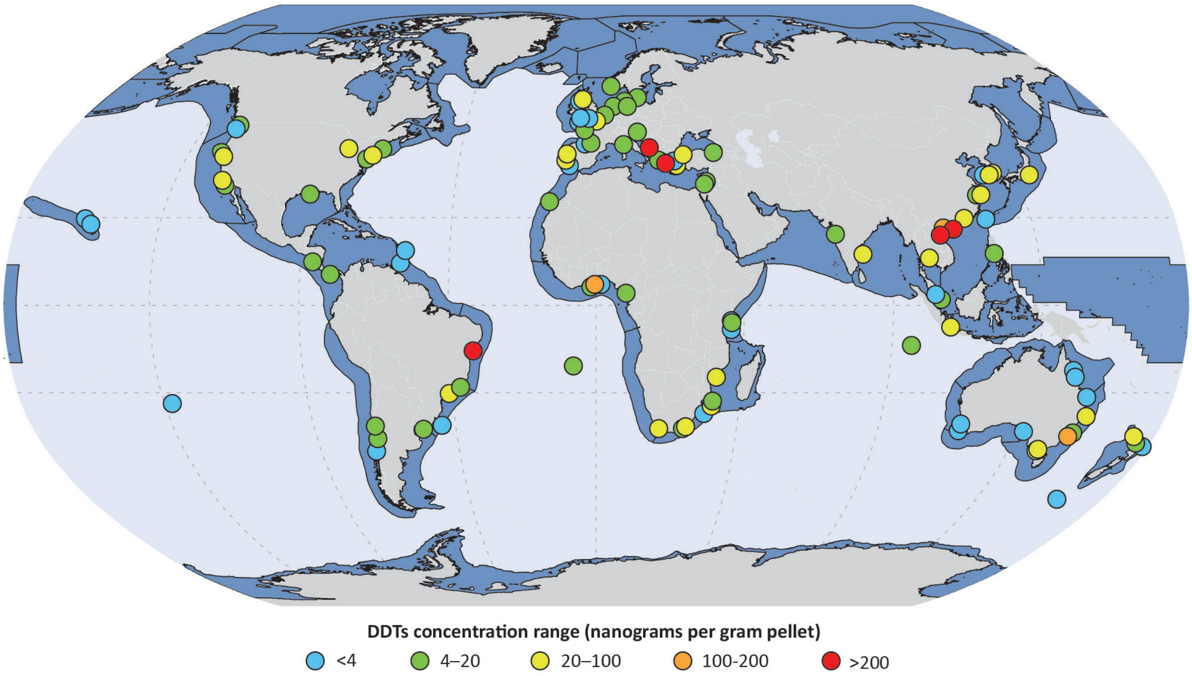
Levels of PCBs significantly higher than global background levels were observed in some developing countries, including Ghana and Equatorial Guinea (Guinea Current LME) and the Philippines (Sulu-Celebes Sea). Current releases of PCBs are likely to be occurring in these areas. Further investigation in Ghana, using pellet analysis combined with riverine sediment surveys, pinpointed electronic waste (e-waste) scrap yards as a plausible source of PCBs to the coastal environment through river run-off (Hosoda *et al.* 2014). Current emission of PCBs from the western African region was demonstrated through analysis of air samples (Gioia *et al.* 2011). In Manila Bay, Philippines (Sulu-Celebes Sea LME) the concentration of PCBs in pellets (140 nanograms per gram) is higher than in surrounding countries. PCB concentrations in the air in Manila are also higher than in other Asian countries (Kwan *et al.* 2014) and higher than in other locations in the world (Pozo *et al.* 2006). Current emission of PCBs is suspected (Kwan *et al.* 2014).

7.2.2.2 DDTs

Hotspots of DDTs (Figure 7.9) were observed on the California coast (California Current LME) Morro de Sao Paulo, Brazil (East Brazil Shelf LME); Durres, Albania, and Athens, Greece (Mediterranean LME); Northern Vietnam and Southern China, including Hong Kong (South China Sea LME); Ghana (Guinea Current LME); and Sydney, Australia (East-Central Australian Shelf LME). The highest concentration of DDTs (1 061 nanograms per gram) was found in samples from Durres, Albania.

Moderate levels of DDTs are widely distributed in 20 of the 37 LMEs examined. High concentrations at some of the hotspots, as well as diffuse pollution, are probably from legacy pollution – left over from the widespread and intensive application of DDT pesticides in catchment areas, mainly in the 1950s to the early 1970s to increase agricultural production. DDT was banned in the 1980s in many countries. As with PCBs, secondary pollution sources of DDTs could be among the major contributors.

Figure 7.9 Concentrations of DDTs in beached plastic pellets within LMEs. Legacy pollution is observed in areas where DDT pesticide was used for agricultural production. For some tropical countries, there is evidence of current and/or recent inputs of DDT used for malaria control.



Dots are sample locations; DDT measurements are sum of *p,p′*-DDT, *p,p′*-DDD, and *p,p′*-DDE.

In addition to legacy DDT pollution, current inputs of DDTs are suggested by the results at some hotspots, such as in Northern Vietnam, Southern China, Sydney Harbour, Athens, and Ghana. Some of these high concentrations, especially in tropical and subtropical regions such as Ghana, may be attributed to its continuing use for malaria control. Illegal application of DDT insecticides is another possibility. Application of antifouling agents containing DDT might be the cause of current pollution in some sites close to harbours, such as Sydney and Athens. Addressing pollution in these locations requires identification of specific DDT sources.

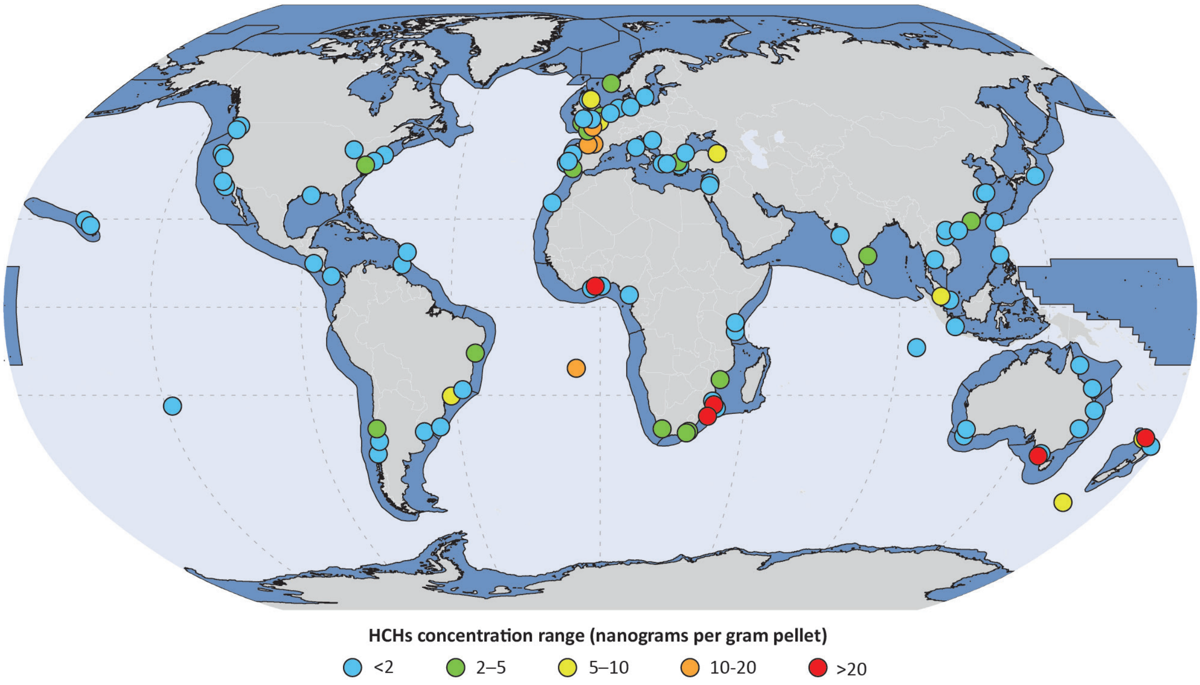
Monitoring in 2014 showed decreasing trends in DDTs at several locations where high concentrations were observed in the period 2005 to 2010, indicating improvement in DDT pollution status. These locations include northern Vietnam, Hong Kong, South Africa (Durban), Mozambique, and Ghana. This improvement is probably due to a cessation of DDT application and rapid dispersion by oceanographic conditions. A decreasing trend in DDT pollution was also observed in the California Current LME.

7.2.2.3 HCHs

HCHs are insecticides that were used from the 1950s to the1970s in many countries and remained in use up to the 2000s in some. Their regulation through the Stockholm Convention started in 2008. Concentration ranges of HCHs (up to 40 nanograms per gram) are one order of magnitude lower than those of PCBs and DDTs. This is probably because HCHs are less hydrophobic than DDTs and PCBs, which causes less partitioning of HCHs from seawater to plastics. In addition, HCHs are more volatile and tend to be partitioned in the atmosphere. Lower production of HCHs may also contribute to the lower concentrations of HCHs in pellets.

At most of the sample locations, HCH concentrations in pellets are relatively low (Figure 7.10). However, some hotspots were observed in the Southern Hemisphere, including Mozambique and South Africa (Agulhas Current LME) and New Zealand (New Zealand Shelf LME). In addition, hotspots were identified on the French coast in the

Figure 7.10 Concentrations of HCHs in beached plastic pellets within LMEs. Only trace levels of HCHs are observed in most locations in the Northern Hemisphere, probably due to this compound's more volatile and water-soluble nature. Higher levels of HCHs are observed in some locations in the Southern Hemisphere, such as South Africa, Mozambique, and New Zealand. This is probably due to current or recent usage of HCH as a pesticide.



Dots are sample locations; HCH measurements are sum of α, β, γ, and δ isomers.

Celtic-Biscay Shelf LME. Gamma-HCH, a major component of the pesticide lindane, which has been banned globally for agricultural use, is predominant in the HCHs detected at these hotspots, suggesting that illegal use of lindane could be occurring. At locations in Mozambique, South Africa (Durban), and Ghana, significant decreases in HCH concentrations (from around 30 to less than 3 nanograms per gram) were observed in the samples collected in 2013 or 2014, compared to 2007 to 2011 samples. This suggests that the Stockholm Convention, which started to regulate HCHs in 2008, has been effective. However, continued monitoring is necessary, especially in the Southern Hemisphere, where higher levels of HCHs were observed in 2011. The specific sources of HCHs should be identified in order to regulate them.

HCH concentration at Macquarie Island, in the sub-Antarctic zone, is 7.7 nanograms per gram, which is higher than the global background level. This is a desert island in a region with a cold climate and where use of HCH insecticide is unlikely. The higher concentration of HCHs may be the result of global distillation of HCHs – the HCHs used in lower latitudes evaporate and are atmospherically transported to higher latitudes, where more HCHs are partitioned into seawater because of lower temperatures. In areas where concentrations of POPs higher than the global background level were observed at high latitudes, the potential contribution of global distillation should be considered, as well as the potential for inputs from local sources. Collection and analyses of pellets from remote islands at higher latitudes are necessary to establish more comprehensive background levels of POPs.

7.2.2.4 Multiple indicators

Several LMEs have relatively high contamination levels (in the 'high' or 'highest' risk categories) for multiple indicators of POPs. The South Brazil Shelf LME has recorded the world's highest concentrations of PCBs and high levels of DDTs. Source identification and necessary regulation and remediation should be implemented, although both contaminants are likely to be from current inputs.

The California Current, Mediterranean, and Kuroshio Current LMEs are the second highest in levels of contamination by PCBs and DDTs. In these locations, the contaminants are derived from secondary sources. Continued monitoring over time should be conducted to determine temporal trends, and some remedial actions such as dredging and capping may be necessary.

In the Southern Hemisphere, the Southeast Australian Shelf LME and Benguela Current LME are polluted by multiple compounds. High levels of HCHs were observed in both LMEs, pointing to the importance of monitoring for HCHs in the Southern Hemisphere. Although high levels of PCBs and DDTs were detected in the East Brazil Shelf LME, this observation is based on a single sample at one location. More locations should be monitored to properly evaluate the Southern Hemisphere LMEs.

7.2.2.5 Confidence levels

One concern is that pellets may not reflect local pollution because they drift. However, most pellets are retained in the coastal zone by near-shore trapping (Isobe *et al.* 2014) and reflect local pollution of these zones. Pellets reflect water pollution, rather than air pollution, as demonstrated by Mato *et al.* (2001), although pellets are exposed to the air during stranding on sandy beaches.

Taking the median concentration among five pooled samples of pellets with a specified range of yellowing (a marker of the age of the pellet, as explained in the methodology section below) allows accurate evaluation of the status of POPs contamination for each location, despite the mobile nature of pellets. However, within each LME, POPs levels are highly variable. They can range over as many as five risk categories in one LME as a result of variation in the magnitude of anthropogenic activities, distances from the sources, and physical characteristics of coastal waters, which determine dispersion and dilution.

Because of this variability and the limited numbers of locations for which samples are available, assessments for LMEs with few samples are not conclusive. There are several LMEs with higher accuracy due to larger numbers of sampling locations, such as the California Current, Insular Pacific-Hawaiian, North Sea, Celtic-Biscay Shelf, Iberian Coastal, Mediterranean, Guinea Current, Agulhas Current, and East-Central Australian Shelf. In general, both spatial pattern (relative evaluation among LMEs) and absolute evaluation of risk for individual LMEs have medium certainty. An increase in the number of samples and sampling locations would be needed to increase the level of confidence for future assessments.

7.2.3 Methodology and analysis

This assessment used 193 samples from 37 LMEs. Of these, 190 were analysed by the Laboratory of Organic Geochemistry of Tokyo University of Agriculture and Technology, Japan. This describes the methodology and analytical procedures used by LOG. Analyses were supported financially by the Mitsui Foundation for Environmental Studies (71-05, R11-G4-1053). The data were obtained from the IPW website (http://www.pelletwatch.org/). Data on Korean pellets (three samples) were taken from Sang *et al.* (2012). The similarity of their methodology to that of the Laboratory of Organic Geochemistry was confirmed at a workshop held in May 2014, and results can be plotted on the same maps.

Despite the advantages of using plastic pellets, their mobile nature may limit their utility as a passive sampler. Some plastics can travel hundreds of kilometres or more. However, most of the polyethylene pellets with sizes of 2 to 4 mm (the target pellet size range for IPW) are retained for a long time within about 5 km from the coast because of near-shore trapping, as demonstrated by Isobe *et al.* (2014). Therefore, the majority of the pellets reflect local pollution of the coastal zone, although pellets are also found on remote beaches. In addition, sorption of pollutants to the plastic pellets is a bidirectional reaction and moves toward equilibrium. This means that even pellets that arrive from other areas can reflect local pollution, as long as they remain in the given location for a long time. Some pellets, however, may have short residence times along the coast and may reflect pollution in other areas, which may interfere with the interpretation of monitoring results. To exclude such outliers (pellets having higher or lower POPs concentrations that reflect pollution status elsewhere), five samples were always analysed for each location and the median value was used.

In order to select and analyse pellets with a consistent range of residence times in the coastal waters, pellets with a specified degree of yellowing were used for the analysis. Yellowing occurs with exposure to the environment and can be used as a practical index of residence time in the sea (Endo *et al.* 2005). Analysis of different colour classes of pellets collected at the same time from Tokyo Bay showed that median concentrations of PCBs in the pellets were: 71 nanograms per gram for white pellets (range of 26 to 172 nanograms per gram), 376 nanograms per gram for yellowing pellets (range of 301 to 2 921 nanograms per gram), and 2 052 nanograms per gram for brown pellets (range of 1 239 to 53 350). Pellets with a yellowness index from 30 to 50 were used for the IPW analysis. This comparison of PCBs in pellets by colour indicates that the yellowing pellets that were used for monitoring were not at equilibrium and were still in the linear uptake phase. This is consistent with the slow sorption/desorption process and long time to reach equilibrium (one year or more) described by Endo *et al.* (2013).

The analytical methodology used by the Laboratory of Organic Geochemistry is outlined below; details are available in Ogata *et al.* (2009). Pellets were instrumentally sorted, and yellowing polyethylene pellets were extracted with hexane by soaking. To minimize piece-to-piece variation in POPs concentrations in pellets, five pools (sub-sets of pellets, with each pool consisting of two to ten – normally five – pellets) were analysed for each location, and the median value was used as the representative pollution status at the site.

PCBs (tetra- to nona-CB congeners) and DDE were quantified using an ion-trap mass spectrometer fitted with a gas chromatograph (GC-MS). The sum of the quantified CB congeners (CB# 66, 101, 110, 149, 118, 105, 153, 138, 128, 187, 180, 170, and 206) is expressed as Σ13 PCBs. DDT and DDD, and the four HCH isomers (α, β, γ, and δ) were determined by an electron capture detector fitted with a gas chromatograph (GC-ECD).

The reproducibility of analyses was confirmed by replicate analyses of aliquots of pellet extracts. The relative standard deviations of the concentrations of the target compounds were 1 to 15 per cent. The recoveries of the target compounds were more than 80 per cent. Thus, no recovery correction was made for any of the target compounds. The efficiency of the extraction was confirmed by re-extraction of extracted pellets. A procedural blank was run in each set analysed (five pools). Analytical values less than three times the corresponding blank are expressed as 'below the limit of quantification (LOQ)'. LOQ for Σ13 PCBs, DDT, DDE, DDD and HCHs was normally 0.3, 0.4, 0.1, 0.2, and 0.9 nanograms per gram, respectively. To get representative analytical values for individual locations, median concentrations were taken among the five pools analysed. Repeated analysis of five pools of pellets taken from the same beach at the same time showed that variations in PCB, DDT, and HCH concentrations were less than 20 per cent.

The concentrations of individual POPs were grouped into five risk categories based on the cut-off points listed in Table 7.3. Categorization was based on the statistical distributions of the analytical values (the concentrations of individual POPs). The upper limit for 'lowest' risk was set as the global background level for each of PCBs, DDTs, and HCHs. These levels were determined by measuring POPs in pellets from seven remote islands around the world (Heskett et al. 2012). The relationship between the lower cut-off level for the 'highest' risk for PCBs and the regulatory basis for seafood consumption is discussed above. Pollution status (by category) of LMEs for PCBs, DDTs, and HCHs is shown in Figure 7.8, Figure 7.9, and Figure 7.10, using the colour codes from Table 7.3.

Table 7.3 Risk categories for concentrations of (a) PCBs, (b) DDTs, and (c) HCHs in plastic pellets in LMEs. Levels of POPs were averaged for all sample locations within each LME. POPs levels for each sample location are shown by risk category in Figure 7.8, Figure 7.9, and Figure 7.10.

INDICATOR: PCBs in pellets

Risk category	Range of values (nanograms per gram)	Number of LMEs	LMEs in each category
Lowest	Below 10	10	Insular Pacific-Hawaiian; Pacific Central-American; Caribbean Sea; Canary Current; Gulf of Thailand; Northeast Australian Shelf; Southwest Australian Shelf; West-Central Australian Shelf; Yellow Sea; Black Sea
Low	10–50	10	Gulf of Alaska; Gulf of Mexico; Humboldt Current; Patagonian Shelf; Guinea Current; Agulhas Current; Somali Coastal Current; Bay of Bengal; New Zealand Shelf; East China Sea
Medium	50–200	11	California Current; East Brazil Shelf; North Sea; Iberian Coastal; Mediterranean; Benguela Current; Arabian Sea; South China Sea; Sulu-Celebes Sea; East-Central Australian Shelf; Southeast Australian Shelf
High	200–500	5	Northeast US Continental Shelf; Baltic Sea; Celtic-Biscay Shelf; Indonesian Sea; Kuroshio Current
Highest	Over 500	1	South Brazil Shelf

INDICATOR: DDTs in plastic pellets

Risk category	Range of values (nanograms per gram)	Number of LMEs	LMEs in each category
Lowest	Below 4	7	Insular Pacific-Hawaiian; Caribbean Sea; Canary Current; Northeast Australian Shelf; Southwest Australian Shelf; West-Central Australian Shelf; Yellow Sea
Low	4–20	14	Gulf of Alaska; Gulf of Mexico; Pacific Central-American; Humboldt Current; Patagonian Shelf; North Sea; Baltic Sea; Celtic-Biscay Shelf; Iberian Coastal; Somali Coastal Current; Arabian Sea; Bay of Bengal; Sulu-Celebes Sea; Black Sea
Medium	20–100	11	California Current; Northeast US Continental Shelf; South Brazil Shelf; Guinea Current; Benguela Current; Agulhas Current; Gulf of Thailand; Southeast Australian Shelf; New Zealand Shelf; East China Sea; Kuroshio Current
High	100–200	3	Mediterranean; South China Sea; East-Central Australian Shelf
Highest	Over 200	2	East Brazil Shelf; Indonesian Sea

INDICATOR: HCHs in plastic pellets

Risk category	Range of values (nanograms per gram)	Number of LMEs	LMEs in each category
Lowest	Below 2	24	Gulf of Alaska; California Current; Gulf of Mexico; Northeast US Continental Shelf; Insular Pacific-Hawaiian; Pacific Central-American; Caribbean Sea; Humboldt Current; Patagonian Shelf; Baltic Sea; Mediterranean; Canary Current; Somali Coastal Current; Arabian Sea; Gulf of Thailand; South China Sea; Sulu-Celebes Sea; Indonesian Sea; Northeast Australian Shelf; East-Central Australian Shelf; Southwest Australian Shelf; West-Central Australian Shelf; East China Sea; Kuroshio Current
Low	2–5	8	South Brazil Shelf; East Brazil Shelf; North Sea; Celtic-Biscay Shelf; Iberian Coastal; Guinea Current; Benguela Current; Bay of Bengal
Medium	5–10	1	Black Sea
High	10–20	3	Agulhas Current; Southeast Australian Shelf; New Zealand Shelf
Highest	Over 20	–	–

Even after application of careful analytical protocols and consideration, as described in this section, a degree of uncertainty (or variability) associated with the use of pellets as a monitoring medium remains, due mainly to the heterogeneity of pellets in terms of routes and time from the source to the sink. Thus, IPW should be regarded as a sentinel or screening tool to monitor POPs in coastal waters. When hotspots of POPs are discovered, monitoring using traditional media such as water, sediment, and biota should be conducted before taking regulatory and/or remedial action. However, plastic pellets are already distributed to beaches of almost all coastal countries. This passive sampler has already been installed globally without funding, and should be used as much as possible.

References

Endo, S., Takizawa, R., Okuda, K. and others (2005). Concentration of polychlorinated biphenyls (PCBs) in beached resin pellets: Variability among individual particles and regional differences. *Marine Pollution Bulletin* 50, 1103-1114

Endo, S., Yuyama, M., and Takada, H. (2013). Desorption kinetics of hydrophobic organic contaminants from marine plastic pellets. *Marine Pollution Bulletin* 74, 125-131

Farrington, J.W., Goldberg, E.D., Risebrough, R.W. and others (1983). U.S. "Mussel Watch" 1976-1978: An overview of the trace-metal, DDE, PCB, Hydrocarbons, and artificial radionuclide data. *Environmental Science and Technology* 17, 490-496

Farrington, J.W. and Takada, H. (2014). Persistent organic pollutants (POPs), polycyclic aromatic hydrocarbons (PAHs), and plastics: Examples of the status, trend, and cycling of organic chemicals of environmental concern in the ocean. *Oceanography* 27, 196-213

Gioia, R., Eckhardt, S., Breivik, K. and others (2011). Evidence for major emissions of PCBs in the West African Region. *Environmental Science and Technology* 45, 1349-1355

Goldberg, E.D. (1975). The mussel watch: a first step in global marine monitoring. *Marine Pollution Bulletin* 6, 111

Heskett, M., Takada, H., Yamashita, R. and others (2012). Measurement of persistent organic pollutants (POPs) in plastic resin pellets from remote islands: Toward establishment of background concentrations for International Pellet Watch. *Marine Pollution Bulletin* 64, 445-448

Hosoda, J., Ofosu-Anim, J., Sabi, E.B. and others (2014). Monitoring of organic micropollutants in Ghana by combination of pellet watch with sediment analysis: E-waste as a source of PCBs. *Marine Pollution Bulletin* 86, 575-581

Isobe, A., Kubo, K., Tamura, Y. and others (2014). Selective transport of microplastics and mesoplastics by drifting in coastal waters. *Marine Pollution Bulletin* 89(1-2), 324-30

Kwan, C.S., Takada, H., Boonyatumanond, R. and others (2014). Historical occurrences of polybrominated diphenyl ethers and polychlorinated biphenyls in Manila Bay, Philippines, and in the upper Gulf of Thailand. *Science of the Total Environment*, 470-471, 427-437

Mato, Y., Isobe, T., Takada, H. and others (2001). Plastic resin pellets as a transport medium for toxic chemicals in the marine environment. *Environmental Science and Technology* 35, 318-324

Mizukawa, K., Takada, H., Ito, M. and others (2013). Monitoring of a wide range of organic micropollutants on the Portuguese coast using plastic resin pellets. *Marine Pollution Bulletin* 70, 296-302

Ogata, Y., Takada, H., Mizukawa, K. and others (2009). International Pellet Watch: Global monitoring of persistent organic pollutants (POPs) in coastal waters. 1. Initial phase data on PCBs, DDTs, and HCHs. *Marine Pollution Bulletin* 58, 1437-1446

Pozo, K., Harner, T., Wania, F. and others (2006). Toward a global network for persistent organic pollutants in air: results from the GAPS study. *Environmental science and Technology* 40, 4867-4873

Rochman, C.M., Hoh, E., Hentschel, B.T. and others (2013). Long-term field measurement of sorption of organic contaminants to five types of plastic pellets: Implications for plastic marine debris. *Environmental science and Technology* 47, 1646-1654

Ryan, P.G., Bouwman, H., Moloney, C.L. and others (2012). Long-term decreases in persistent organic pollutants in South African coastal waters detected from beached polyethylene pellets. *Marine Pollution Bulletin* 64, 2756-2760

Sang, H.H., Han, G.M., Heo, N.W. (and others) (2012). Organic micropollutants in plastic resin pellets from sand beaches of South Korea. PICES annual meeting. Hiroshima, Japan

Takada, H. (2006). Call for pellets! International Pellet Watch global monitoring of POPs using beached plastic resin pellets. *Marine Pollution Bulletin* 52, 1547-1548

© Shutterstock

Chapter 7.3. Nutrient inputs from river systems to coastal waters

Lead Author

Sybil Seitzinger (International Geosphere-Biosphere Programme, Royal Swedish Academy of Sciences)

Contributing Author

Emilio Mayorga (Applied Physics Laboratory, University of Washington)

Chapter Citation

Seitzinger, S., Mayorga, E. (2016). Chapter 7.3: Nutrient inputs from river systems to coastal waters. In IOC-UNESCO and UNEP (2016). *Large Marine Ecosystems: Status and Trends*. United Nations Environment Programme, Nairobi, pp 179-195.

7.3 Nutrient inputs from river systems to coastal waters

SUMMARY

Land use and human activities in watersheds are affecting nutrients transported by rivers into LMEs. Excess nutrients – nitrogen (N), phosphorus (P), and silica (Si) – entering coastal waters can result in eutrophication: high-biomass algal blooms, depletion of oxygen, increased turbidity, changes in community composition, and other effects. In addition to the amount of nutrients, changes in the ratios of nutrients entering LMEs can result in dominance by algal species (such as dinoflagellates) that can be toxic to marine biota and to humans, or can have deleterious effects on ecosystems, such as through clogging the gills of shellfish.

An overall indicator of coastal eutrophication was developed for 63 LMEs. It is based on two sub-indicators: 1) the amount of nitrogen carried by rivers as they enter the land–sea boundary of the LME, and 2) nutrient ratios. LMEs were grouped into five risk categories according to the indicator values. Inputs of nutrients from watersheds draining into the LMEs were calculated by the Global Nutrient Export from WaterSheds (NEWS) model for contemporary conditions and for one future scenario for 2030 and 2050. These calculated nutrient inputs were used to develop the indicators. The level of uncertainty of the LME scores for the overall indicator of coastal eutrophication is medium. A related study was conducted for the Bay of Bengal, providing a more detailed view of sources of nutrients and spatial patterns of nutrient inputs from river basins draining to this LME.

Key Messages

1. **Coastal eutrophication is associated with large urban populations and intense agricultural production that has high fertilizer use and/or large numbers of livestock.** Of the 63 LMEs assessed, 16 per cent are in the ‘high’ or ‘highest’ risk categories for coastal eutrophication. They are mainly in Western Europe and southern and eastern Asia, and the Gulf of Mexico. Most LMEs, however, are in the ‘lowest’ or ‘low’ risk category.
2. **In many watersheds around the world, nutrient loads in rivers are projected to increase as a result of increasing human activities.** Based on current trends, the risk of coastal eutrophication will increase in 21 per cent of LMEs by 2050. Most of the projected increase is in LMEs in southern and eastern Asia, but also in some in South America and Africa. Only two LMEs (Iberian Coastal and Northeast US Continental Shelf) are projected to lower their coastal eutrophication risk by 2050.
3. **To reduce current and future risks, reductions in nutrient inputs to specific watersheds are required.** This can include increased nutrient-use efficiency in crop production, reduction in livestock and better management of manure, and increased treatment level of human sewage.
4. **Analysis at the sub-LME scale is needed to identify sources and spatial variations of nutrients in order to develop effective nutrient reduction strategies.** Nutrient yields, eutrophication potential, and sources of nitrogen can vary considerably within an LME, as shown by a study of the Bay of Bengal LME.

7.3.1 Introduction

Land use and human activities in watersheds are resulting in nutrients that are being transported by rivers into LMEs. Excess nutrients – nitrogen (N), phosphorus (P), and silica (Si) – entering coastal waters of LMEs can result in high-biomass algal blooms, leading to hypoxic (low oxygen) or anoxic (no oxygen) conditions, increased turbidity, changes in community composition, and other effects. In addition to ecosystem impacts from the total amount of nutrients, changes in the ratio of different nutrients can result in dominance by algal species that have deleterious effects on ecosystems and humans (effects such as toxicity from Red Tides, or clogging of shellfish gills) (Glibert *et al.* 2010; Granéli and Turner 2006; Howarth and Marino 2006).

An understanding of nutrient loads and ratios is therefore a key component of identifying the risk of coastal eutrophication. The major anthropogenic sources of river nutrient loads are associated with the production of food and energy. The sources include run-off from fertilizer use and livestock production, sewage, and atmospheric nitrogen deposition. In many watersheds around the world, river nutrient loads are projected to increase due to further increase in human activities (Seitzinger *et al.* 2010).

A nutrient indicator was developed for this component of the TWAP assessment to improve understanding of the risk of coastal eutrophication in LMEs. It is based on two sub-indicators: a nitrogen load indicator and a nutrient ratio indicator. We focus on contemporary (approximately year 2000) and future trends in river export of nutrients to LMEs globally. Specifically, the sub-indicators and overall indicator are based on river-delivered loads of N, P, and Si to LMEs for contemporary conditions and for one future scenario for 2030 and 2050 as calculated by the Global NEWS model (Mayorga *et al.* 2010; Seitzinger *et al.* 2010; Beusen *et al.* 2009). The calculations for future years are based on a 'current trends' scenario, which describes a globalized world with a focus on economic development with rapid economic and urbanization growth and reactive environmental management. This scenario is based on the Global Orchestration scenario of the Millennium Ecosystem Assessment (Alcamo *et al.* 2005).

This study builds directly on the river basin component of the TWAP, which also uses the Global NEWS model and addresses contemporary conditions and 2030 and 2050 assessments using the same 'current trends' scenario to develop a river nutrient pollution indicator. A related assessment was conducted for the Bay of Bengal LME (BOB LME), which went substantially beyond the TWAP Level 1 baseline assessment in both the level of spatial detail of nutrient input to the LME (individual river basin information) and in providing N and P source information in the river basins draining into the BOB LME (including sewage, agriculture from crops and from livestock, and atmospheric deposition directly to the watershed). This BOB LME nutrient assessment represents a TWAP Level 2 LME assessment, involving a more detailed analysis at the sub-LME scale.

7.3.2 Findings, discussion, and conclusions

An overall nutrient indicator for coastal eutrophication was developed, based on two sub-indicators. Based on the values of the sub-indicators and the overall indicator, LMEs were placed into five risk categories: lowest, low, medium, high, and highest. In this section, the results of the two sub-indicators are discussed, followed by discussion of the overall nutrient indicator.

7.3.2.1 N load sub-indicator

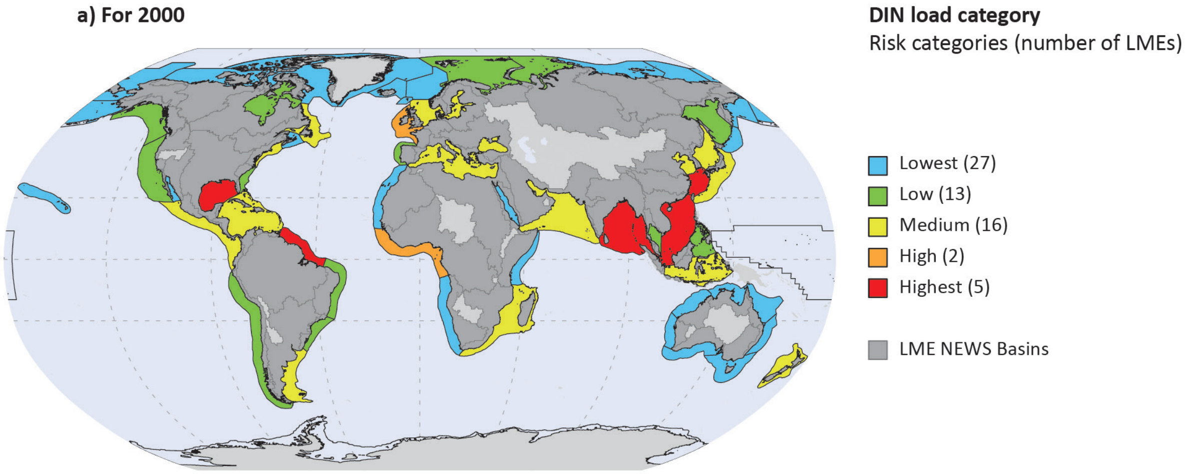
The N load sub-indicator (measured as teragrams, which is 10^{12} grams, per year) is a measure of the amount of N carried by rivers as they enter the land–sea boundary of the LME. Nitrogen is the nutrient generally most relevant to biomass production in coastal waters, and the form of N most rapidly used is dissolved inorganic N (DIN, which is ammonia plus nitrate). Nitrogen is usually the limiting nutrient – meaning the production of biomass continues until the available nitrogen is used up. DIN is also the form of N that increases the most in rivers (and is subsequently delivered to LMEs) as a result of increases in human activity (Seitzinger *et al.* 2010). The N load indicator is therefore based on the river DIN load.

On the basis of the N load sub-indicator, 40 out of 63 LMEs are currently at 'low' to 'lowest' risk for coastal eutrophication (Figure 7.11 (a)). Many of these LMEs are in high-latitude regions where population is low and there is little agriculture in the watersheds. Sixteen LMEs distributed around the world are in the 'medium' risk category.

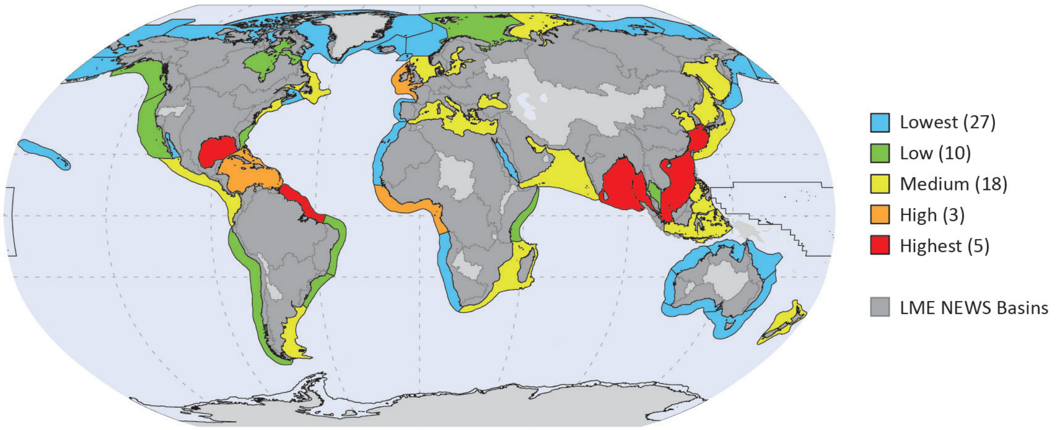
Seven LMES are in the 'high' or 'highest' risk categories, including the Celtic-Biscay Shelf, Gulf of Mexico, Bay of Bengal, South China Sea, and East China Sea LMEs. The regions that feed into these five LMEs have high populations and/or high fertilizer use and animal production in their watersheds (Seitzinger *et al.* 2010). Problems with eutrophication have been reported for coastal and/or open waters in many of these LMEs (Rabalais *et al.* 2009; Wang and Wu 2009, Tang *et al.* 2006). The two other LMEs in the 'high' or 'highest' risk categories are the North Brazil Shelf LME and the Guinea Current LME. While human population and fertilizer use is quite low in the watersheds of these LMEs, both

Figure 7.11 Nitrogen load risk categories for LMEs for a) 2000, b) 2030, and c) 2050. River nitrogen loads to LMEs have significantly increased from food and energy production in their watersheds, especially in southern and eastern Asia, Western Europe, and in watersheds draining to the Gulf of Mexico. If current trends continue, the risk of eutrophication from increased dissolved inorganic nitrogen (DIN) loads will have increased in 11 LMEs by 2050 relative to 2000 conditions.

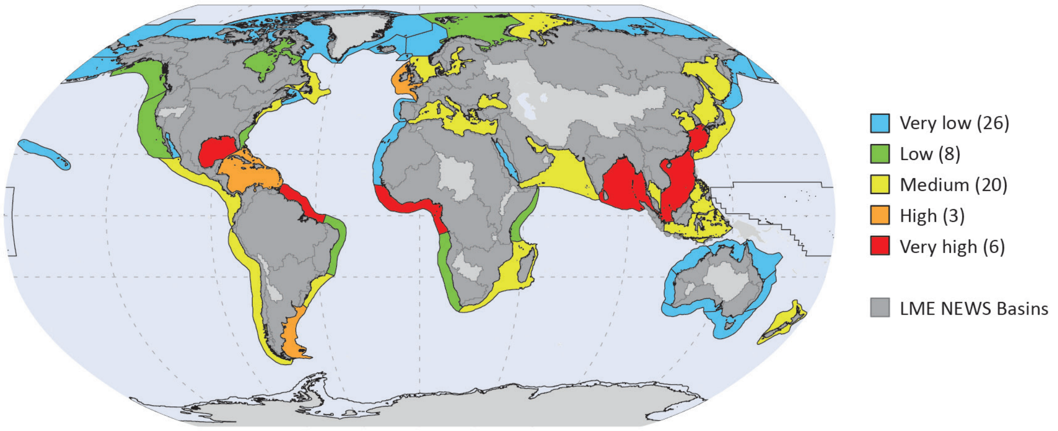
a) For 2000



b) For 2030



c) For 2050



have very large watersheds and high water run-off (Amazon and Congo rivers), which leads to large amounts of DIN from natural sources. It is notable that the Baltic Sea LME is in the 'medium' risk category for N load, although this is a region of hypoxic bottom water and blue-green algal blooms. The Baltic Sea is highly stratified, which is known to enhance hypoxia in coastal waters, and its slow flushing rate can also increase the build-up of algal biomass.

If current trends continue, by 2030 five LMEs will have increased their risk by one category, and one by two categories (based on the Global Orchestration scenario; Figure 7.11(b) and Table 7.4). The risk is projected to decrease in only one LME (Iberian Coastal). By 2050 an additional six LMEs will have increased their risk by one category (Figure 7.11(c)). The number of LMEs that will be at 'high' to 'highest' risk of coastal eutrophication, based on the N load indicator, increases to eight by 2030, and nine by 2050. These LMEs are generally in areas projected to have considerable further increases in population and/or agriculture (Seitzinger *et al.* 2010; Bouwman *et al.* 2009; Van Drecht *et al.* 2009).

Table 7.4 LMEs with risk category changes between 2000 and 2030, and between 2030 and 2050

Indicator type and time period	**Change in risk category**		
	+1	**+2**	**-1**
DIN 2000–2030	Caribbean Sea; Somali Coastal Current; Sulu-Celebes Sea; Sea of Okhotsk; Kara Sea		Iberian Coastal
DIN 2030–2050	Humboldt Current; Patagonian Shelf; South Brazil Shelf; Guinea Current; Benguela Current; Gulf of Thailand		
ICEP 2000–2030	Gulf of California; Northeast US Continental Shelf; Scotian Shelf; South Brazil Shelf; Gulf of Thailand	Guinea Current; South China Sea	Canadian Eastern Arctic-West Greenland; Greenland Sea; Iberian Coastal
ICEP 2030–2050	Humboldt Current; South Brazil Shelf; East Brazil Shelf; Somali Coastal Current; Arabian Sea		California Current; Northeast US Continental Shelf; Scotian Shelf; Kuroshio Current
Merged 2000–2030	Northeast US Continental Shelf; Caribbean Sea; Somali Coastal Current; Sulu-Celebes Sea; Sea of Okhotsk; Kara Sea		Iberian Coastal
Merged 2030–2050	Humboldt Current; Patagonian Shelf; Guinea Current; Benguela Current; Arabian Sea; Gulf of Thailand	South Brazil Shelf	Northeast US Continental Shelf

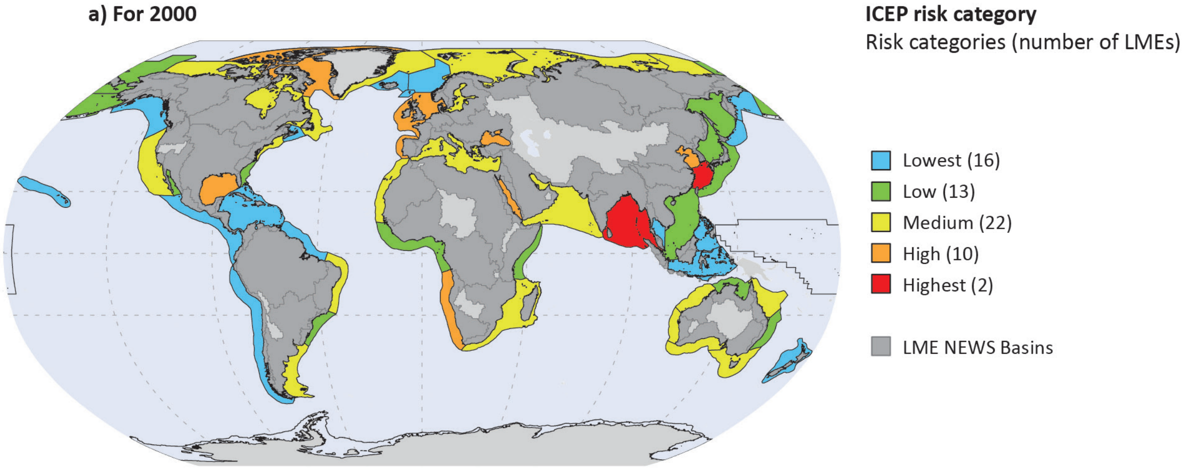
7.3.2.2 Nutrient ratio sub-indicator

The second sub-indicator used in this study, the Index of Coastal Eutrophication Potential (ICEP), represents the potential for new production of harmful algal biomass in coastal waters. It is based on nutrient ratios in the nutrient loads delivered by river systems to the LMEs, more specifically, on the ratio of dissolved Si to N or P, compared to the ratio required for diatom growth (Garnier *et al.* 2010). This indicator, based on the N, P, and Si concentrations, assumes that if there is excess N or P relative to Si the growth of potentially harmful non-siliceous algae will be favoured instead of siliceous algae (diatoms), which are generally not harmful. ICEP is expressed in kilograms of carbon (of potential new non-siliceous algal growth) per km^2 of river basin area per day.

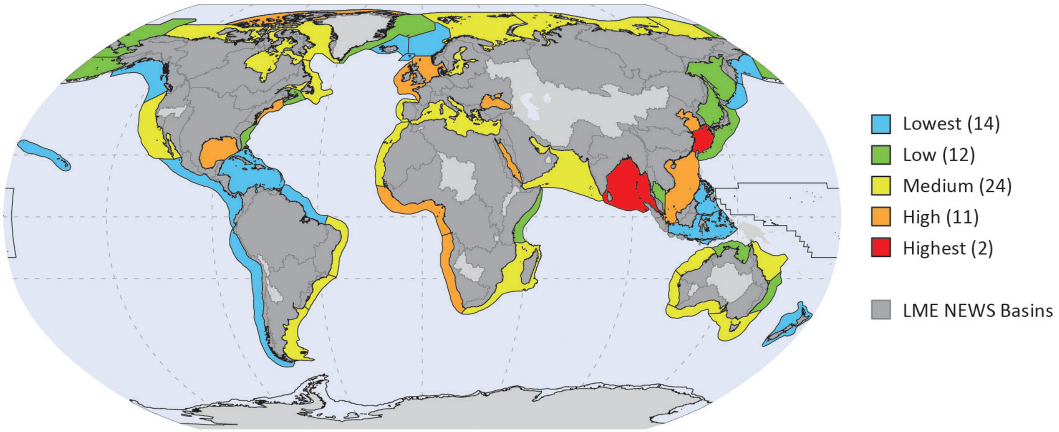
Currently, 29 out of 66 LMEs are in the low to 'lowest' risk category with respect to potentially harmful non-siliceous algae (Figure 7.12(a)); another 22 are in the 'medium' risk category. Of particular note are the twelve LMEs in the 'high' or 'highest' risk category. Many of these are in regions where a low proportion of Si in nutrients (limiting diatom growth) has been reported (Gulf of Mexico) and/or regions with recurring, harmful non-siliceous blooms. For example, deleterious effects of non-siliceous algae are reported in the continental coast of the Southern North Sea (*Phaeocystis* foam), the coasts of Brittany (macroalgae proliferation and dinoflagellates blooms), and the western Black Sea (change in food chain structure) (Billen 2011); the Bohai Sea and the East China Sea (Anderson *et al.* 2012; GEOHAB 2010; Zhou *et al.* 2006; Yan *et al.* 2002); and the coastal waters of the Benguela Current LME.

Figure 7.12 Index of Coastal Eutrophication Potential (ICEP) risk categories for LMEs for a) 2000, b) 2030, and c) 2050. Based on the ratio of nutrients (N and P relative to Si) entering LMEs from rivers, potential for non-siliceous harmful algae blooms is 'high' or 'highest' in 12 LMEs. The risk is most evident in portions of southern and eastern Asia, Western Europe and Gulf of Mexico, although also applying to LMEs in a number of other regions. If current trends continue, the potential for non-siliceous harmful algae blooms will have increased in 12 LMEs by 2050 relative to 2000 conditions.

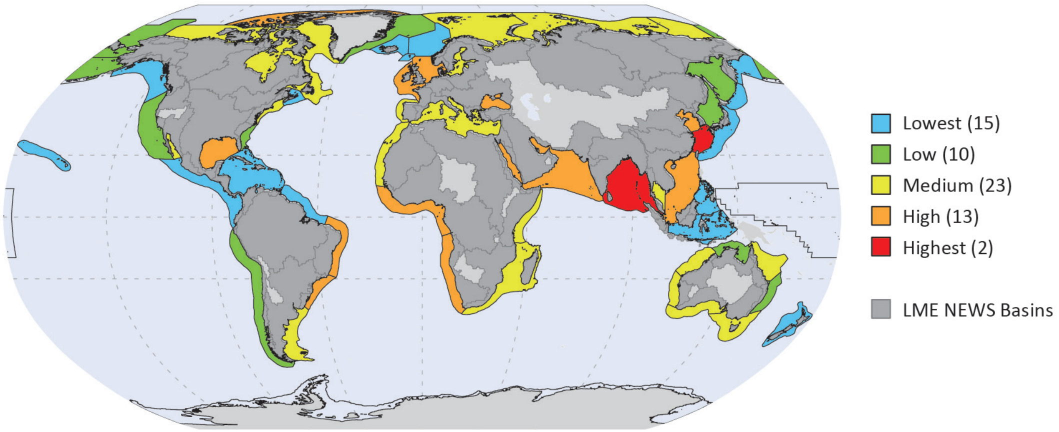
a) For 2000



b) For 2030



c) For 2050



Harmful algal blooms occur in some regions that are indicated as low risk, such as the South China Sea (Anderson *et al.* 2012; GEOHAB 2010; Zhou *et al.* 2006). As discussed below, neither the N load nor the ICEP indicators are perfect predictors of coastal nutrient problems, because of the many factors that control ecosystem effects.

According to the Global Orchestration scenario, if current trends continue, by 2030 five more LMEs will have increased their ICEP risk by one category and two by two categories, while an improvement by one category is projected in three LMEs (Canadian Eastern Arctic-West Greenland, Greenland Sea, and Iberian Coastal LMEs) (Figure 7.12(b); Table 7.4). Between 2030 and 2050, in this scenario, the ICEP sub-indicator will have increased by one risk category in six LMEs and decreased in four (Figure 7.12(c)); Table 7.4). Overall, the LMEs with future increases in ICEP risk are in regions projected to have increased anthropogenic activity in their watersheds, which would increase nutrient loads but not Si loads, and would therefore tend to create a Si deficit relative to N and P.

7.3.2.3 Merged nutrient risk indicator

The N load and nutrient ratio sub-indicators were used as the basis for a merged nutrient risk indicator. The indicators were merged on the basis of their risk categorization. For example, LMEs at 'highest' risk due to high N loads were placed in the 'highest' merged nutrient risk category, irrespective of ICEP level, and LMEs with only 'medium' risk from N load but at higher risk as assessed by ICEP were placed in the 'high' merged risk category. This focuses attention on LMEs with relatively high N loads, irrespective of nutrient ratios, and on LMEs with 'medium' N loads and nutrient ratio indicator (ICEP) scores in the 'high' and 'highest' risk categories.

On the basis of the merged nutrient risk indicator, under current conditions, 40 of 63 LMEs are in the 'low' to 'lowest' risk category, (Figure 7.13(a)). This includes all the LMEs in the high-latitude regions and in Australia, plus many in South America and Africa. Ten LMEs are in the 'high' to 'highest' risk categories. Most of these are located in Western Europe, southern and eastern Asia, and the Gulf of Mexico, as would be anticipated from the two sub-indicators.

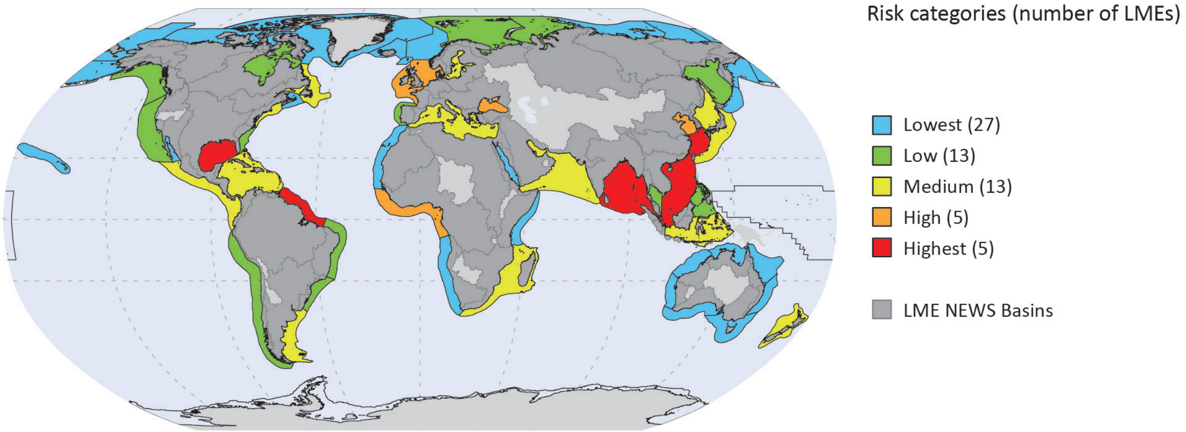
According to the Global Orchestration scenario, if current trends continue, six LMEs will have increased their risk by one category of the merged indicator, and one (Iberian Coastal) will have lowered its risk by one category (Figure 7.13(b)); Table 7.4). Between 2030 and 2050, in this scenario, the risk of coastal eutrophication will have increased by one category in an additional six LMEs, and by two categories in the South Brazil Shelf LME (Figure 7.13(c)). In the Northeast US Continental Shelf LME, the risk is projected to decrease by one category, in this scenario.

7.3.2.4 Overall analysis and discussion

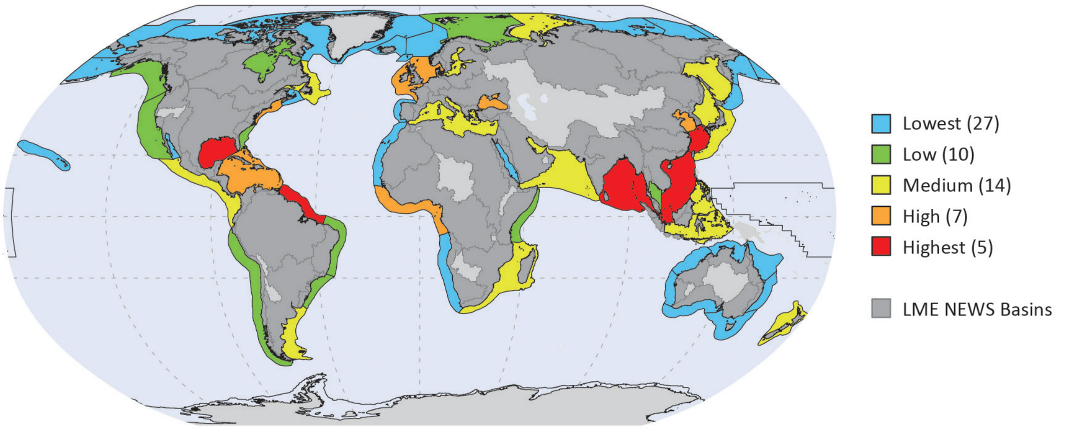
Current (approximately year 2000) conditions based on results from the eutrophication index and sub-indicators are generally consistent with published information on coastal ecosystem status. They are also consistent with the global distribution of nutrient input intensity (addition of nutrients per unit area) in watersheds, and are associated with large urban populations, intense agricultural production supported by high fertilizer use, and/or large numbers of livestock. Reductions in nutrient inputs to specific watersheds are required to lower the risks. This can include, for example, increased nutrient-use efficiency in crop production, reduction in livestock and better management of manure, and increased treatment level (increased N and P removal) of human sewage. In order to develop appropriate reduction strategies for an LME, information on the relative contribution and location of nutrient sources within river basins and across the LME is needed, and could be developed by further analysis. Box 7.1 describes a within-LME study that provides this type of information.

Figure 7.13 Merged nutrient risk categories for LMEs for a) 2000, b) 2030, and c) 2050. Based on merging the nitrogen load and Index of Coastal Eutrophication Potential sub-indicators, the combined risk rated as 'high' to 'highest' for ten LMEs. Most of these are located in Western Europe, southern and eastern Asia, and the Gulf of Mexico, as would be anticipated from the two sub-indicators. If current trends continue 13 LMEs will have increased their risk for eutrophication by 2050 (relative to 2000 conditions) due to a combination of increased nitrogen loads and excess N or P relative to silica.

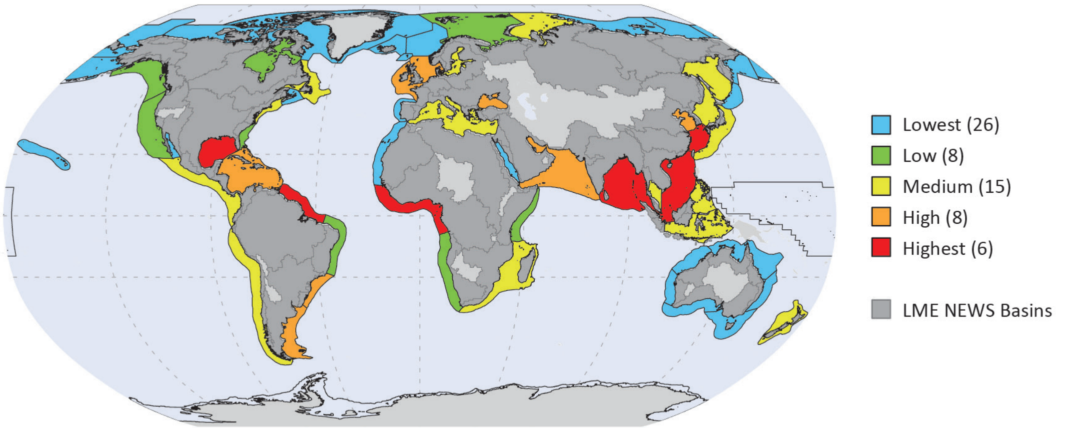
a) For 2000



b) For 2030



c) For 2050

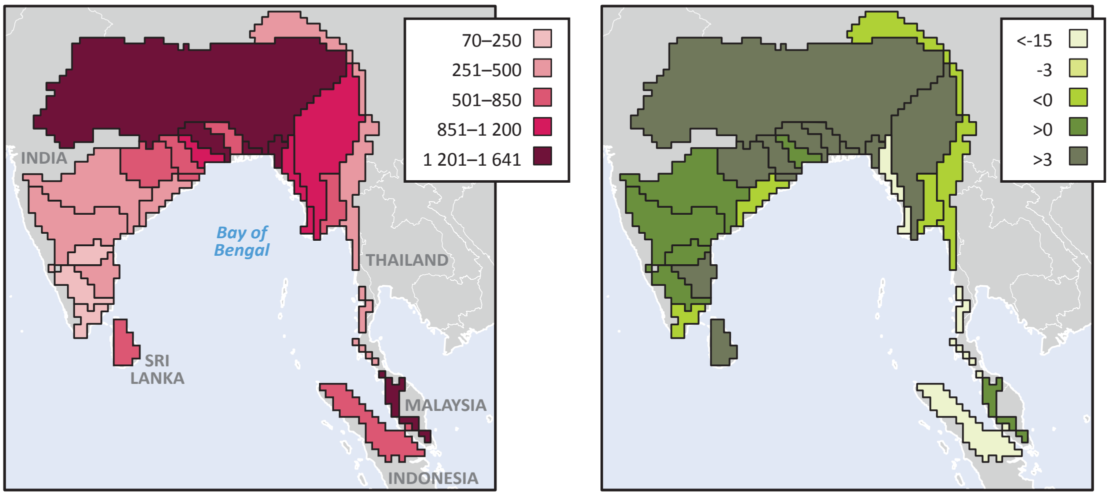


Box 7.1 An example of within-LME variation of nutrient loads and sources: The Bay of Bengal LME

Each LME has many rivers flowing into it, and there can be wide variation in nutrient loads and ratios between rivers. The level of analysis in this assessment is at the whole-LME scale. Both the N loads and nutrient ratios were calculated on the basis of the nutrient inputs summed across all rivers within an LME.

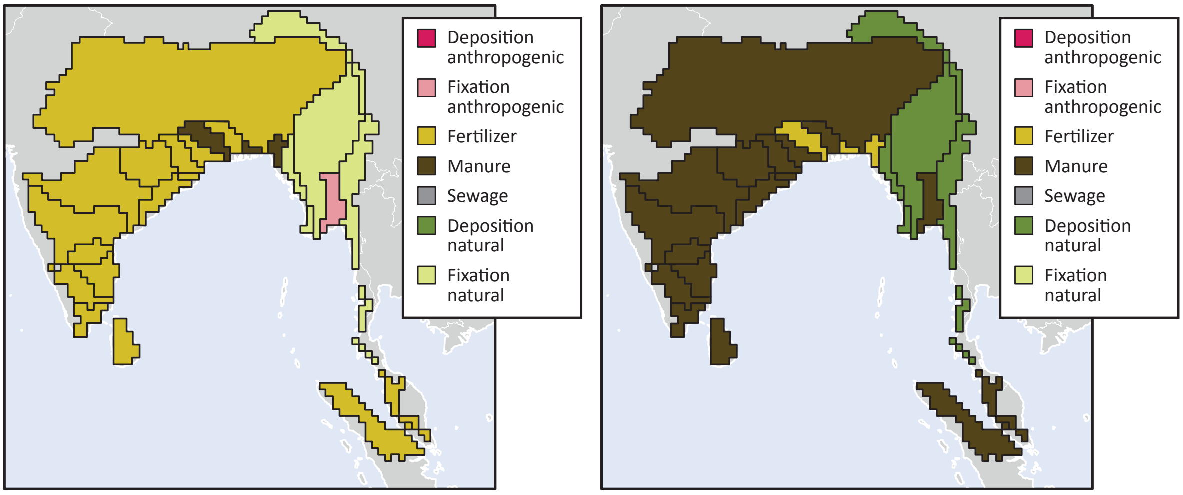
The within-LME variation is illustrated by the Bay of Bengal LME nutrient load and sources project (Seitzinger *et al.* 2014). Figure 7.14 shows that there is considerable variation in the nutrient yields, ICEP values, and N sources among the river basins that drain to this LME. Such information will be important in the next steps of identifying the spatial variations of nutrient effects and their sources to achieve reductions within LMEs.

Figure 7.14 Dissolved inorganic nitrogen (DIN) yield, Index of Coastal Eutrophication Potential (ICEP), and sources of DIN in river basins draining to the Bay of Bengal LME. A detailed analysis of the watersheds draining to the Bay of Bengal LME illustrates the spatial variation in nutrient loads, ratios, and sources of nutrients. The dominance of fertilizer and manure in many of these basins as sources of dissolved inorganic nitrogen is evident.



a) DIN yield (kilograms per km² per year)

b) ICEP sub-indicator (kilograms of carbon per km² per day)



c) Primary DIN sources

d) Secondary DIN sources

Source: Seitzinger *et al*. (2014)

7.3.2.5 Limitations

While both the amount (load) and the ratio of nutrients (N, P, and Si) are important in determining the response of coastal systems to nutrient input, the effects are likely to be most directly expressed in the near-coastal regions (estuaries and bays), since the nutrients are substantially altered through biological processing and dilution both within near-coastal regions and in the open waters of the LMEs. In addition to nutrients, the particular morphological, climatic, and hydrological conditions, including temporal variations, also are important in determining the responses of both the near-coastal receiving systems and the open waters of the LMEs. Thus, further insight into the effects of the nutrient loads and ratios in the LMEs would require advanced biogeochemical–ecosystem–hydrodynamic models of each LME.

One of challenges of relating nutrient inputs to water quality conditions in LMEs is the limited data available for water quality. A number of countries are developing water quality (eutrophication) criteria for estuaries and coasts (Ferreira *et al.* 2011; Canadian Council of Ministers of the Environment 2007; Bricker *et al.* 2003; US EPA 2001). However, methodologies vary and generally require much more extensive data on coastal water quality (such as chlorophyll *a*, coastal nutrient concentrations, and oxygen concentrations) and biogeophysical conditions (see above) than are available for LMEs. Therefore, for this assessment, we have combined published literature and expert knowledge to develop and apply two sub-indicators and a merged indicator for coastal eutrophication, using existing data.

In addition to river-transported nutrient inputs from watersheds, aquaculture in some coastal regions, particularly in Asia, can be an important source of nutrients contributing to eutrophication (Bouwman *et al.* 2011 and 2013).

Certainty/uncertainty and comparisons of results with published literature are discussed in a number of places in this report. However, we do not have a quantitative approach for establishing confidence levels for the risk sub-indicators or the combined indicator. Given the various uncertainties and gaps in data noted in the text, there is a medium level of uncertainty in the overall scores for LME coastal condition.

7.3.3 Methodology and analysis

Nutrient loads and ratios for the LMEs were developed as sub-indicators of coastal eutrophication. Few measurements are available of river nutrient loads over annual cycles in many rivers discharging to LMEs. Furthermore, analysis of nutrient sources contributing to the loads from natural and anthropogenic sources is generally not available, particularly outside North America and Europe. The Global NEWS model (version 2) was therefore used to develop this information on the basis of globally-gridded databases of watershed properties (including biogeophysical, natural and anthropogenic nutrient sources, and in-watershed and in-river removal processes) (Mayorga *et al.* 2010; Seitzinger *et al.* 2010). The Global NEWS model has been validated and calibrated at the global scale, and used to analyse global trends in nutrient exports by rivers (Mayorga *et al.* 2010; Seitzinger *et al.* 2010). It has also been successfully applied in continental-scale studies for South America (Van der Struijk and Kroeze 2010), Africa (Yasin *et al.* 2010), and China (Qu and Kroeze 2010 and 2012), and validated for the Bay of Bengal (Sattar *et al.* 2014).

7.3.3.1 Nitrogen load sub-indicator risk categories

The risk categories for this sub-indicator are based on DIN loads from the Global NEWS model and were assigned as indicated in Table 7.5. The ranges for each category are based on expert knowledge and published N load rates in regions of low and high anthropogenic river N loads (Sutton *et al.* 2011; Seitzinger *et al.* 2010; Boyer and Howarth 2002; Meybeck and Ragu 1996).

Table 7.5 Risk categories for the nitrogen load sub-indicator

Risk category	N load range (teragrams of N per year)
Lowest	≤0.1
Low	>0.1 and ≤0.25
Medium	>0.25 and ≤0.60
High	>0.60 and ≤1.00
Highest	>1.00

7.3.3.2 ICEP sub-indicator development and risk categories

ICEP is based on the Redfield molar ratio (C:N:P:Si = 106:16:1:20) (Garnier *et al.* 2010). This indicator assumes that N and P concentrations in excess of Si (above the Redfield ratio) may favour growth of potentially harmful non-siliceous algae such as dinoflagellates.

According to Garnier *et al.* (2010), ICEP is calculated for N (when N is limiting) and P (when P is limiting) as shown in the following equations:

$\text{N-ICEP} = [\text{NFlux}/(14 \times 16) - \text{SiFlux}/(28 \times 20)] \times 106 \times 12$, and
$\text{P-ICEP} = [\text{PFlux}/31 - \text{SiFlux}/(28 \times 20] \times 106 \times 12$,

where PFlux, NFlux, and SiFlux are the fluxes of total N, total P, and dissolved Si, respectively, delivered at the mouth of the river. N, P, and Si fluxes are expressed in kilograms per km^2 of river basin area per day. ICEP is expressed in kilograms of carbon per km^2 of river basin area per day.

Si fluxes are derived from Beusen *et al.* (2009). Total N and P fluxes are calculated as the sum of the three constituent elemental forms, as shown in the following equations:

$\text{NFlux} = \text{DINFlux} + \text{DONFlux} + \text{PNFlux}$, and
$\text{PFlux} = \text{DIPFlux} + \text{DOPFlux} + \text{PPFlux}$,

where DON = dissolved organic nitrogen; PN = particulate nitrogen; DIP = dissolved inorganic phosphorus; DOP = dissolved organic phosphorus; and PP = particulate phosphorus.

To estimate the potential for development of non-diatom algal species in the near-shore waters of the LMEs, we calculated ICEP by following the approach described above, but using nutrient fluxes aggregated from all rivers in an LME.

Considering that the N:P ratio is indicative of which nutrient (N or P) is most limiting, we opted for a combined ICEP (indicated simply as ICEP), for which we use the N or P ICEP with the lowest value (Garnier *et al.* 2010). The combined ICEP is used in this report as a sub-indicator.

ICEP values were allocated to five risk categories (Table 7.6). A positive ICEP indicates a risk of potentially harmful non-siliceous algal development (Garnier *et al.* 2010), while a zero or negative ICEP favours siliceous algae (such as diatoms), which, unless they are in high abundance (high nutrient load rates), are generally not harmful. We therefore assigned LMEs with ICEPs between -1 and +1 to the 'medium' risk category, reflecting an uncertainty around a zero ICEP because of spatial and temporal variations within an LME, and model uncertainty. The two lower risk categories ('lowest' and 'low') and the two higher risk categories ('high' and 'highest') were then distributed around the 'medium' risk category, using information from studies that compared ICEP with dinoflagellate and other non-siliceous algae development in specific coastal waters (Billen 2011).

Table 7.6 Risk categories for the Index of Coastal Eutrophication Potential (ICEP) sub-indicator

Risk category	ICEP range (kg C per km^2 per day)
Lowest	≤ -5
Low	> -5 and ≤ -1
Medium	> -1 and ≤ +1
High	> +1 and ≤ +5
Highest	> +5

7.3.3.3 Merged nutrient risk indicator categories

The N load and nutrient ratio sub-indicators were used as the basis of a merged nutrient risk indicator. Harmful blooms of dinoflagellates are found in regions with low nutrient loads (for example, Gulf of Maine) as well as in regions of high load. However, ICEP was developed and validated mainly in coastal regions where nutrient loads are high (Billen 2011; Billen and Garnier 2007). Therefore, for the merged nutrient risk indicator, the N load was weighted more heavily, and we assigned the risk category for the merged nutrient risk indicator following combinations of the two sub-indicator risk categories (Table 7.7). LMEs with N load indicator scores in the lower and higher categories are rated using the N load indicator, irrespective of nutrient ratios. LMEs with 'medium' N loads are subdivided based on the nutrient ratio indicator (ICEP) scores. This has the effect of elevating the risk level for LMEs with 'medium' risk from N load but 'high' to 'highest' risk from nutrient ratios.

Table 7.7 Risk categories for the merged nutrient risk indicator

N load risk category	ICEP risk categories	Merged nutrient risk category
Lowest	All categories	Lowest
Low	All categories	Low
Medium	Lowest to medium	Medium
Medium	High to highest	High
High	All categories	High
Highest	All categories	Highest

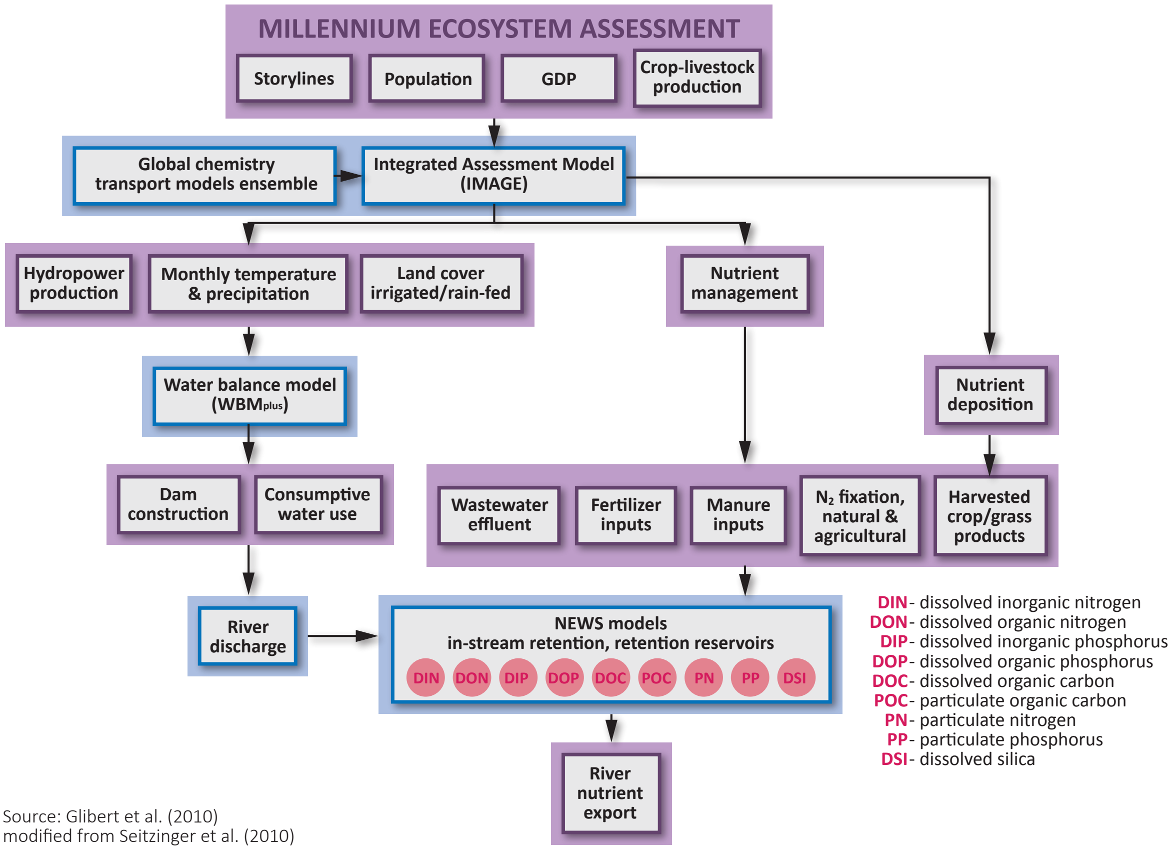
7.3.3.4 Global NEWS model

The Global NEWS model quantifies multi-form and multi-element nutrient export loads of more than 5 000 world rivers to coastal waters (Mayorga *et al.* 2010; Seitzinger *et al.* 2010; Beusen *et al.* 2009). It represents river networks and basins using the Simulated Topological Network at 0.5-degree x 0.5-degree grid-cell spatial resolution (STN-30p, version 6.01) (Mayorga *et al.* 2010; Vörösmarty *et al.* 2000). The relevant output of Global NEWS with respect to this project consists of basin-scale annual export at the river mouth of dissolved inorganic N and P, dissolved organic N and P, particulate forms of N and P, and dissolved Si (Figure 7.15). Total N and total P were calculated as the sum of the dissolved inorganic, organic and particulate forms. For this work, we rebuilt previous assignments of Global NEWS (version 2) basins to the LME they drain into, using the 2013 revision of the LME dataset ('LME66').

Inputs and drivers for the Global NEWS model consist of a range of natural and anthropogenic N and P sources within watersheds, in-watershed and in-river transformation and removal processes, climatic data, and other information as detailed in the original model description (Mayorga *et al.* 2010; Seitzinger *et al.* 2010; Figure 7.15).

The future scenario is a quantitative interpretation of the Global Orchestration scenario of the Millennium Ecosystem Assessment (MA) (Alcamo *et al.* 2005). This is a 'current trends' scenario that describes a globalized world with a focus on economic development, with rapid economic and urbanization growth and reactive environmental management. The Global Orchestration scenario has been used to develop model input datasets for diffuse sources from natural processes, fertilizer leaching from crop production, livestock production, and atmospheric N deposition (Bouwman

Figure 7.15 Conceptual diagram of the Global NEWS model construction, sub-models, and parameters. This model (its full name is Global Nutrient Export from WaterSheds) is used to project future nutrient loads delivered by river systems to LMEs.



Source: Glibert et al. (2010)
modified from Seitzinger et al. (2010)

et al. 2009); point sources from urban wastewater (Van Drecht *et al.* 2009); and hydrology (Fekete *et al.* 2010). Globally gridded datasets for NEWS input were assembled (most at 0.5 degree latitude x 0.5 degree longitude) for 2000, and, for the future scenario, for 2030 and 2050.

7.3.3.5 Development of gridded databases for 2030 and 2050

Input datasets for the 2030 and 2050 Global Orchestration scenario analysis were developed for Global NEWS (Seitzinger *et al.* 2010) (summarized in Table 7.8). Inputs for population, gross domestic product, and crop–livestock production were taken directly from the MA. Additional input data sets were developed by interpreting the original MA scenario. For example, agricultural areas used net surface N and P balances as inputs. These are based on N and P inputs from fertilizer use, animal manure application, N_2-fixation by crops, atmospheric N deposition, and sewage N and P, minus N and P removal from crop harvest and animal grazing (Bouwman *et al.* 2009). The surface nutrient balances form the basis of the scenario assumptions for nutrient management in agriculture. The quantitative nutrient management scenarios used an updated version (2.4) of the Integrated Model for the Assessment of the Global Environment (IMAGE) (Bouwman *et al.* 2006). Regional scenarios for N and P fertilizer use are based on efficiency of N and P uptake in crop production (Bouwman *et al.* 2009). Manure production was computed from livestock production, animal numbers, and excretion rates, and distributed over different animal manure management systems (Bouwman *et al.* 2009). Livestock production was related to a number of factors, including human population and diet. Atmospheric N deposition from natural and anthropogenic sources to all watersheds was from Bouwman *et al.* (2009). Natural ecosystem inputs include biological N_2-fixation and atmospheric nitrogen deposition.

Table 7.8 Input data sets used in the Global NEWS model for nitrogen and phosphorus

Dataset	Resolution	Time-Varying						Sources
Hydrography, areas and regions								
Basins and river networks	0.5°		X	X	X	X	X	1
Cell and land area	0.5°		X	X	X	X	X	1, 2, 3
Continents, oceans[a]	basin		X	X	X	X	X	1, 2
Latitude bands[a]	basin		X	X	X	X	X	2
Geophysical								
Lithology	1°						X	2, 4
Topography	0.5°						X	2, 4
Climate and hydrology								
Precipitation	0.5°	X					X	2, 5, 6
Run-off and discharge	0.5°	X	X	X	X	X	X	5
Consumptive water use	0.5° and basin	X	X	X	X	X		5, 7
Reservoirs	0.5° and dams	X	X		X		X	5, 8
Land use and ecosystems								
Agriculture and sub-classes	0.5°	X	X	X	X	X		2
Wetland rice and marginal grassland	0.5°	X					X	2
Wetlands	0.5 minute							9
Humid tropical forests (Köppen climate zones)	0.5°		X					10
Point sources (socio-economic and sanitation drivers)								
Gross domestic product	nation	X	X	X	X	X		11
Total and urban population density	0.5°	X	X	X	X	X		
Sanitation statistics	nation/region	X	X	X	X	X		
Detergent emissions	nation/region	X			X	X		
Diffuse sources								
Fertilizers, manure, crop harvest and animal grazing	0.5°	X	X	X	X	X		2
N fixation, atmospheric N deposition	0.5°	X	X					2

[a]*Used for analysis of results.*
Data sources: [1]*Vörösmarty et al. (2000)* [2]*Bouwman et al. (2009);* [3]*Processed as described in Global NEWS model description (Mayorga et al. 2010);* [4]*Beusen et al. (2009);* [5]*Fekete et al. (2010);* [6]*New et al. (1999);* [7]*Meybeck and Ragu (1996);* [8]*Vörösmarty et al. (2003);* [9]*Lehner and Döll (2004);* [10]*Kottek et al. (2006);* [11]*Van Drecht et al. (2009)*
DIN = dissolved inorganic N; DON = dissolved organic N; DIP = dissolved inorganic P; DOP = dissolved organic P; PN = particulate N; PP = particulate P
Table adapted from Mayorga et al. (2010)

N and P flows in urban wastewater for 2030 and 2050 were calculated from inflows to wastewater treatment systems, computed from per capita incomes and stemming from human N and P emissions and P-based detergent use (Van Drecht *et al.* 2009). Each MA story line was interpreted to generate differing degrees of access to improved sanitation, connection to sewage systems, and nutrient removal in wastewater treatment systems (Van Drecht *et al.* 2009).

For hydropower production, the $\mathrm{WBM}_{\mathrm{plus}}$ hydrological model was driven with scenario estimates of monthly temperature and precipitation, land use, and irrigated and rain-fed crop production areas from the IMAGE model, to develop projections for construction of reservoirs (dams) and for consumptive water use and irrigation (Fekete *et al.* 2010).

The published global scenario application of Global NEWS was based on modelled climate drivers ('Modelled Hydrology') for both contemporary (year 2000) and future conditions (Seitzinger *et al.* 2010). To adjust modelled results for future conditions to the 'Realistic Hydrology' baseline for contemporary conditions used here, we scaled published future nutrient exports ('X') as follows:

$$X_{\text{year}} = (X_{\text{2000 Realistic Hydrology}} / X_{\text{2000 Modelled Hydrology}}) * X_{\text{year Modelled Hydrology}}$$

where 'year' is the scenario year (2030 or 2050) and ($X_{\text{2000 Realistic Hydrology}}$ / $X_{\text{2000 Modelled Hydrology}}$) is the scaling factor.

References

Alcamo, J., Van Vuuren, D., Cramer, W. and others (2005). Chapter 9. Changes in ecosystem services and their drivers across the scenarios. In *Millennium Ecosystem Assessment. Volume 2: Scenarios* (eds. Carpenter, S., Pingali, P., Bennet, E. and Zurek, M.). Washington, Island Press

Anderson, D.M., Cembella, A.D. and Hallegraeff, G.M. (2012). Progress in understanding harmful algal blooms: Paradigm shifts and new technologies for research, monitoring and management. *Annual Review of Marine Science* 4, 143-176

Beusen, A.H.W., Bouwman, A.F., Dürr, H.H. and others (2009). Global patterns of dissolved silica export to the coastal zone: Results from a spatially explicit global model. *Global Biogeochemical Cycles,* 23, GB0A02, doi:10.1029/2008GB003281

Billen, G. (2011). Nitrogen flows from European regional watersheds. In *The European Nitrogen Assessment: Sources, Effects and Policy Perspectives (eds.* Sutton, M.A., Howard, C.M. Erisman, J.W. and others, 2012). Chapter 13. Cambridge University Press

Billen, G., and Garnier, J. (2007). River basin nutrient delivery to the coastal sea: assessing its potential to sustain new production of non-siliceous algae. *Marine Chemistry* 106, 148-160, doi:10.1016/j.marchem.2006.12.017

Bouwman, A.F., Beusen, A.H.W. and Billen, G. (2009). Human alteration of the global nitrogen and phosphorus soil balances for the period 1970-2050. *Global Biogeochemical Cycles,* 23, GB0A04, doi:10.1029/2009GB003576

Bouwman, A.F., Kram, T. and Klein Goldewijk, K. (eds.) (2006). *Integrated Modelling of Global Environmental Change. An overview of IMAGE 2.4,* Bilthoven: Netherlands Environmental Assessment Agency (MNP)

Bouwman, A.F., Beusen, A.H.W., Overbeek, C.C. and others (2013). Hindcasts and future projections of global inland and coastal nitrogen and phosphorus loads due to finfish aquaculture. *Reviews in Fisheries Science* 21(2), 112-156, doi: 10.1080/10641262.2013.790340

Bouwman, A.F., Pawłowski, M. Liu, C. and others (2011). Global hindcasts and future projections of coastal nitrogen and phosphorus loads due to shellfish and seaweed aquaculture. *Reviews in Fisheries Science* 19, 331-357

Boyer, E.W. and Howarth, R.W. (eds.) (2002). *The Nitrogen Cycle at Regional to Global Scales*. Kluwer Academic Publishers, Dordrecht. 519 pages

Bricker, S.B., Ferreira, J.G. and Simas, T. (2003). An integrated methodology for assessment of estuarine trophic status. *Ecological Modeling* 169, 39-60

Canadian Council of Ministers of the Environment (2007). Canadian guidance framework for the management of nutrients in nearshore marine systems. Scientific supporting document. PN 1387. ISBN 978-1-896997-70-4 PDF

Fekete, B.M., Wisser, D., Kroeze, C. and others (2010). Millennium Ecosystem Assessment scenario drivers (1970-2050): Climate and hydrological alterations. *Global Biogeochemical Cycles,* doi:10.1029/2009GB003593

Ferreira, J.G., Andersen, J.H., Borja, A. and others (2011). Overview of eutrophication indicators to assess environmental status within the European Marine Strategy Framework Directive. *Estuarine, Coastal and Shelf Science* 93(2), 117-131

Garnier, J., Beusen, A.H.W., Thieu, V. and others (2010). *N:P:Si nutrient export ratios and ecological consequences in coastal seas evaluated by the ICEP approach Global Biogeochemical Cycles,* doi:10.1029/2009GB003583

Glibert, P.M., Allen, J.I., Bouwman, A.F. and others (2010). Modeling of HABs and eutrophication: Status, advances, challenges. *Journal of Marine Systems* 83, 262-275

GeoHab (2010). *Global Ecology and Oceanography of Harmful Algal Blooms, Harmful Algal Blooms in Asia.* (eds. Furuya, K., Glibert, P.M., Zhou, M. and Raine, R.) IOC and SCOR, Paris and Newark, Delaware. 68 pages

Granéli, E. and Turner, J.T. (eds.) (2006). *Ecology of Harmful Algae*. Springer

Howarth, R.W. and Marino, R. (2006). Nitrogen as the limiting nutrient for eutrophication in coastal marine ecosystems: Evolving views over three decades. *Limnology and Oceanography* 51, 364-376

Kottek, M., Grieser, J., Beck, C. and others (2006). World Map of the Köppen-Geiger climate classification updated. *Meteorologische Zeitschrift* 15**,** 259-263

Lehner, B. and Döll, P. (2004). Development and validation of a global database of lakes, reservoirs and wetlands. *Journal of Hydrology* 296, 1-22

Mayorga, E., Seitzinger, S.P., Harrison, J.A. and others (2010). Global Nutrient Export from WaterSheds 2 (NEWS 2): Model development and implementation. *Environmental Modelling and Software* 25**,** 837-853

Meybeck, M. and Ragu, A. (1996). *River discharges to the oceans: An assessment of suspended solids, major ions, and nutrients.* United Nation Environment Programme, Paris

New, M., Hulme, M. and Jones, P. (1999). Representing twentieth-century time climate variability. Part I: Development of a mean monthly terrestrial climatology. *Journal of Climate* 12**,** 829-856

Qu, H. and Kroeze, C. (2012). Nutrient export by rivers to the coastal waters of China: Management strategies and future trends. *Regional Environmental Change* 12**,** 153-167

Qu, H. J. and Kroeze, C. (2010). Past and future trends in nutrients export by rivers to the coastal waters of China. *Science of The Total Environment* 408**,** 2075-2086

Rabalais, N.N., Turner, R.E., Díaz, R.J. and Justić, D. (2009). Global change and eutrophication of coastal waters. *ICES Journal of Marine Science* 66, 1528-1537

Sattar, M.A., Kroeze, C. and Strokal, M. (2014). The increasing impact of food production on nutrient export by rivers to the Bay of Bengal 1970-2050. *Marine Pollution Bulletin* 8, 168-178

Seitzinger, S.P., Pedde, S., Koreze, C. and Mayorga, E. (2014). Understanding nutrient loading and sources in the Bay of Bengal Large Marine Ecosystem. BOBLME-2014-Ecology-18, 32 pages

Seitzinger, S.P., Mayorga, E., Bouwman, A. F. and others (2010). Global river nutrient export: A scenario analysis of past and future trends. *Global Biogeochemical Cycles.* doi:10.1029/2009GB003587

Sutton, M.A., Howard, C.M., Erisman, J.W. and others (eds.) (2011). *The European nitrogen assessment: Sources, effects and policy perspectives.* Cambridge University Press, 612 pages

Tang, D., Di, B., Wei, G. and others (2006). Spatial, seasonal and species variations of harmful algal blooms in the South Yellow Sea and East China Sea. *Hydrobiologia* 568, 245-253

US EPA (2001). *Nutrient criteria technical guidance manual: Estuarine and coastal waters.* United States Environmental Protection Agency EPA-822-B-01-003

Van Der Struijk, F. and Kroeze, C. (2010). Future trends in nutrient export to the coastal waters of South America: Implications for occurrence of eutrophication. *Global Biogeochemical Cycles,* doi:10.1029/2009GB003572

Van Drecht, G., Bouwman, A.F., Harrison, J. and Knoop, J.M. (2009). Global nitrogen and phosphate in urban wastewater for the period 1970 to 2050. *Global Biogeochemical Cycles* 23, GB0A03

Vörösmarty, C., Meybeck, M., Fekete, B. and others (2003). Anthropogenic sediment retention: major global impact from registered river impoundments. *Global and Planetary Change* 39**,** 169-190

Vörösmarty, C.J., Fekete, B.M., Meybeck, M. and Lammers, R.B. (2000). Global system of rivers: Its role in organizing continental land mass and defining land-to-ocean linkages. *Global Biogeochemical Cycles* 14**,** 599-621

Wang, J. and Wu, J. (2009). Occurrence and potential risks of harmful algal blooms in the East China Sea. *Science of Total Environment* 407, 4012-4021

Yan, T., Zhou, M-J., and Zou, J-Z. (2002). A national report on harmful algal blooms in China. Report 23, In *Harmful algal blooms in the PICES region of the North Pacific* (eds. Taylor, F.J.R. and Trainer, V.L. 2002). North Pacific Marine Science Organization (PICES), 152 pages https://www.pices.int/publications/scientific_reports/Report23/default.aspx

Yasin, J.A., Kroeze, C. and Mayorga, E. (2010). Nutrients export by rivers to the coastal waters of Africa: Past and future trends. *Global Biogeochemical Cycles* 24**,** GB0A07

Zhou, W., Yin, K. and Zhu, D. (2006). Phytoplankton biomass and high frequency of *Prorocentrum donghaiense* harmful algal bloom in Zhoushan Sea area in spring. *Chinese Journal of Applied Ecology* 17, 887-893

Chapter 7.4. Extent of mangroves and drivers of change

Lead Authors

Chris McOwen, Jan-Willem van Bochove, Miranda Jones (United Nations Environment Programme World Conservation Monitoring Centre)

Contributing Authors

Simon Blyth, Damon Stanwell-Smith, Emma Sullivan (United Nations Environment Programme World Conservation Monitoring Centre)

Chapter Citation

McOwen, C., Jones, M., van Bochove, J.-W., Blyth, S., Stanwell-Smith, D., Sullivan, E. (2016). Chapter 7.4: Extent of mangroves and drivers of change. In IOC-UNESCO and UNEP (2016). *Large Marine Ecosystems: Status and Trends*. United Nations Environment Programme, Nairobi, pp 197-203.

7.4 Extent of mangroves and drivers of change

SUMMARY

Mangroves are highly productive tropical coastal systems consisting mainly of trees and shrubs that are adapted to marine and estuarine conditions. Mangroves are widespread – they are found in 123 countries – but relatively rare, making up less than 1 per cent of all tropical forests. Located at the interface of land and sea, mangroves are interconnected with adjacent seagrass beds, coral reefs, and intertidal mud and sand flats. Ecosystem services provided by mangroves include filtration of pollutants from coastal waters and reduction of risk of damage from storms, floods, and erosion. They are important fish nurseries and enhance fisheries for surrounding areas. Mangroves are experiencing extensive loss and degradation from pressures that include deforestation, land clearing, and sea-level rise.

The first global baseline of mangrove extent in LMEs and the Western Pacific Warm Pool was derived from the US Geological Survey's Global Distribution of Mangroves data set. Analysis of mangrove distribution shows that, for the 33 LMEs with mangroves, the average proportion of the LME covered by mangroves is only 0.25 per cent. The North Brazil Shelf LME has the highest proportion of mangrove cover (still less than 1 per cent), while the Bay of Bengal LME has the largest area of mangroves (more than 19 000 km^2). Limitations of the results are related to insufficient ground-truthing in some areas and the absence of time-series data across all LMEs. This baseline data set was augmented with results from an online survey of mangrove experts. This used an iterative process to document expert knowledge about drivers of change for mangroves and how these drivers vary from region to region. The process provided information on the relative importance of specific key drivers of mangrove loss in different regions and the likely increases in their impacts in the future.

The level of confidence in the results in this chapter is assessed as medium.

Key Messages

1. **About 20 per cent of total global mangrove area was lost between 1980 and 2005 due to human activities including coastal development, aquaculture expansion, and timber extraction.** The impact of coastal development has widespread, and increasing, importance. The impact of climate change on mangroves is largely unknown, but is projected to increase.
2. **Mangrove habitat continues to decline at an estimated 1 per cent per year; actual rates and key drivers of loss vary between regions.** Overexploitation for timber, fuel wood, and charcoal is the main driver of mangrove loss, in particular in Africa and South and Southeast Asia, although the future impacts of this driver are largely unknown.
3. **Due to the high rates of mangrove deforestation in many areas, current calculations probably overestimate the extent of mangrove cover.** Future mangrove assessments in LMEs can be improved by using more recent data on mangrove coverage as a baseline and by more frequent ground-truthing, which will also allow change in coverage to be estimated. Assessments of the impacts of key drivers of mangrove loss would benefit from the incorporation of surveys from a greater number of experts and at the LME scale.

7.4.1 Introduction

Mangroves are found in 123 tropical and sub-tropical nations and territories. They have limited latitudinal distribution, and their area accounts for less than 1 per cent of all tropical forests worldwide (van Lavieren *et al.* 2012; Spalding *et al.* 2010a; FAO 2006). Despite this, mangroves provide important habitats for a variety of terrestrial, estuarine, and marine species. Ecosystem services from the tidal marsh/mangrove biome have an estimated annual value of $US25 trillion (Costanza *et al.* 2014). They include enhancing fisheries (Hutchinson *et al.* 2014), for example by providing important fish nurseries, and filtering pollutants and contaminants from coastal waters. Mangroves also contribute

© Bachellier Christian/flickr

to coastal protection, reducing the risk of damage from storms, floods, and erosion (McIvor *et al*. 2012a and 2012b; Murray *et al.* 2011), and are estimated to be worth $US33 000 to $US57 000 per hectare per year to the national economies of developing countries with mangroves (UNEP 2014). Together with seagrass meadows and salt marshes, mangroves are recognized as one of the key 'blue carbon' habitats. Blue carbon describes the carbon captured by living marine organisms and stored in coastal and ocean ecosystems. Mangroves are the most carbon-rich forests in the tropics, able to sequester 6 to 8 tonnes of carbon dioxide equivalent per hectare per year. This rate is two to four times greater than global rates observed in mature tropical forests (Murray *et al.* 2011). Most of the carbon stored by mangroves is in the form of below-ground biomass (Alongi 2014).

Baseline data on mangrove extent, needed for monitoring change over time for management and conservation of mangrove habitats, have not previously been available globally for LMEs. The results presented here represent the first assessment of mangrove extent by LME, and thus provide valuable baseline data for refining and validating existing data. In addition, baseline data are vital for future monitoring of change, for example, following conservation or management initiatives, or for evaluating the impacts of human and natural pressures on components of biodiversity that provide benefits to human societies. The analyses of mangrove extent presented here are from the Global Distribution of Mangroves dataset, compiled by the US Geological Survey (Giri *et al.* 2011). This data set was chosen because it uses a globally consistent methodology; the analysis, however, could also be carried out using data collated from national datasets and remotely sensed data (Spalding *et al.* 2010b).

Over the past century there has been extensive loss and degradation of mangrove habitats because of coastal development, pollution, aquaculture, and logging for timber and fuel wood. As a result, 20 per cent of the total area of mangroves was lost between 1980 and 2005 (Spalding *et al.* 2010a). Mangrove habitat continues to decline at an estimated rate of 1 per cent per year (FAO 2003), with other estimates as high as 2 to 8 per cent per year (Miththapala 2008). Although rates of mangrove cover loss decreased to an annual average of 0.66 per cent between 2000 and 2005 (FAO 2007), this still equals or exceeds declines in more charismatic ecosystems such as coral reefs and tropical forests (Duke *et al*. 2007; Stone 2007; FAO 2003).

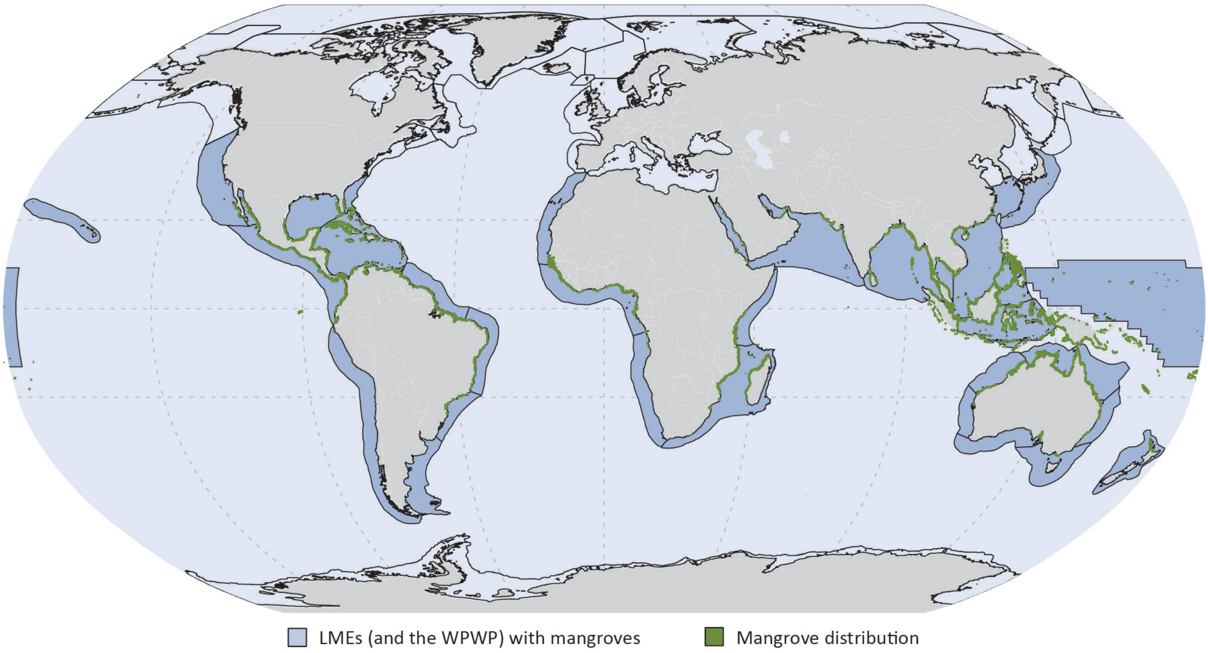
Rates of mangrove degradation vary significantly between countries, often due to differences in environmental policies, legislation, and management. For example, although total mangrove loss in many of the Asian and Pacific regions between 1980 and 2005 is estimated as being consistent with the global rate of 20 per cent, East African and Australian regions lost less than 10 per cent over the same period (Spalding *et al.* 2010a). Mangrove cover in Sri Lanka experienced deforestation rates of only 0.1 per cent between 1975 and 2005 (Giri *et al.* 2007), while rates of loss in both the Philippines and Honduras have been increasing since the 1990s because of promotion of shrimp culture and aquaculture.

This chapter presents data on the major drivers of mangrove loss and their relative impacts in different regions, based on Delphi-type surveys that engaged mangrove experts, conducted for a previous study (UNEP 2014). Projections are also presented for changes in the contributions of drivers of mangrove loss, using the results obtained from the surveys.

7.4.2 Findings and discussion

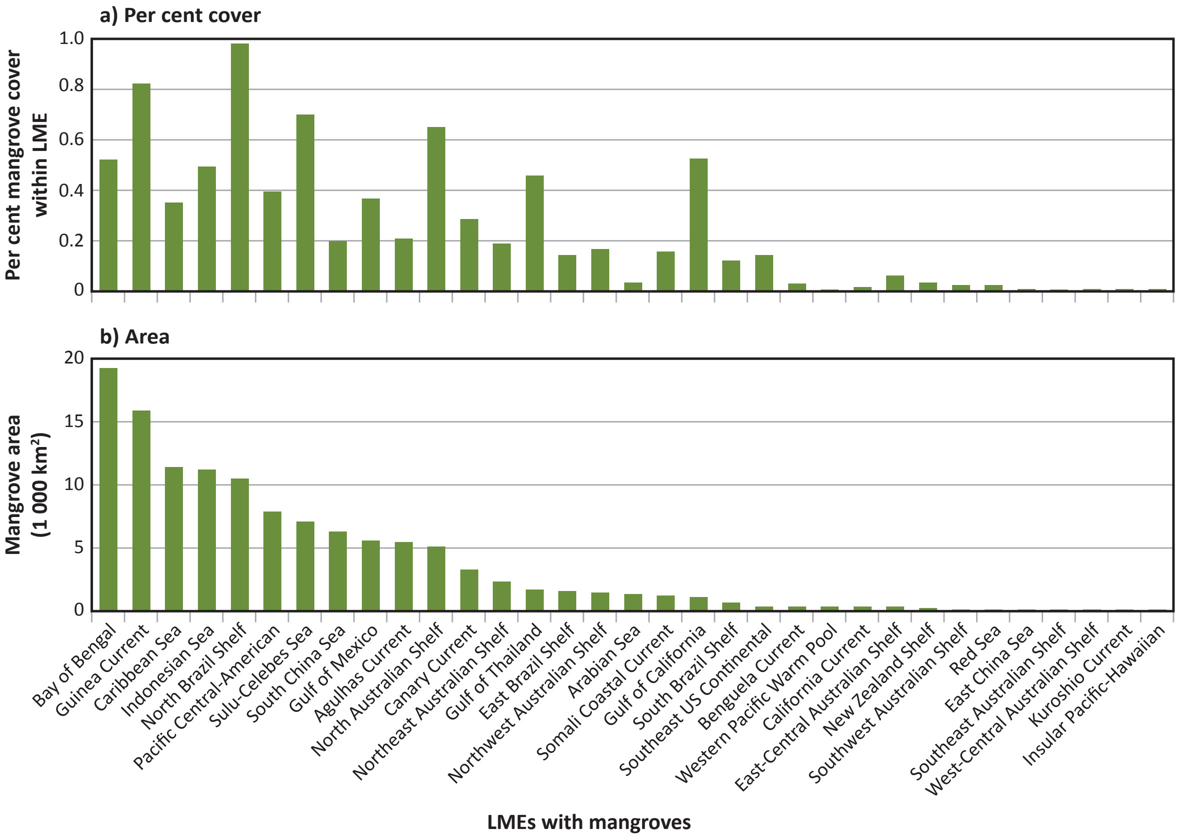
Of the 66 LMEs analysed, 33 (54 per cent) contain mangroves. Figure 7.16 shows the global mangrove distribution and overlays this with the LME boundaries. Overall, across these 33 LMEs, mangroves cover an estimated 123 205 km^2, which is about 0.25 per cent of the total area of the LMEs. These values, however, vary spatially (Figure 7.17). The North Brazil Shelf LME has the highest coverage in terms of percentage (nearly 1 per cent, or 10 429 km^2) and the Bay of Bengal LME (which includes the Sundarbans, the largest single block of mangrove forest in the world) has the highest coverage (0.52 per cent, or 19 151 km^2). The Guinea Current LME also has a relatively high mangrove coverage, at nearly 0.8 per cent (16 000 km^2), while only 0.003 per cent (410 km^2) of the Western Pacific Warm Pool, whose area is almost 3.5 times greater than any of the LMEs, is covered by mangroves.

Figure 7.16 Mangrove areas within LMEs. Of the 66 LMEs analysed, 33 (54 per cent) contain mangroves; covering an estimated 123 205 km^2, which is about 0.25 per cent of the total area of the LMEs.



Source: UNEP-WCMC; mangrove distribution from Global Distribution of Mangroves data set compiled by the US Geological Survey (Giri et al. 2011)

Figure 7.17 Mangrove extent within each LME, and the WPWP, expressed as a) per cent cover and b) area. The North Brazil Shelf LME has the highest coverage in terms of percentage, and the Bay of Bengal LME (which includes the Sundarbans, the largest single block of mangrove forest in the world) has the highest coverage in terms of area. The Guinea Current LME also has a relatively high mangrove coverage.

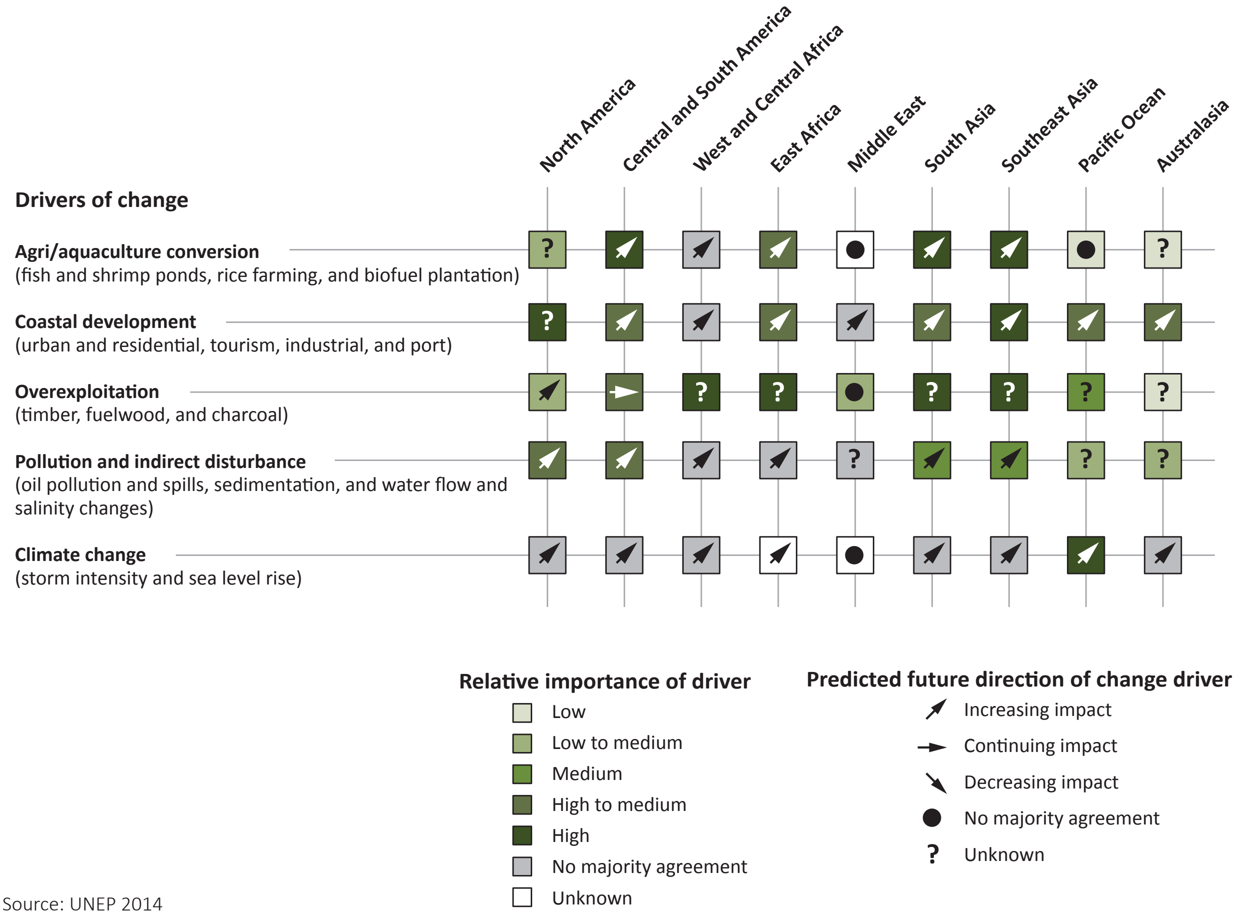


The relative importance of drivers of mangrove loss by region, and the projected changes in their impact, are presented in Table 7.9. This assessment of drivers is based on results from the survey by mangrove experts. Overexploitation for timber, fuel wood, and charcoal was assessed as having the greatest impact on mangrove loss across four regions, although the future impacts of this driver are largely unknown. But the most widespread driver of mangrove loss is coastal development, and its impact is projected to increase in almost all regions. Although the impacts of climate change are relatively unknown, they are also projected to increase. This assessment also shows that the relative impact of different drivers of mangrove loss is highest, and increasing, in Southeast Asia, while most drivers have relatively lower importance in Australasia.

7.4.3 Methodology

An assessment of the relative importance of various drivers of mangrove loss and their projected rate of change for different regions was conducted in a previous study using a Delphi-type survey (UNEP 2014). The online survey presented the relative impact of key drivers of regional change in mangroves as a matrix. Experts were asked to rate the importance of each driver of change in each region, relative to other regions, as one of six categories on a scale from 'high' through 'medium' to 'low', with the added option of 'unknown'.

Table 7.9 Relative importance of drivers of mangrove loss and their projected changes, by region



Drivers of change	North America	Central and South America	West and Central Africa	East Africa	Middle East	South Asia	Southeast Asia	Pacific Ocean	Australasia
Agri/aquaculture conversion (fish and shrimp ponds, rice farming, and biofuel plantation)	Low to medium ?	High ↗	No majority agreement ↗	High to medium ↗	Unknown ●	High ↗	High ↗	Low ●	Low ?
Coastal development (urban and residential, tourism, industrial, and port)	High ?	High to medium ↗	No majority agreement ↗	High to medium ↗	No majority agreement ↗	High to medium ↗	High ↗	High to medium ↗	High to medium ↗
Overexploitation (timber, fuelwood, and charcoal)	Low to medium ↗	High to medium →	High ?	High ?	Low to medium ●	High ?	High ?	Medium ?	Low ?
Pollution and indirect disturbance (oil pollution and spills, sedimentation, and water flow and salinity changes)	High to medium ↗	High to medium ↗	No majority agreement ↗	No majority agreement ↗	No majority agreement ?	Medium ↗	Medium ↗	Low to medium ?	Low to medium ?
Climate change (storm intensity and sea level rise)	No majority agreement ↗	No majority agreement ↗	No majority agreement ↗	Unknown ↗	Unknown ●	No majority agreement ↗	No majority agreement ↗	High ↗	No majority agreement ↗

Relative importance of driver

- Low
- Low to medium
- Medium
- High to medium
- High
- No majority agreement
- ☐ Unknown

Predicted future direction of change driver

- ↗ Increasing impact
- → Continuing impact
- ↘ Decreasing impact
- ● No majority agreement
- ? Unknown

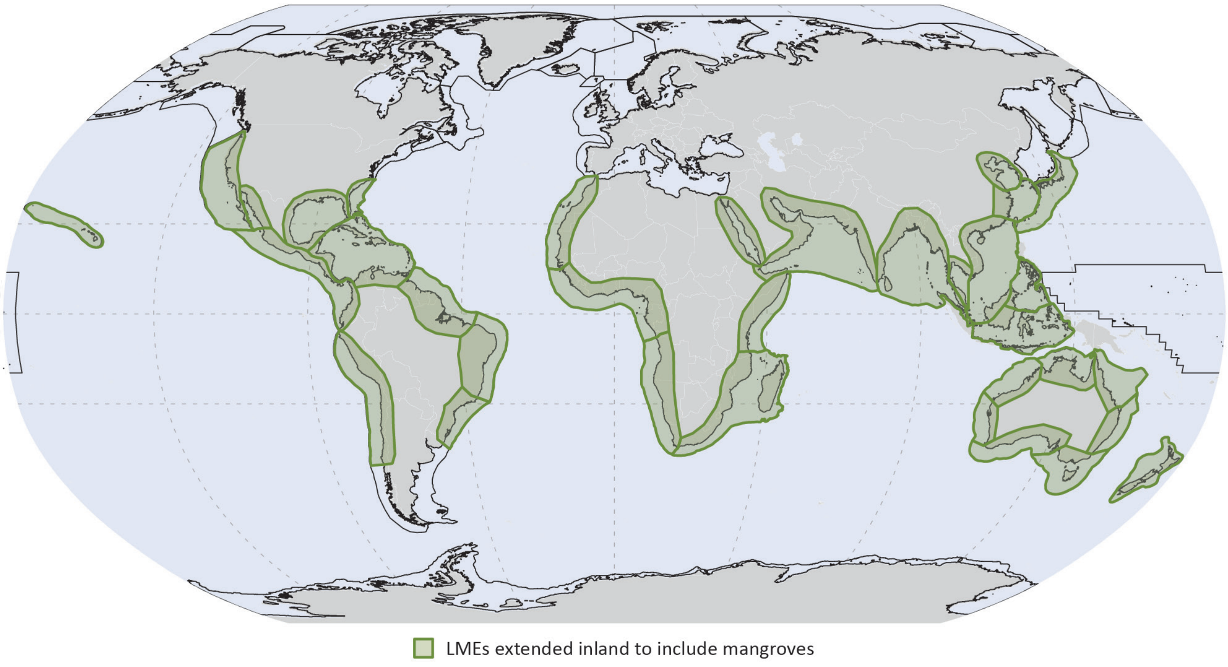
Source: UNEP 2014

Experts were then asked whether each driver of change is expected to increase, decrease or continue at the same impact level. Following a first round of surveys among ten mangrove experts, responses were collated and re-circulated to the expert panel for a second and third round, with an invitation to review responses and re-submit the survey with comments. Where no consensus was reached for a particular category, a range was provided within the matrix. Experts remained anonymous throughout.

The extent of mangroves within LMEs is based on the most recent Global Distribution of Mangroves dataset, compiled by the US Geological Survey (Giri *et al.* 2011). The dataset has a resolution of 30 m and can be downloaded from the Ocean Data Viewer (http://data.unep-wcmc.org/). It was created using classification techniques based on approximately 1 000 remotely-sensed Landsat images covering 1997 to 2000. Classification results were then validated using existing geographical datasets and published information. The dataset contains more than 1 400 000 polygons of mangrove presence and represents the best available dataset for mangroves. In spite of the consistent approach, however, some errors were identified. These were corrected as follows: LME boundary polygons (downloaded from NOAA 2013) were overlaid with the USGS mangrove dataset to derive statistics on mangrove area within the LMEs for which mangroves were found to be present.

In calculating mangrove coverage, we noted that mangroves inland and adjacent to LMEs were not included in the analysis following the application of the NOAA LME shapefile, which excluded areas beyond LMEs. These adjacent mangroves were therefore re-included within this assessment, as highlighted in Figure 7.18. The global mangrove dataset was further updated by removing duplicate features, and areas were re-calculated using the Global Mollweide equal-area projection. This revised dataset was used for further analysis.

Figure 7.18 LME regions extended to incorporate inland mangrove areas into the analysis



Source: UNEP-WCMC

7.4.4. Limitations

The assessment of relative impacts of key drivers of mangrove loss would benefit from the incorporation of surveys from a larger number of experts to increase confidence in the results and overcome the lack of consensus in particular areas and concerning particular drivers. This is particularly the case for West and Central Africa and the Middle East, regions for which a consensus was frequently not reached. A further limitation is the fact that the Delphi-type survey was conducted at a country, rather than an LME scale.

Mangroves were incorrectly located in some areas (particularly New Zealand); checking and manual relocation is therefore required. For example, trees along main streets may have been recorded as mangroves, suggesting insufficient ground-truthing of the dataset in certain areas. Interpreting Landsat imagery also has a number of challenges. For example, it was not possible to identify small patches of mangrove cover, and there were problems stemming from the noise associated with satellite imagery (such as cloud cover). Efforts should therefore be made to refine and validate the data.

Another limitation is that calculations rely on Landsat imagery covering 1970 to 2000. Because of the high rates of mangrove deforestation in many areas, calculations are likely to be overestimates of current mangrove cover. The accuracy of this indicator would therefore be improved by acquiring a more recent baseline mangrove layer, together with frequent updating with monitoring data. The incorporation of updated data would allow estimates of change in coverage, and thus provide information relevant to the risk of mangrove loss.

Based on the above points, we put the confidence surrounding this chapter at medium, since it is based on the best available data, but is limited by a small number of methodological and technical aspects, specifically the lack of sufficient ground-truthing and the age of the baseline data.

References

Alongi, D.M. (2014). Carbon cycling and storage in mangrove forests. *Annual Review of Marine Science* 6, 195-219

Costanza, R., de Groot, R., Sutton, P., van der Ploeg, S. and others (2014). Changes in the global value of ecosystem services. *Global Environmental Change* 26, 152–158

Duke, N.C, Meynecke, J-O., Dittmann, S. and others (2007). A world without mangroves? *Science* 317, 41-42

FAO (2003). *Status and trends in mangrove area extent world-wide*. Wilkie, M.L. and Fortuna, S. Forest Resources Assessment Working Paper 63. Rome (Italy): Forest Resources Division of the Food and Agricultural Organization of the United Nations

FAO (2006). *Global forest resources assessment 2005: progress towards sustainable forest management*. FAO Forestry Paper 147. Rome (Italy): Food and Agricultural Organization of the United Nations. 350 pages

FAO (2007). *The world's mangroves 2980-2005.* FAO Forestry Paper 153

Giri, C., Pengra, B., Zhu, Z. and others (2007). Monitoring mangrove forest dynamics of the Sundarbans in Bangladesh and India using multi-temporal satellite data from 1973 to 2000. *Estuarine Coastal and Shelf Science* 73, 91-100

Giri, C., Ochieng, E., Tieszen, L.L. and others (2011). *Global distribution of mangroves.* A product of US Geological Survey, in collaboration with ARSC Research and Technology Solutions. United Nations Environment Programme, NASA and the University of Queensland, Cambridge (UK): UNEP World Conservation Monitoring Centre. URL: http://data.unep-wcmc.org/datasets/21

Hutchison, J., Spalding, M., and zu Ermgassen, P. (2014). *The role of mangroves in fisheries enhancement.* The Nature Conservancy and Wetlands International. 54 pages

McIvor, A.L., Spencer, T., Möller, I. and Spalding. M. (2012a). *Storm surge reduction by mangroves. Natural Coastal Protection Series: Report 2*. Cambridge Coastal Research Unit Working Paper 41. The Nature Conservancy and Wetlands International. 35 pages. ISSN 2050-7941

McIvor, A.L., Möller, I., Spencer, T. and Spalding. M. (2012b) *Reduction of wind and swell waves by mangroves. Natural Coastal Protection Series: Report 1*. Cambridge Coastal Research Unit Working Paper 40. The Nature Conservancy and Wetlands International. 27 pages. ISSN 2050-7941

Miththapala, S. (2008) Mangroves. *Coastal Ecosystem Series Volume 2*. Colombo Sri Lanka: Ecosystems and Livelihoods Group Asia IUCN. 28 pages

Murray, B.C., Pendleton, L., Jenkins, W.A., and Sifleet, S. (2011). *Green payments for blue carbon economic incentives for protecting threatened coastal habitats.* Nicholas Institute for Environmental Policy Solutions Report, 44 pages

NOAA (2013). Large Marine Ecosystems of the World: LME Boundaries Download Page. http://lme.edc.uri.edu/index.php?option=com_content&view=article&id=177&Itemid=61 (accessed 1 July 2013)

Spalding, M., Kainuma, M., and Collins, L. (2010). *World Atlas of Mangroves*. London (UK) and Washington (USA). Earthscan, 319 pages

Spalding, M., Kainuma, M., and Collins, L. (2010b). *Data layer from the World Atlas of Mangroves*. Supplement to: Spalding *et al.* (2010a). Cambridge (UK): UNEP World Conservation Monitoring Centre. URL: data.unep-wcmc.org/datasets/22

Stone, R. (2007). A world without corals? *Science* 316, 678-681

UNEP (2014). *The Importance of Mangroves to People: A Call to Action* (eds. Van Bochove, J., Sullivan, E. and Nakamura, T.). United Nations Environment Programme World Conservation Monitoring Centre, Cambridge, 128 pages

van Lavieren, H., Spalding, M., Alongi, D. and others (2012). *Securing the future of mangroves.* A Policy Brief. UNU-INWEH, UNESCO-MAB with ISME, ITTO, FAO, UNEP-WCMC and TNC. Hamilton (Canada): United Nations University, Institute for Water, Environment and Health (UNU-INWEH). 53 pages

Chapter 7.5. Reefs at Risk Index

Lead Authors

Chris McOwen, Jan-Willem van Bochove, Miranda Jones (United Nations Environment Programme World Conservation Monitoring Centre)

Contributing Authors

Simon Blyth, Damon Stanwell-Smith, Emma Sullivan (United Nations Environment Programme World Conservation Monitoring Centre)

Chapter Citation

McOwen, C., Jones, M., van Bochove, J.-W., Blyth, S., Stanwell-Smith, D., Sullivan, E. (2016). Chapter 7.5: Reefs at Risk Index. In IOC-UNESCO and UNEP (2016). *Large Marine Ecosystems: Status and Trends*. United Nations Environment Programme, Nairobi, pp 205-215.

7.5 Reefs at Risk Index

SUMMARY

Warm-water coral reefs are the most biodiverse marine habitat per unit area, but are highly restricted in their geographic distribution. Coral reefs are also one of the most endangered habitats on the planet, threatened by anthropogenic pressures such as warming waters, ocean acidification, pollution, overfishing, and extraction. Projected increases in these threats may impact human societies through losses in fishery resources, income from tourism, building materials, and coastal protection.

This first assessment of the threats faced by coral reefs within LMEs and the Western Pacific Warm Pool (WPWP) is based on the Global Distribution of Coral Reef data set and the Reefs at Risk GIS data set. Coral reefs were assessed using an integrated threat score that incorporates threats from overfishing and destructive fishing, coastal development, pollution, and damage, plus a global threat score that incorporates threats from rising sea temperatures and ocean acidification. The first global baseline assessment of coral reef extent by LME is also provided – this is needed for monitoring future changes and effective management and conservation of coral reefs. The confidence level surrounding the results is assessed as medium.

For the 24 LMEs that contain coral reefs, plus the WPWP, reefs cover an average of 0.52 per cent of the total LME area. The Northeast Australian Shelf LME (which includes the Great Barrier Reef) has the largest extent of coral reef (2.83 per cent of its area), followed by the Indonesian Sea LME (2.66 per cent). Based on the integrated threat score, 28 per cent of reefs in LMEs and the WPWP face 'high' to 'highest' levels of threat.

© David Burdick/flickr

Key Messages

1. **One quarter of LMEs have more than 50 per cent of their coral reef area under 'high' to 'highest' threat from local, present-day threats.** Overfishing and destructive fishing practices are of greater threat to coral reefs than coastal development and marine pollution.
    - LMEs with high local, present-day threats: Somali Coastal Current, Kuroshio Current, Sulu-Celebes Sea, East China Sea, and others.
    - LME with lowest level of local threats to coral reefs: North Brazil Shelf.
2. **Ocean warming and acidification is projected to increase the threats faced by coral reefs.** By 2030, over 50 per cent of coral reefs are projected to be at 'high' to 'critical' risk, increasing to almost 80 per cent by 2050. By 2050, only four LMEs are projected to have any reef area left under 'low' threat.
    - Conditions may be particularly severe in the Gulf of California and Kuroshio Current LMEs.
3. **Implementing measures such as marine protected areas may enhance ecosystem resilience in the face of increasing global threats.** The extent of the negative impact on coral reefs will depend on their resilience, as well as on measures to manage and protect them and their associated biodiversity. Multiple local threats are likely reduce the ability of coral reefs to respond and adapt to ocean warming and acidification.
4. **Monitoring coral reef health is important for assessing the impacts on this threatened ecosystem from both local and global threats.** The Reefs at Risk indicator is not a direct measure of coral reef condition. Monitoring coral reef health by tracking, for example, species diversity, algal cover, and live coral cover, provides information needed to understand the extent and nature of impacts from the identified threats.

7.5.1 Introduction

Warm-water coral reefs have a biodiversity comparable to rainforests but only occupy an area of 260 000 to 600 000 km^2, less than 0.1 per cent of the Earth's surface, or 0.2 per cent of the ocean's surface (Reaka-Kudla 2005). This restricted distribution reflects the need for areas of warm, shallow, stable waters to produce the limestone necessary for coral reef formation. Coral reef species diversity is concentrated in the central Indo-Pacific (the 'Coral Triangle') and decreases with increasing distance from the Indo-Australian archipelago (Hughes *et al.* 2002).

Coral reefs are some of the most economically valuable ecosystems on earth, and their declines are likely to have severe consequences for the estimated 500 million people who depend on them for food, coastal protection, building materials, and tourism (Wilkinson 2008). Not only do coral reef ecosystems provide habitat for fish that are important as a source of food and income, they contribute to protecting coastlines from storms and erosion and provide jobs through fisheries and tourism. Hawaii's coral reefs, for example, are estimated to have direct economic benefits of US$360 million per year, when combining recreational, amenity, fishery, and biodiversity values (Cesar 2003).

Coral reefs are one of the most endangered habitats on the planet (Bellwood *et al.* 2004), facing dramatic population declines as a result of bleaching and diseases driven by elevated sea surface temperatures. Increasing ocean acidification also decreases the availability of minerals such as calcite and aragonite that are required for coral skeletons. Declines in coral populations and coral reef extent will have significant consequences for the estimated 500 million people who depend on coral reefs for food, coastal protection, building materials, and income from tourism (Wilkinson 2008). Extinction risk is exacerbated by local-scale anthropogenic disturbances, such as coral mining, agricultural and urban run-off, pollution, and fisheries. More than 60 per cent of the world's reefs are under immediate and direct threat from one or more local sources (Burke *et al.* 2010). As it is estimated that 50 per cent of the world's population will live along coasts by 2050, pressures on these habitats are likely to grow, bringing increasing challenges to managers of coastal habitats and coral reefs (Wilkinson 2008).

The Reef at Risk indicator was calculated using the Reefs at Risk Revisited (Burke *et al*. 2010) GIS data set (available from the World Resources Institute). LMEs and WPWP boundary polygons were overlaid with the Reefs at Risk Revisited Index data sets to undertake the first assessment of the threats faced by coral reefs in LMEs and the WPWP. The Reefs at Risk data sets assign a level of threat to coral reefs around the world for a set of key threats. The data sets analysed include the Integrated Local Threat Index, which combines the threats from overfishing and destructive fishing, coastal development, watershed-based pollution, and marine-based pollution and damage. In addition, indices combining the Local Threat Index with the global-scale threats of ocean warming and acidification were assessed. The data set used to determine coral reef extent is the Global Distribution of Coral Reef data set (IMaRS-USF 2005), which is the most comprehensive global data set of warm-water coral reefs to date, with approximately 85 per cent of the data set originating from the Millennium Coral Reef Mapping Project. Further details are given in the methodology section below.

7.5.2 Findings and discussion

7.5.2.1 Reefs at Risk Index

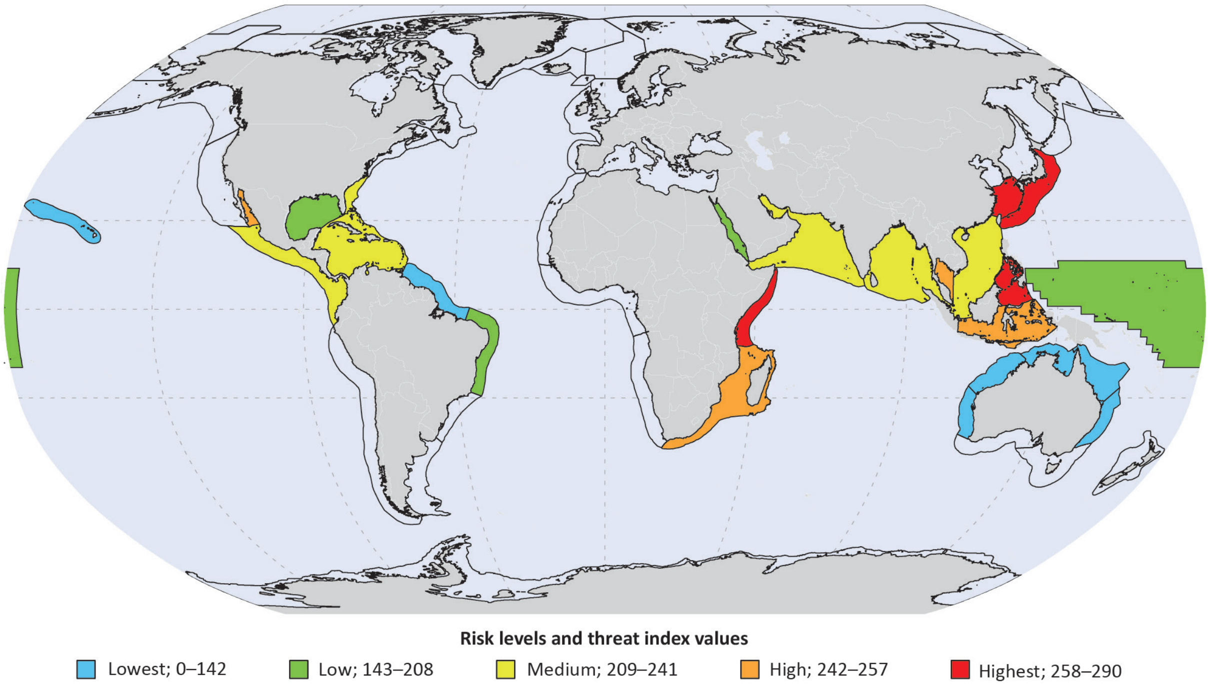
The present-day Integrated Local Threat Index scores for each LME and the WPWP are listed in Table 7.10. The LMEs and WPWP were divided into five categories of potential risk based on these index scores, as defined in Table 7.10 and mapped in Figure 7.19. The North Brazil Shelf LME has the lowest score and the Kuroshio Current LME the highest. The majority of LMEs are assessed as facing a local threat level of at least ‘medium’. This index does not include global threats such as ocean acidification and other projected changes due to climate change.

Table 7.10 Risk categories based on Integrated Local Threat Index scores for LMEs containing coral reefs and the WPWP

Risk category	Range of index scores	Number of LMEs	LMEs and WPWP in category (Integrated Local Threat Index score)
Lowest	0–142	7	North Brazil Shelf (103); West-Central Australian Shelf (111); North Australian Shelf (114); Northeast Australian Shelf (115); Northwest Australian Shelf (118); East-Central Australian Shelf (137); Insular Pacific-Hawaiian (142)
Low	143–208	4	Western Pacific Warm Pool (152); Gulf of Mexico (174); Red Sea (187); East Brazil Shelf (208)
Medium	209–241	6	Caribbean Sea (221); Arabian Sea (231); Pacific Central-American Coastal (235); Southeast US Continental Shelf (236); Bay of Bengal (238); South China Sea (241)
High	242–257	4	Indonesian Sea (250); Gulf of Thailand (253); Gulf of California (255); Agulhas Current (257)
Highest	258–290	4	Somali Coastal Current (282); East China Sea (283); Sulu-Celebes Sea (284); Kuroshio Current (289)

Figure 7.20 (a) shows the proportion of coral reef area in each LME by Integrated Local Threat Index score. The ‘lowest and ‘low’ risk categories (Table 7.10) are combined in this analysis. One-quarter of the LMEs have more than 50 per cent of their coral reef area rated as under ‘high’ to ‘highest’ threat, based on local, present-day threats. LMEs with a relatively high proportion under ‘high’ to ‘highest’ threat include the East China Sea (66.9 per cent of coral reef extent rated as ‘high’ to ‘highest’ threat), Gulf of California (58.9 per cent), Kuroshio Current (63.7 per cent), Somali Coastal Current (62.9 per cent), and Sulu-Celebes Sea (62.3 per cent). In contrast, the Australian Shelf, North Brazil Shelf, and Insular Pacific-Hawaiian LMEs have a high proportion (more than 80 per cent) of their coral reef area at low threat. It is worth noting that the North-East Australian Shelf LME contains the largest extent of coral reef of any LME and has one of the lowest present-day threat indicator levels. About 11 per cent of the WPWP coral reef area is under ‘high’ to ‘highest’ local integrated threat.

Figure 7.19 Integrated Local Threat Index scores for LMEs containing coral reefs and the WPWP, shown by risk category. The North Brazil Shelf LME has the lowest score and the Kuroshio Current LME the highest. The majority of LMEs are assessed as facing a local threat level of at least 'medium'.

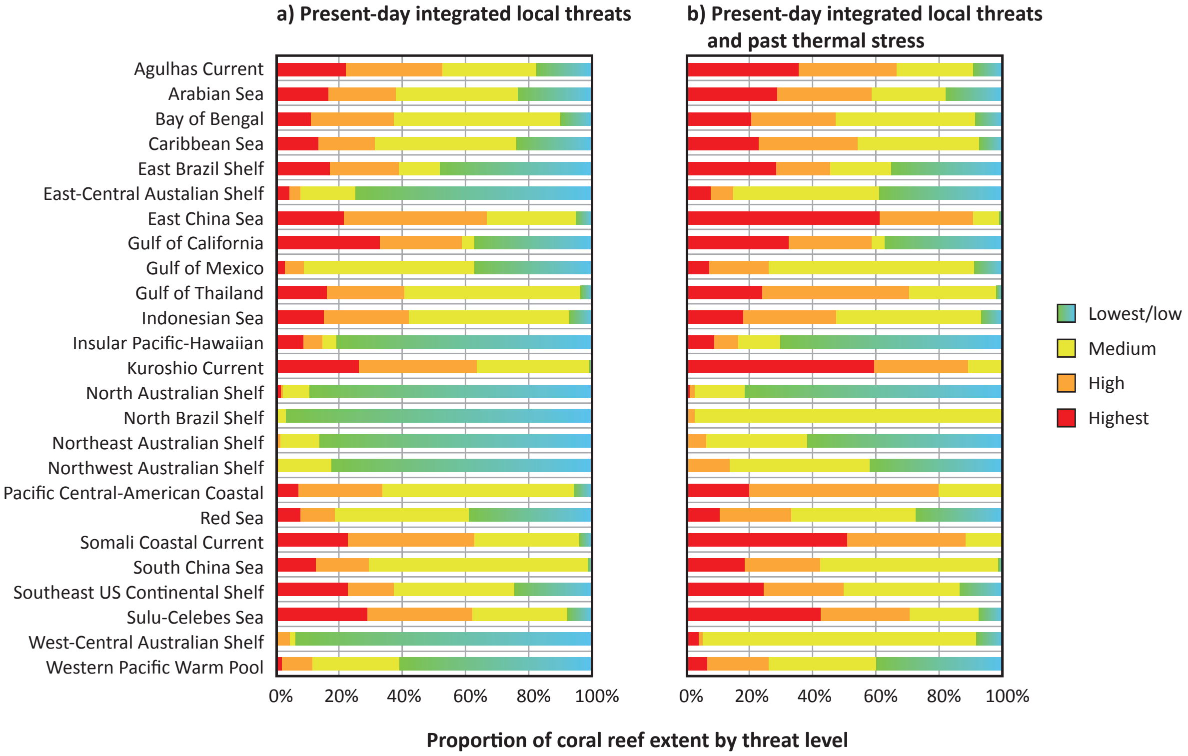


Source: UNEP-WCMC

Figure 7.20(b) shows integrated local threat combined with past thermal stress estimated between 1998 and 2007. When past thermal stress is added to the analysis, the proportion of LMEs with 50 per cent or more of their coral reef area rated as 'high' or 'highest' threat almost doubles (to 11, compared with 6 when this factor is not considered). For the Gulf of Thailand, Pacific Central-American Coastal, Kuroshio Current, and East China Sea LMEs, the inclusion of past thermal stress results in a particularly large increase in coral reef area under 'high' to 'highest' threat. Overall, there is a 32.8 per cent decrease across all LMEs in the coral reef area experiencing low threat, and a 60 per cent increase in the area experiencing high threat. For the WPWP, the extent of area under 'high' to 'highest' threat increases to between 11 and 26.4 per cent.

Figure 7.21(a) shows the proportion of coral reef area projected to face global threats (from ocean warming and acidification) by 2030. If reefs are at high threat for both thermal stress and acidification, the threat classification is increased by two levels. In order to portray some nuance in the degree of threat, the rating scale has been extended to include one additional threat category above 'highest' called 'critical'. The projected increase in threat due to warming and acidification is apparent across most LMEs. The East China Sea, Gulf of California, North Brazil Shelf, Pacific Central-American Coastal, and Sulu-Celebes Sea LMEs have no coral reef area remaining in the low-threat category. More than half the LMEs have more than 50 per cent at 'high' to 'critical' threat levels. LMEs projected to be particularly threatened are the Pacific Central-American Coastal (94.3 per cent 'high' to 'critical'), Sulu-Celebes Sea (91.3 per cent), Agulhas Current (82.6 per cent), and East China Sea (80.9 per cent). Areas that are projected to be less threatened by global threats by 2030 are the East-Central Australian Shelf LME (74.9 per cent of coral reef area at low threat) and the West-Central Australian Shelf LME (57 per cent at low threat). The WPWP has around 39 per cent of coral reef area at 'high' to 'critical' threat levels.

Figure 7.20 Proportion of LME and WPWP coral reef extent by threat level for a) present-day integrated local threats and b) present-day integrated local threats and past thermal stress. One-quarter of the LMEs have more than 50 per cent of their coral reef area rated as under 'high' to 'highest' threat. These include the East China Sea, Gulf of California, Kuroshio Current, Somali Coastal Current, and Sulu-Celebes Sea. In contrast, the Australian Shelf, North Brazil Shelf, and Insular Pacific-Hawaiian LMEs have a high proportion (more than 80 per cent) of their coral reef area at low threat.



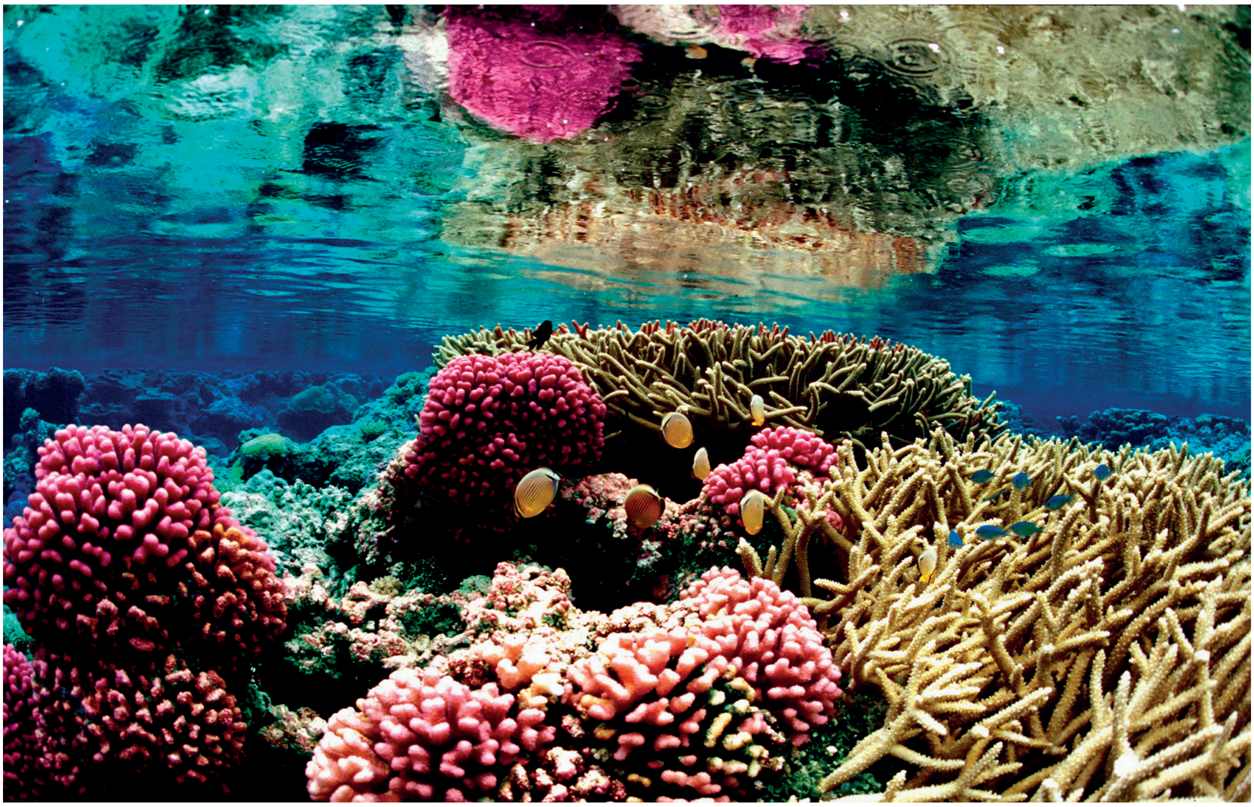
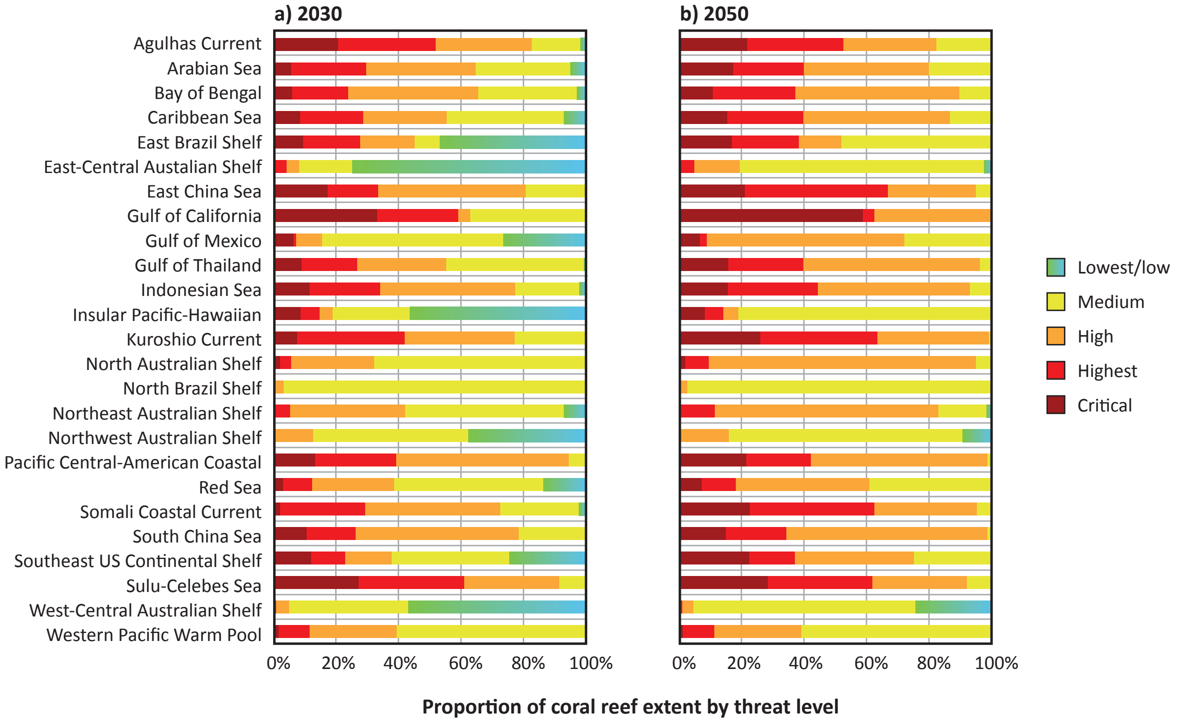

© Jim Maragos/U.S. Fish and Wildlife

Figure 7.21 Projected proportion of LMEs and WPWP coral reef area by threat level for global threats (warming and acidification) by a) 2030 and b) 2050. By 2050, only four LMEs have any coral reef area remaining under low threat, while over half have at least 80 per cent of coral reef area at 'high' threat or above. If reefs are at high threat from both thermal stress and acidification, the threat classification is increased by two levels. To show this increased range of threat levels, the rating scale has been extended to include a 'critical' category, one additional threat category above 'highest' threat.



By 2050, only four LMEs have any coral reef area remaining under low threat: Western-Central Australian Shelf, Northwest Australian Shelf, Northeast Australian Shelf, and East-Central Australian Shelf (Figure 7.21(b)). Over half the LMEs (15) have at least 80 per cent of coral reef area at 'high' threat or above. Those LMEs with the highest proportion of area under 'high' to 'critical' threat are Gulf of California (100 per cent), Kuroshio Current (99.4 per cent), Pacific Central-American Coastal (99 per cent), and the South China Sea (99 per cent). For the WPWP, there is no change in the proportion of area under 'high' to 'critical' threat.

7.5.2.2 Extent of coral reef by LME

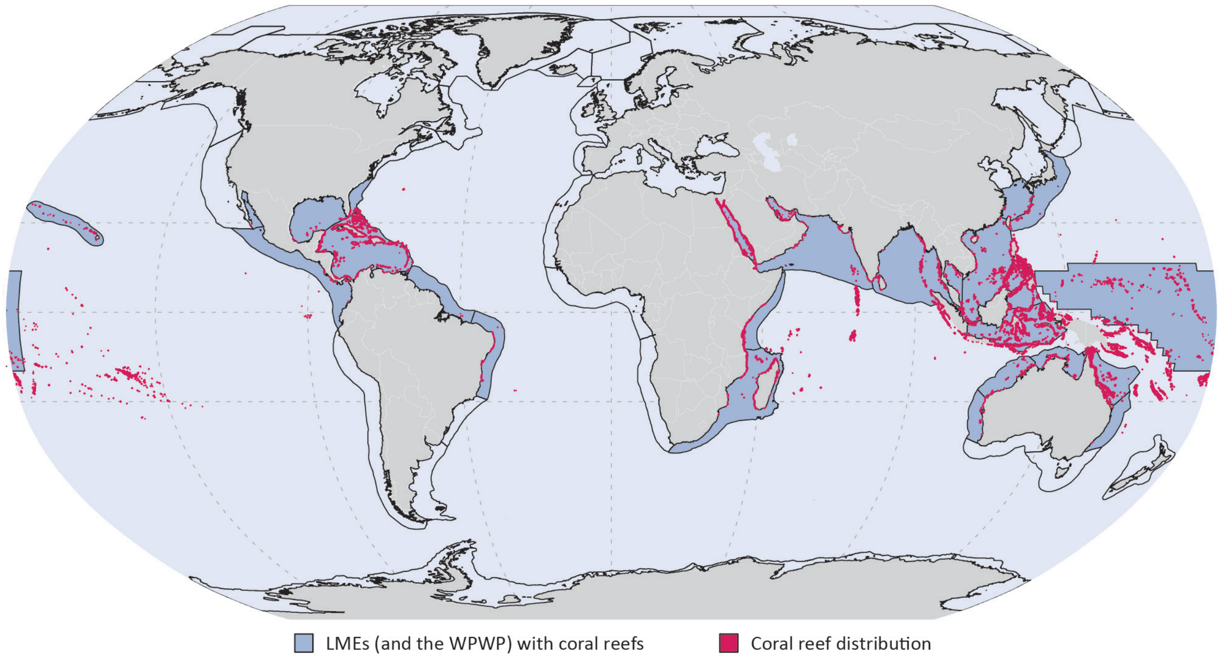
The distribution of warm-water coral reefs in the LMEs the WPWP is shown in Figure 7.22.

Figure 7.23 (a) shows the proportion of coral reef area in each LME and the WPWP. On average, coral reefs extend over 0.52 per cent of the total LME area. The Northeast Australian Shelf LME, which includes the Great Barrier Reef, has the largest extent (2.83 per cent of its area), followed by the Indonesian Sea LME (2.66 per cent).

Figure 7.23 (b) shows the area (in km^2) of coral reefs in each LME and the WPWP. In total, coral reefs cover an area of 184 577 km^2. The Northeast Australian Shelf LME contains the largest estimated area, at 36 315 km^2. The Indonesian Sea and Caribbean Sea LMEs also have relatively large areas, at 25 673 km^2 and 20 791 km^2, respectively. Other areas with large coral reef extent include the Sulu-Celebes Sea LME and the WPWP.

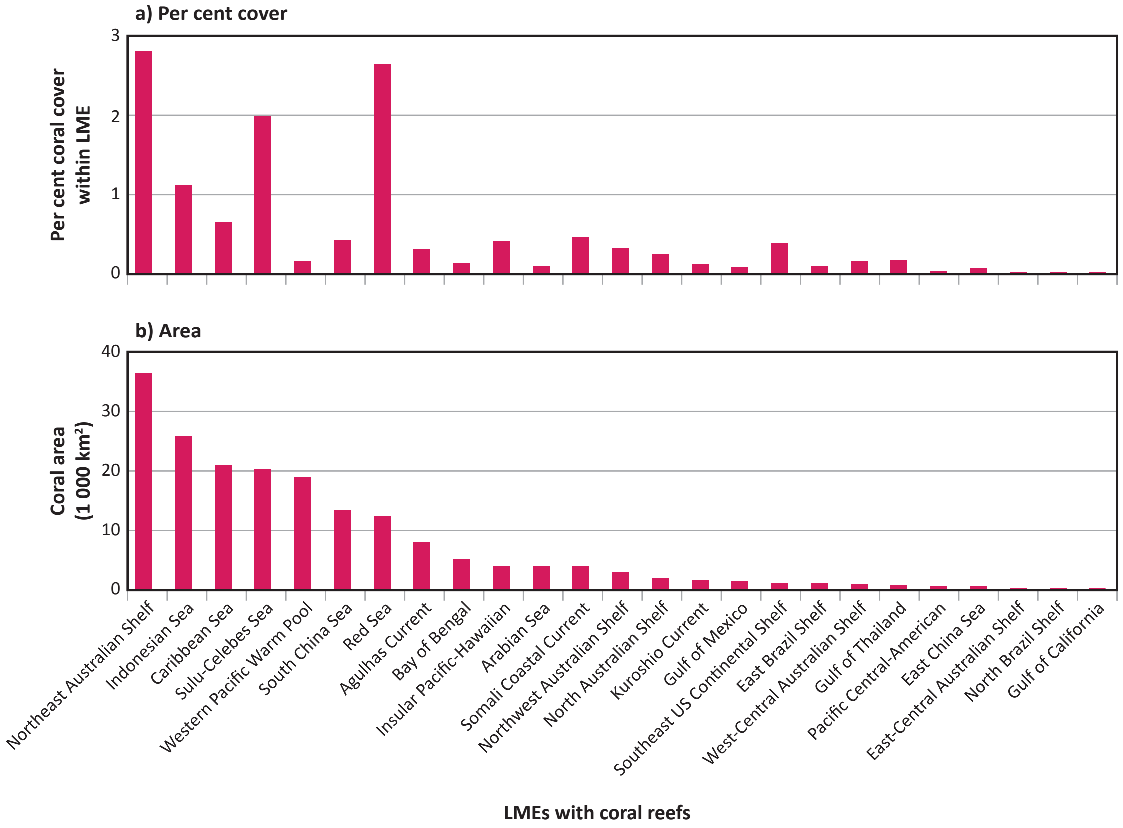
The confidence level surrounding these results is medium, the rationale being that the results are based on the best available data but limited by a small number of methodological and technical aspects, specifically the lack of sufficient ground-truthing and the age of the baseline data.

Figure 7.22 Warm-water coral reef areas within LMEs and the WPWP



Source: UNEP-WCMC

Figure 7.23 Coral cover within each LME and the WPWP shown as a) percentage and b) area. On average, coral reefs extend over 0.52 per cent of the total LME area, representing an area of 184 577 km².



7.5.3 Methodology

7.5.3.1 Reefs at Risk Index

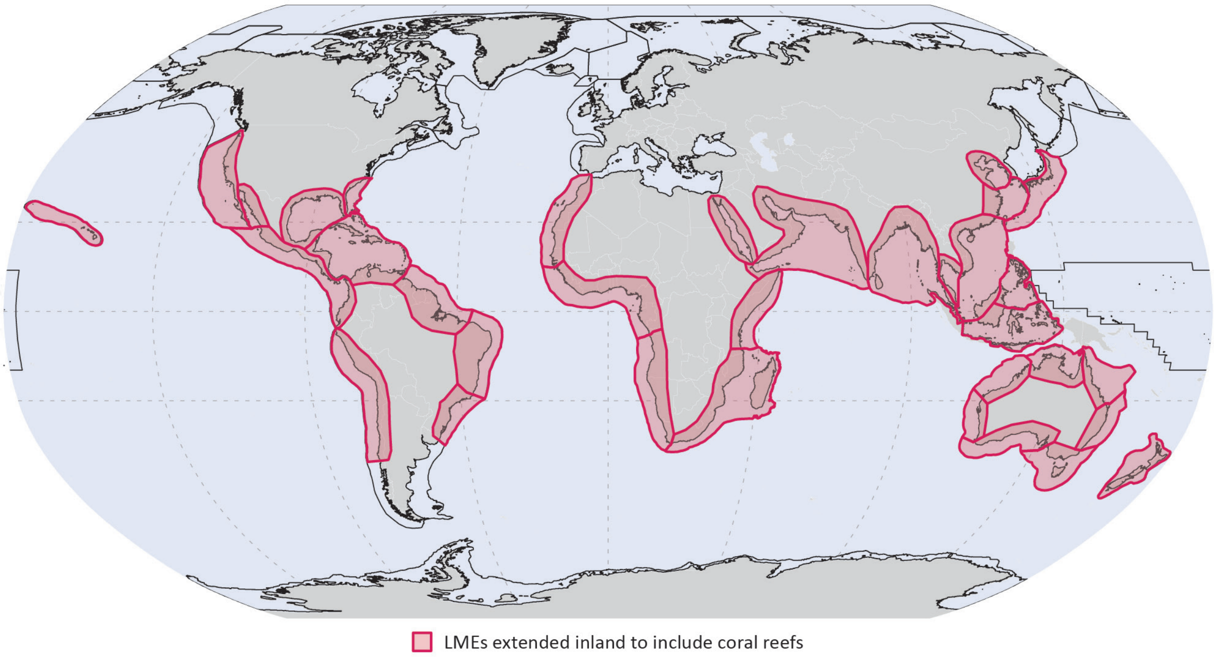
LME and WPWP boundary polygons were overlaid with the global coral reef data set to derive statistics on coral reef extent for each LME and the WPWP. LME boundary polygons were from the National Oceanic and Atmospheric Administration (NOAA 2013), while the WPWP polygon data were provided by the Sea Around Us, University of British Columbia.

During this analysis we noted that, due to the coarseness of the global land boundaries, coral reef sites sometimes fall over areas demarcated as land. For this reason, we included coral reef sites over coastal margins, using a buffer for each LME (shown in Figure 7.24). As the Reefs at Risk indicators give the proportions of different risk categories faced by coral reefs within a given LME, any changes as a result of buffering would probably be negligible. The adjustment was not made for the WPWP, as it did not present an issue for this region, which contains only relatively small island states.

The Reefs at Risk Revisited GIS data sets are available from the World Resources Institute, with more information given in Burke *et al.* (2010). Burke and Reytar (2011) assign threat levels to coral reefs around the world. The Reefs at Risk Revisited report (Burke *et al.* 2010) provides a detailed assessment of the status and threats to coral reefs from human activities and climate-related threats. It also includes a series of maps depicting the distribution of local and climate-related threats to coral reefs. These spatial data sets were used to calculate the Reefs at Risk indicator within each LME and the WPWP.

The indicator is not a direct measure of reef status or condition. Some areas rated as threatened may have already suffered considerable loss or degradation, such as reduced live coral cover, increased algal cover, or reduced species diversity. Using the indices calculated by the Reefs at Risk Revisited Project, we assess 1) the present-day Integrated Local Threat Index, 2) the Integrated Local Threat accounting for the impact of past thermal stress, and 3) the Integrated Local Threat combined with estimates of future (2030 and 2050) thermal stress and ocean acidification.

Figure 7.24 LMEs extended inland to incorporate all coral reef areas within LMEs into the analysis



Source: UNEP-WCMC

Threats faced by coral reefs may be divided into local and global. For each local threat, sources of stress that could be mapped were identified and combined into a proxy indicator that reflect the degree of threat. For example, stressors may include human population density and infrastructure features such as the size and location of cities and ports. Distance-based rules were then developed for each threat, with threat declining as distance from stressor increases. Thresholds for low, 'medium', 'high', and 'highest' threats were developed using information on observed impacts of threats to coral reefs. Four calculated local threats, coastal development, watershed-based pollution, marine-based pollution and damage, and overfishing and destructive fishing, were combined into a single Integrated Local Threat Index in order to obtain a single, broad measure of threat and represent the cumulative impact of these threats on coral reefs.

Threats to coral reefs from coastal development were modelled on the basis of size of cities, ports, and airports; size and density of hotels; and coastal population pressure (a combination of population density, growth, and tourism growth). Threats from watershed-based pollution were modelled on the basis of relative erosion rates, sediment delivery, and sediment plume dispersion. The indicator of threat from marine-based pollution and damage was based on the size and volume of commercial shipping ports, size and volume of cruise ship ports, intensity of shipping traffic, and location of oil infrastructure. Threats to coral reefs from overfishing were evaluated on the basis of coastal population density and extent of fishing areas (coral reef and shallow shelf areas), with adjustments to account for the increased demand due to proximity to large populations and market centres. Areas where destructive fishing (explosives or poisons) occurs were also included, based on expert monitoring and mapping. The threat estimate was reduced inside marine protected areas that had been rated by experts as having 'effective' or 'partially effective' management.

For each LME and the WPWP, the percentage of coral reef area under each of the four Reefs at Risk threat categories (low, medium, high, and highest) was calculated (threat per cent). This percentage was then multiplied by a weighting factor, depending on the threat level, as follows:

low = threat per cent X 1
medium = threat per cent X 2
high = threat per cent X 3
highest = threat per cent X 4

The overall integrated threat score was then calculated by summing the values for each threat score, as outlined in Table 7.11.

Table 7.11 Example of how the total integrated threat scores were calculated for three of the LMEs

LME name	LME area (km^2)	LME coral area (km^2)	Threat	Coral area (km^2)	Threat per cent	LME threat score	Total integrated threat score
Agulhas Current	2 626 582	7 923	Highest	1 738	21.9	87.7	257
			High	2 437	30.8	92.3	
			Medium	2 370	29.9	59.8	
			Low	1 379	17.4	17.4	
Arabian Sea	3 932 202	3 845	Highest	630	16.4	65.5	231
			High	816	21.2	63.7	
			Medium	1 504	39.1	78.2	
			Low	895	23.3	23.3	
Northeast Australian Shelf	1 281 700	36 315	Highest	67	0.2	0.7	115
			High	288	0.8	2.4	
			Medium	4 660	12.8	25.7	
			Low	31 301	86.2	86.2	

The addition of global threats addresses the impacts of climate and ocean chemistry on coral reefs. The stressors used for these models were derived from satellite observations of sea surface temperature, coral bleaching observations, and modelled estimates of future warming and ocean acidification. The global threats assessed were then used to explore the cumulative effects of integrated local and global threats on coral reefs, as follows:

The Integrated Local Threat Index was adjusted to account for the impact of past thermal stress, using data indicating the locations of severe thermal stress events between 1998 and 2007. For example, reefs in areas of thermal stress increase in threat by one level, reflecting the ability of thermal stress to cause coral bleaching on otherwise healthy reefs.

The Integrated Local Threat Index was combined with modelled future estimates of thermal stress and ocean acidification to project threats to reefs in 2030 and 2050, based on an IPCC A1B ('business-as-usual') emissions scenario, and adjusted to account for historic temperature variability.

7.5.3.2 Extent of coral reef by LME

The coral reef data set used to support this analysis is the Global Distribution of Coral Reefs (UNEP-WCMC, WorldFish Centre, WRI, TNC 2010)[1]. It is the most comprehensive global data set of warm water coral reefs to date, acting as a foundation baseline map for future more detailed investigations.

Approximately 85 per cent of this data set originates from the Millennium Coral Reef Mapping Project (35 per cent validated and 50 per cent unvalidated) and is the highest resolution global coral reef data set available to date, mapped at 30 metres resolution. The validated data correspond to the final standard of the Millennium Coral Reef Mapping Project products, and consists of vector spatial data (polygons) with attributes. The contours of polygons and final labels for the unvalidated data, in contrast with the validated products, have not been entirely determined. The remaining 15 per cent of the data set is a mosaic of data from various sources. All original source information is maintained within the global layer.

---

[1] Millennium Coral Reef Mapping Project validated maps provided by the Institute for Marine Remote Sensing, University of South Florida (IMaRS/USF) and Institut de Recherche pour le Développement (IRD, Centre de Nouméa), with support from NASA.
Millennium Coral Reef Mapping Project unvalidated maps provided by the Institute for Marine Remote Sensing, University of South Florida (IMaRS/USF), with support from NASA. Unvalidated maps were further interpreted by UNEP-WCMC. Institut de Recherche pour le Développement (IRD, Centre de Nouméa) does not endorse these products.

References

Bellwood, D.R., Hughes, T.P., Folke, C. and Nystrom, M. (2004). Confronting the coral reef crisis. *Nature* 429, 827-833

Burke, L., Reytar, K., Spalding, M. and Perry, A. (2010). *Reefs at Risk Revisited*. World Resources Institute, Washington, DC. 114 pages

Burke, L. and Reytar, K. (2011). *Reefs at Risk Revisited: Technical notes on modelling threats to the world's coral reefs.* World Resources Institute, Available online at: http://d7.wri.atendesigngroup.com/sites/default/files/docs/reefs_at_risk_revisited_technical_notes.pdf (accessed 21 February 2014)

Cesar, H.J.S., Burke, L. and Pet-Soede, L. (2003). *The economics of worldwide coral reef degradation*. Cesar Environmental Economics Consulting, Arnhem, and WWF-Netherlands, Zeist, The Netherlands. 23 pages

Hughes, T.P., Bellwood, D.R. and Connolly, S.R. (2002). Biodiversity hotspots, centres of endemicity, and the conservation of coral reefs. *Ecology Letters* 5, 775-784

NOAA (2013). Large Marine Ecosystems of the World: LME Boundaries Download Page. http://lme.edc.uri.edu/index.php?option=com_content&view=article&id=177&Itemid=61 (accessed 7 January 2013)

Reaka-Kudla, M.L. (2005). II.5 Biodiversity of Caribbean coral reefs. In: *Caribbean Marine Biodiversity: The known and the unknown* (eds. Miloslavich, P, and Klein, E.). DEStech Publications, Lancaster (Pennsylvania), 310 pages

UNEP-WCMC, WorldFish Centre, WRI, TNC (2010). Global distribution of warm-water coral reefs, compiled from multiple sources including the Millennium Coral Reef Mapping Project. Includes contributions from IMaRS-USF and IRD (2005), IMaRS-USF (2005) and Spalding *et al.* (2001). Cambridge (UK): UNEP World Conservation Monitoring Centre. URL: http://data.unep-wcmc.org/datasets/1

Wilkinson, C. (2008). *Status of the coral reefs of the world: 2008*. Global Coral Reef Monitoring Network and Reef and Rainforest Research Centre. Townsville, Australia

Chapter 7.6. Change in protected area coverage within large marine ecosystems.

Lead Authors

Chris McOwen, Miranda Jones (United Nations Environment Programme World Conservation Monitoring Centre)

Contributing Authors

Simon Blyth, Damon Stanwell-Smith (United Nations Environment Programme World Conservation Monitoring Centre)

Chapter Citation

McOwen, C., Jones, M., Blyth, S., Stanwell-Smith, D. (2016). Chapter 7.6: Change in protected area coverage within large marine ecosystems. In IOC-UNESCO and UNEP (2016). *Large Marine Ecosystems: Status and Trends*. United Nations Environment Programme, Nairobi, pp 217–223.

7.6 Change in protected area coverage within large marine ecosystems

SUMMARY

The oceans are home to an estimated 50 to 80 per cent of all life on Earth and provide vital goods and services to human populations. However, marine and coastal ecosystems are facing increasing threats from pollution, extractive infrastructure, fisheries, coastal development, and the changing environmental conditions associated with climate change. Marine Protected Areas (MPAs) are vital for conserving the ocean's biodiversity and productivity. Aichi Target 11 of the Convention on Biological Biodiversity (CBD) aims to effectively conserve 10 per cent of the world's coastal and marine areas by 2020.

This is the first assessment of protected areas in the world's LMEs and the Western Pacific Warm Pool (WPWP). It is based on the latest version of the World Database on Protected Areas, which is available online. Changes in the areas protected between 1983 and 2014 were calculated, and LMEs were divided into five categories based on the extent of the change. The confidence level for this assessment is rated as high because the database was updated in 2014.

Key Messages

1. **The continuing designation of MPAs in recent decades has led to a 15-fold increase in global MPA extent between 1983 and 2014.** The total extent of protected areas with marine components increased from about one-third of a million km^2 in 1982 to more than 5 million km^2 in 2014. The increase in global MPA extent indicates progress towards the CBD's target to conserve 10 per cent of the world's coastal and marine areas by 2020 – it is currently about 2.3 per cent.
    - LMEs with the highest percentage change in area of MPAs include three Australian Shelf LMEs, Gulf of California and Red Sea;
    - LMEs with the lowest percentage change include the Arctic LMEs: Beaufort Sea, Canadian High Arctic-North Greenland, and Northern Bering-Chukchi Seas;
    - LMEs with no MPAs in 2014: Faroe Plateau and Central Arctic Ocean.
2. **Monitoring the effectiveness of designated MPAs and analysing how increasing coverage relates to the conservation of ocean biodiversity and productivity remain of high importance.** This type of analysis cannot be based only on the distribution of MPAs because countries vary in their interpretation and classification of MPA types, and also in the degree of implementation and enforcement of protection measures. Distribution of MPA coverage does, however, indicate areas where potential threats to marine biodiversity may be reduced by the creation of new MPAs.

7.6.1 Introduction

The world's oceans provide 20 per cent of the animal protein consumed by 1.5 billion people (FAO 2009). Oceans contribute US$ 230 billion annually to the global economy through fisheries alone (Dyck and Sumaila 2010). However, marine and coastal ecosystems and the benefits they provide are facing increasing threats from pollution, extractive infrastructure, fisheries, coastal development and the changing environmental conditions associated with climate change (Halpern *et al.* 2008). An estimated 60 per cent of the world's marine ecosystems that underpin livelihoods have been degraded or are being used unsustainably (UNESCO 2014; Pauly *et al*. 2002).

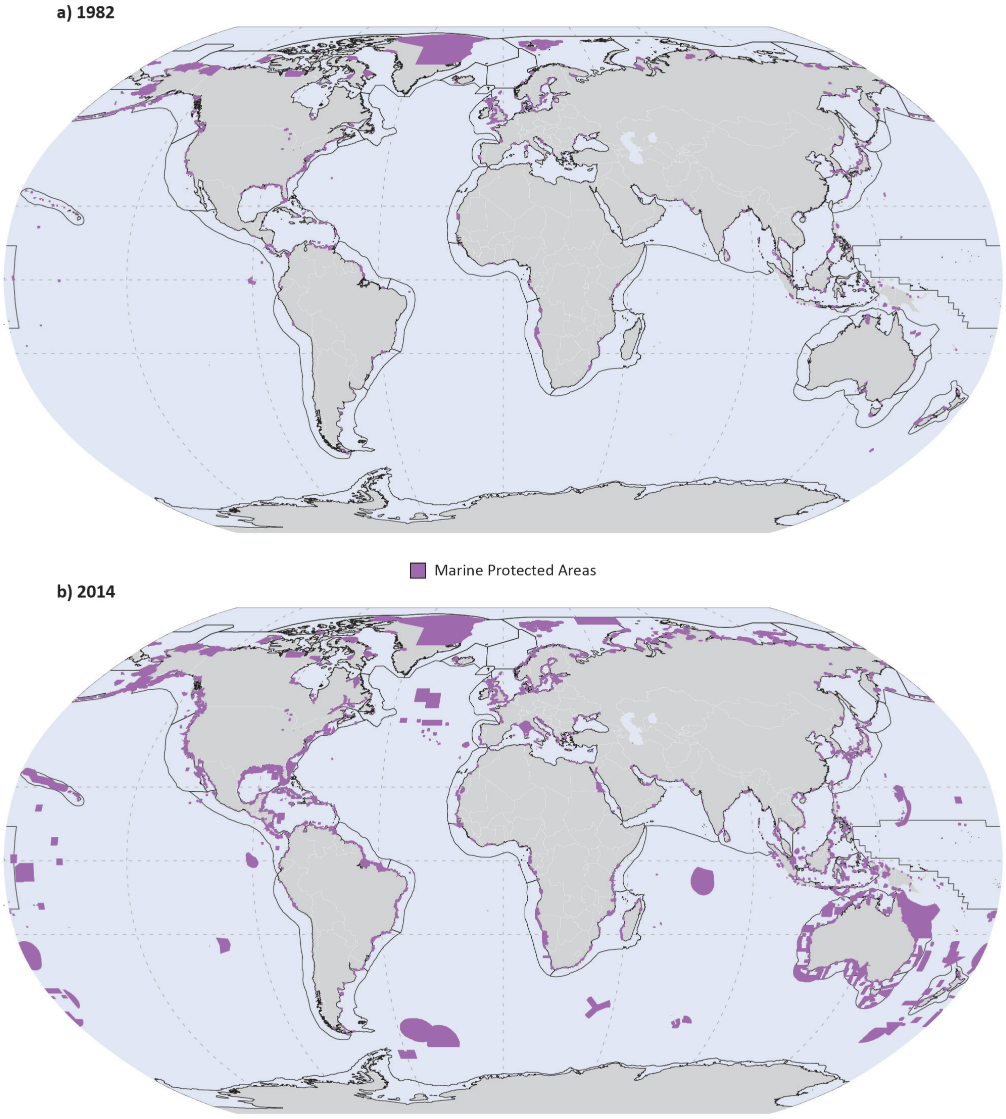
There is an extensive research base on the most effective ways to implement MPAs (Gaines *et al.* 2010; McLeod *et al*. 2009; Halpern 2003; Walters 2000). MPA implementation often depends on the objectives of MPA designation (for example, for species conservation or for managing fisheries), as well as on socio-ecological context (Kaiser 2005) and governance (Garcia *et al.* 2014). Furthermore, benefits realized from MPAs may vary, depending on the biology of the species being protected (Halpern 2003), the links between ecosystem services and the underlying species biology or ecosystem relationships on which they depend (such as for fishing or tourism), whether it is possible to exclude threats, and how threats might act synergistically. Lack of reliable, accurate data on marine species and habitats frequently hinders protected area planning and assessment of effectiveness. This lack of data and knowledge may partly explain why only 2.3 per cent of the global ocean is now protected, compared to 14 per cent of the land (Thomas *et al.* 2014; Protected Planet 2014). Results presented here are derived from the latest World Database on Protected Areas (WDPA) (UNEP-WCMC 2014). Further details are given in the section on methodology.

The CBD's Aichi Target 11 specifies that "*by 2020 10 per cent of the coastal and marine areas, especially areas of particular importance for biodiversity and ecosystem services, are conserved through effectively and equitably managed, ecologically representative and well-connected systems of protected areas and other effective area-based conservation measures, and integrated into the wider landscape and seascape*" (CBD 2014).

7.6.2 Findings and discussion

The two maps in Figure 7.25 show the global distribution of MPAs that were designated by 1982 and by 2014, together with LME boundaries.

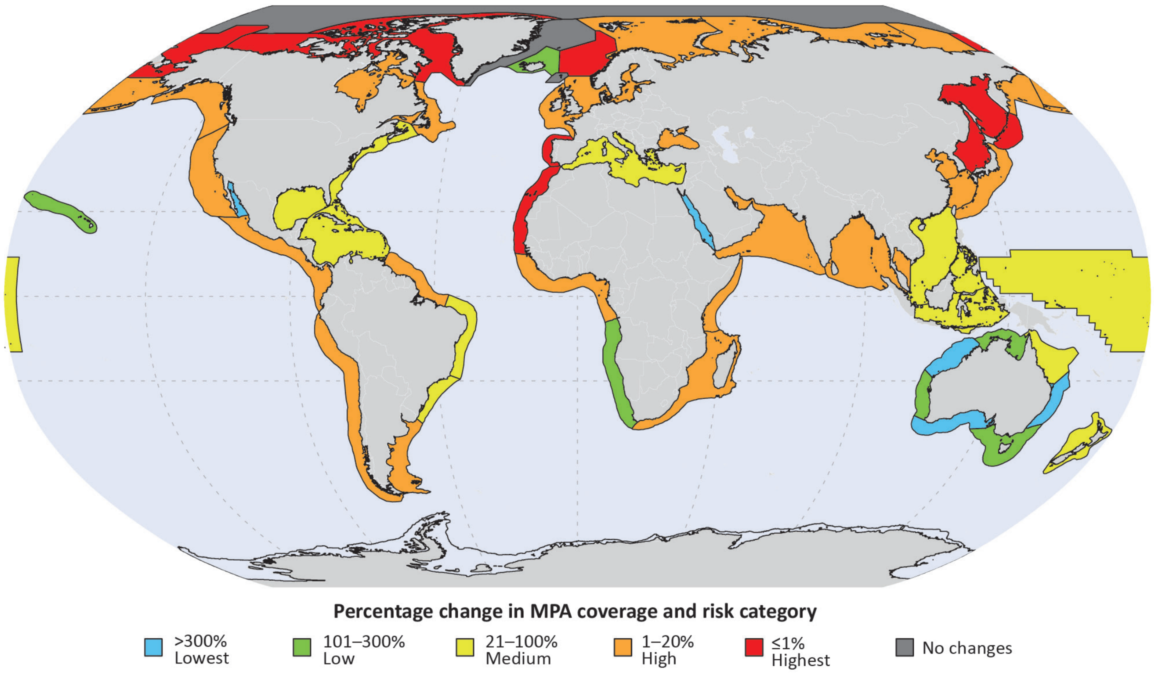
Figure 7.25 Marine Protected Areas designated by a) 1982 and b) 2014. Over this time period the number, total area, and geographic extent of MPAs increased significantly.



Source: UNEP-WCMC 2014

Figure 7.26 shows the percentage increase in the total area of each LME covered by MPAs, arranged into five categories (with categories corresponding to highest to lowest level of relative risk of potential biodiversity degradation). LMEs with the highest percentage change in MPA coverage (blue, ‘lowest’ risk category) include the East Central Australian Shelf, Gulf of California, Red Sea, Northwest Australian Shelf, and South West Australian Shelf. LMEs with the lowest percentage change (red, ‘highest’ risk category) include the Beaufort Sea, Canadian High Arctic-North Greenland, and Northern Bering-Chukchi Seas. In 1983, five LMEs contained no MPAs (Gulf of California, Northwest Australian Shelf, West-Central Australian Shelf, Faroe Plateau, and Central Arctic Ocean). By 2014 only two LMEs remained with no MPAs: Faroe Plateau and Central Arctic Ocean.

Figure 7.26 Index of percentage change (1982–2014) in total area covered by MPAs per LME. The East Central Australian Shelf, Gulf of California, Red Sea, Northwest Australian Shelf, and Southwest Australian Shelf LMEs had the highest percentage of increase in LME area, while the Beaufort Sea, Canadian High Arctic-North Greenland, and Northern Bering-Chukchi Seas LMEs had the least. In 1983, five LMEs contained no MPAs; by 2014 only two LMEs remained with no MPAs: Faroe Plateau and Central Arctic Ocean.

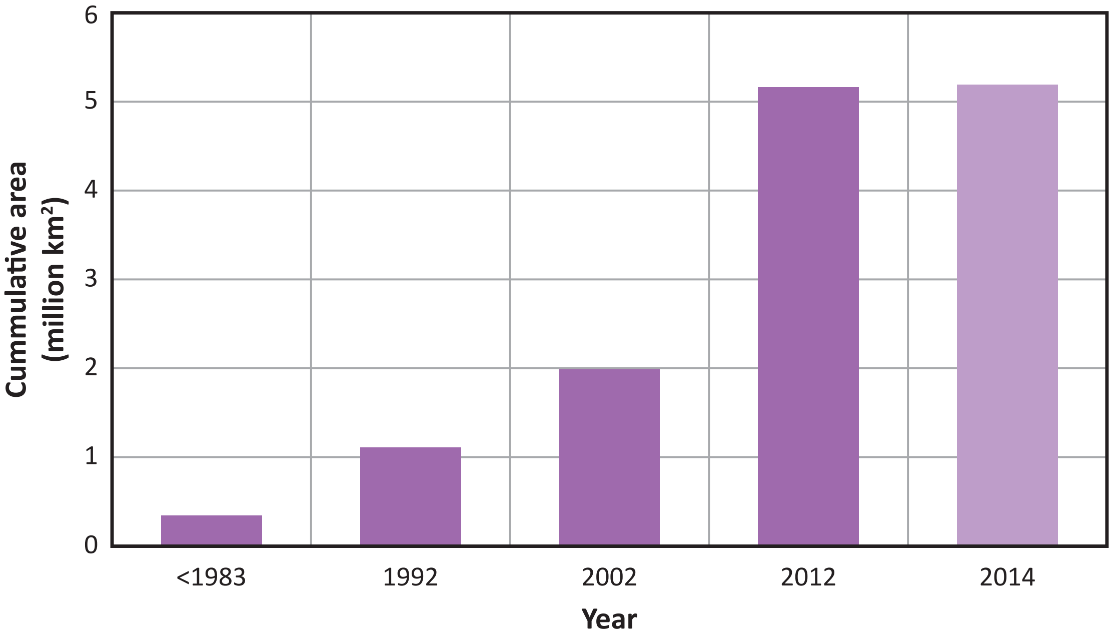


Source: UNEP-WCMC 2014

The purpose of this assessment is to assess changes in the extent of MPAs. Figure 7.27 therefore cannot be used to assess the actual level of threat to the marine environment following MPA designation, although it might be inferred that LMEs with high MPA coverage face a lower level of threat. A comprehensive assessment of the change in threat levels following MPA designation would require more monitoring data for biodiversity as well as information on management strategies and the compliance and attitudinal acceptance necessary for MPA effectiveness.

The continuing designation of MPAs in recent decades led to a large (15-fold) increase in global MPA extent from 1983 to 2014 (Figure 7.27). This illustrates progress towards the CBD’s Aichi Target 11, which aims to conserve 10 per cent of the world’s coastal and marine areas by 2020. The small difference in area between 2012 and 2014 reflects both the short time frame and the fact that only four polygons and one point were recorded as being designated after 2012. One of these was removed from the area calculation as it fell outside LME boundaries. The others lie within the East China Sea and Patagonian Shelf LMEs.

Figure 7.27 Cumulative area of MPAs in all LMEs and the WPWP. Between 1983 and 2014 there was a 15-fold increase in global MPA extent, with the largest increase occurring between 2002 and 2012.



Bar shading highlights that time periods cover decades except the final category (2013–2014).

MPA extent within all LMEs shows a geographic bias, with large areas protected in the Australian Shelf seas. Most of the MPAs in this area were designated between 2003 and 2012. In particular, the largest MPA area (1 240 237 km^2) is within the Northeast Australian Shelf, partly because of the designation of the Great Barrier Reef Marine Park. Initially designated in 1975, this park protects an area of high marine biodiversity (home to 600 types of soft and hard corals, 1 625 species of bony fishes, and 133 species of sharks and rays) from damaging activities such as fishing, commercial shipping, and removal of coral (GBRMPA 2015).

There have also been significant increases in the number and areas of MPAs beyond the LME boundaries considered here. Most notable are the Natural Park of the Coral Sea, the Pacific Remote Islands Marine National Monument, and the South Georgia and South Sandwich Islands Marine Protected Area. Each of these protects an area of more than 1 million km^2.

Based on the above, we put the confidence surrounding this chapter at 'high'. Over 83 per cent of sites were updated during the past 12 months so that the assessment uses the most comprehensive and up-to-date information available.

7.6.3 Methodology

The results discussed here derive from the most recent update of the WDPA (April 2014), available at www.protectedplanet.net. MPAs in this database have varying levels of protection, and the efficacy and enforcement of any restrictions and management measures also vary significantly. However, since data on these variables are not consistently provided to the WDPA, the scope of the assessment has limitations, discussed below.

Protected areas were assessed by LME, to which the WPWP was added, for a total of 67 areas. The subset of nationally-designated protected areas containing marine elements was obtained, providing 6 107 polygons and 1 372 points, with points that overlap polygons being subsequently removed. Both polygon and point records contain data on the extent of a protected area. All sites recorded as having a marine component are included as MPAs in this assessment. Subsets of MPAs were grouped according to the year of designation. The time frames for subsets were: before 1983, 1983 to 1992, 1993 to 2002, 2003 to 2012, and 2013 to 2014. The extent of coverage by MPAs in LMEs and the WPWP was assessed for each of these time frames, assuming no change in the size of individual MPAs. Those situated in areas beyond national jurisdiction were excluded from the area analyses unless they fall within an LME (like the Pelagos Sanctuary in the Mediterranean LME). However, all MPAs recorded in the WDPA are presented in Figure 7.25 and Figure 7.26 for information purposes.

Based on the percentage change in total area covered by MPAs between 1982 and 2014, LMEs were assigned to five categories (Table 7.12) and mapped in Figure 7.26. LMEs with progressively higher coverage by MPAs were inferred to face progressively lower levels of threats, under the assumption that MPA implementation is effective in reducing threats to marine biodiversity.

Table 7.12 Threat level categories based on change in MPA coverage in LMEs

Threat level category	Percentage change in area covered by MPAS (1982–2014)
Lowest	Over 300% (highest change)
Low	101–300% (high change)
Medium	21–100% (medium change)
High	2–20% (low change)
Highest	Less than or equal to 1% (lowest change)

© Nutrients Nelson Tasman Tourism/flickr

7.6.3.1 Limitations

Any protected area recorded as having a marine element was included in the analysis. Some of the sites, however, mainly cover land and may reflect objectives of conserving or managing terrestrial species or habitats. The level of protection provided by MPAs may also vary significantly. Protection levels are not comparable across all areas and countries from the data available in the WDPA. For example, some areas are classified as No Take Zones (NTZs). At their highest level of protection, NTZs are permanently set aside from direct human disturbance, with all methods of fishing and extraction of natural materials, dumping, dredging, and construction activities prohibited, and the removal of resources, living or dead, also prohibited. Other MPAs may be subject to fisheries management measures such as seasonal closures and fishing gear restrictions, or may be classified according to the IUCN categories (IUCN 2014). Because countries may vary in their interpretation and classification of particular types of MPA, and because levels of implementation and enforcement of restrictions in MPAs may also vary, no data can be presented on the degree of protection provided by MPAs. This analysis, therefore, is not able to include an assessment of the likely effectiveness of MPAs in conserving marine biodiversity.

Some MPA records had no information on the year of designation, or had revisions of the date of designation over time. All these were included in the final coverage assessment (2014). However, to prevent all these sites appearing in the final time period and presenting a misleading view of year of designation, they were combined with data from 2002, whether or not they were present in 2002 was assessed, and points and polygons were retained if they were present. For years before 2002, sites with no recorded designation date were excluded from the analyses.

MPA records for Antarctica were present in the WDPA in 2002 but were subsequently removed, either because the sites were deemed not to qualify as Protected Areas as defined by IUCN, or because the whole of Antarctica may be deemed ‘protected’. Since retaining these data in an assessment of the change in global MPA coverage would confound results, the records were removed for this calculation. The records have, however, been displayed in Figure 7.25 for information.

References

CBD (2014). Aichi Biodiversity Targets. https://www.cbd.int/sp/targets/ (accessed 24/09/14)

Dyck, A.J. and Sumaila, U.R. (2010). Economic impact of ocean fish populations in the global fishery. *Journal of Bioeconomics* 12, 227-243

FAO (2009). *Climate change implications for fisheries and aquaculture*. FAO Fisheries and Aquaculture Technical Paper 530, 212 pages

Gaines, S.D., White, C., Carr, M.H. and Palumbi, S.R. (2010). *Designing marine reserve networks for both conservation and fisheries management*. Proceedings of the National Academy of Sciences of the United States of America 107, 18286-18293

Garcia, S.M., Rice, J. and Charles, A. (eds.) (2014). *Governance of marine fisheries and biodiversity conservation: Interaction and coevolution*. John Wiley & Sons, Ltd. Chichester, UK

GBRMPA (2015). http://www.gbrmpa.gov.au/about-the-reef/animals

Halpern, B. (2003). The impact of marine reserves: do reserves work and does reserve size matter? *Ecological applications* 13, 117-137

Halpern, B.S., Walbridge, S., Selkoe, K.A and others (2008). A global map of human impact on marine ecosystems. *Science* 319, 948-952

IUCN (2014). IUCN Protected Areas Categories System. http://www.iucn.org/pa_categories

Kaiser, M.J. (2005). Are marine protected areas a red herring or fisheries panacea? *Canadian Journal of Fisheries and Aquatic Sciences* 62, 1194-1199

McLeod, E.E., Salm, R., Green, A. and Almany, J. (2009). Designing marine protected area networks to address the impacts of climate change. *Frontiers in Ecology and the Environment* 7, 1-10

Pauly, D., Christensen, V., Guénette, S. and others (2002). Towards sustainability in world fisheries. *Nature* 418, 689-695

Protected Planet (2014). http://www.protectedplanet.net/ (accessed 24 September 2014)

Thomas, H.T., MacSharry, B., Morgan, L. and others (2014). Evaluating official marine protected area coverage for Aichi Target 11: appraising the data and methods that define our progress. *Aquatic Conservation: Marine and Freshwater Ecosystems* 24, 8–23. doi: 10.1002/aqc.2511 (accessed 24 September 2014)

UNEP-WCMC (2014). World Database on Protected Areas. http://www.protectedplanet.net/

UNESCO (2014). http://www.unesco.org/ (accessed 24 September 2014)

Walters, C. (2000). Impacts of dispersal, ecological interactions, and fishing effort dynamics on efficacy of marine protected areas: how large should protected areas be? *Bulletin of Marine Science* 66, 745-757

Chapter 7.7. Cumulative human impacts in the world's large marine ecosystems.

Lead Author

Benjamin Halpern (Bren School of Environmental Science and Management, University of California, Santa Barbara)

Contributing Author

Melanie Frazier (National Center for Ecological Analysis and Synthesis, University of California, Santa Barbara)

Chapter Citation

Halpern, B., Frazier, M. (2016). Chapter 7.7: Cumulative human impacts in the world's large marine ecosystems. In IOC-UNESCO and UNEP (2016). *Large Marine Ecosystems: Status and Trends*. United Nations Environment Programme, Nairobi, pp 225-237.

7.7 Cumulative human impacts in the world's large marine ecosystems

SUMMARY

Marine ecosystems in general, and coastal systems in particular, experience a wide range of stressors associated with human activities. These multiple stressors impact systems cumulatively, in ways that are not always known, and with a combined impact that is always greater than that of the individual stressors. Assessing and mapping the cumulative impact of human activities on marine ecosystems provides a unique perspective and understanding of the condition of marine regions, and of the relative contributions of different human stressors to creating that condition. Focusing on the combined impact of multiple stressors within a common assessment framework allows direct comparison among stressors and regions. Cumulative human impact (CHI) assessments can inform policy by identifying the stressors with the greatest impact, rank regions most or least impacted, or highlight stressors that originate from one location but have key impacts in another region. The same approach has been applied to the open ocean component of the Transboundary Water Assessment Project, allowing for direct comparison between the LMEs and open ocean assessments.

To understand the relative importance of each stressor for a location, cumulative human impact assessments draw on data that map the intensity of stressors associated with human activities and the vulnerability of each habitat type to each stressor. Stressors affecting marine ecosystems, specifically LMEs and the WPWP, fall mainly into four main categories: climate change, commercial fishing, land-based pollution, and commercial activity (such as shipping). This assessment draws on data for 19 stressors and 20 marine habitats. Data are from a variety of sources that provide globally consistent outputs. Scores for individual stressors and for cumulative human impacts for each LME and the WPWP were calculated by averaging the per-habitat scores for each 1 km^2 pixel within the area of each LME and the WPWP. Risk categories were then assigned, based on the rank order of the CHI scores.

© Kokfoong7/flickr

Key Messages

1. **Stressors associated with climate change, most notably ocean acidification and increasing frequency of anomalously high sea-surface temperatures, are the top stressors for nearly every LME.** However, this result emerges partly from the scale of the assessment. At smaller scales, particularly along coastlines, many other stressors, such as land-based pollution and fishing, play a dominant role.
2. **Commercial shipping and demersal commercial fishing are the other two main stressors at the scale of LMEs.** Stressors associated with these activities tend to affect different parts of the ecosystem, so that where they overlap in space, cumulative impacts are likely to directly affect the entire food web.
3. **In general, LMEs adjacent to heavily populated coastlines, particularly in developed countries that encompass large watersheds, have the highest impact scores.**
    - The most heavily impacted LMEs are adjacent to China and Europe. The most impacted regions also contain most of the highest cumulative impact scores based on assessments at scales smaller than LMEs, indicating a need to improve ecosystem conditions in these regions.
    - The least impacted LMEs are in polar and subarctic regions. However, this assessment does not include projected impacts. Climate change and other human stressors are projected to lead to a rapid increase in polar LME impact scores in the near future.
4. **Efforts to manage marine ecosystems at the scale of LMEs will require coordination not only among countries bordering the LME but also among sectors.** Coordination at the sector scale is critical to successful management because the key stressors are global in nature, and are therefore beyond the scope of what can be identified and addressed through single-sector management. Cumulative human impact assessments provide a tool for transparently and quantitatively informing such policy processes and decisions.

7.7.1 Introduction

For millennia, humans have used the oceans for a wide range of purposes, including obtaining food through fisheries, eliminating wastes, and navigating the planet. In the last century, due to rapid human population growth and the industrial revolution, these uses have become much more intense, widespread, and overlapping. We now live on a planet where no single patch of ocean remains untouched by human activities (Halpern *et al.* 2008), and a vast majority of marine ecosystems experience the impacts of multiple human uses simultaneously.

Because LMEs are coastal regions of the ocean, the confluence of human impacts is generally even more intense, with most coastal waters experiencing significant impacts from land-based pollution, coastal small-scale and commercial fishing, climate change, invasive species, oil and gas development, coastal modification and habitat destruction, and many more stressors. Emerging uses such as offshore aquaculture and wind energy can only exacerbate the impact of overlapping human activities. To understand the condition of LMEs, one must therefore consider the cumulative impacts of multiple stressors – any single-issue indicator, by default, will give an incomplete picture of the overall condition.

Managing multiple stressors is inherently a transboundary challenge, as most stressors cross many national boundaries, including: pollutants travelling through watersheds and pouring into coastal areas; pollutants, invasive species, and other unwanted materials transported by coastal currents and shipping along coastlines; fishing that targets fish stocks straddling EEZ boundaries; and the infrastructure needed to support commercial shipping for global commerce. LMEs provide a valuable lens through which to view these challenges and identify key opportunities for conservation and mitigation.

Cumulative human impact assessments track the changes in intensity of human drivers and their associated stressors and model the expected changes in ecosystem condition in response to these stressors. CHI assessments therefore capture stage 2 (human drivers), stage 3 (associated stress), and stage 4 (ecosystem state) in the conceptual model (Chapter 2, Figure 2.1), spanning both the human and natural system. In combination with the Ocean Health Index, measures of ecosystem service valuation, and governance assessments, a complete picture of LME condition emerges.

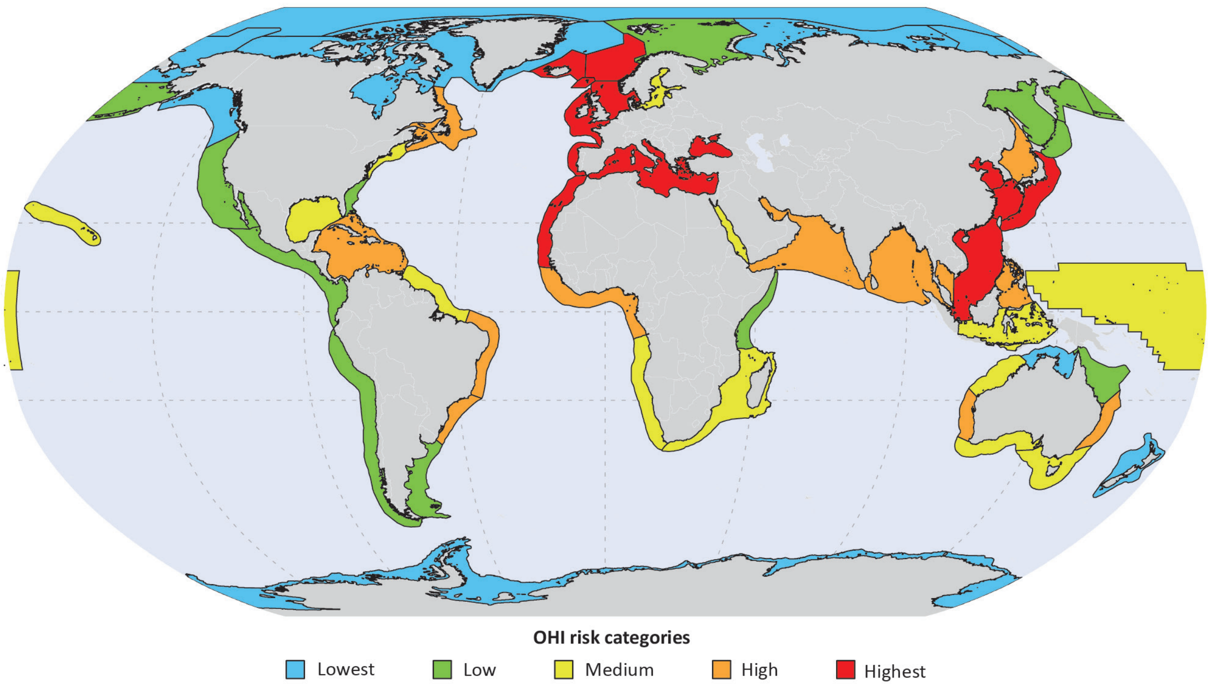
7.7.2 Findings, discussion, and conclusions

Each LME was assigned one of five risk categories based on the rank order of cumulative human impact scores across all LMEs. Nearly all (11 of 13) of the LMEs with the highest average cumulative human impact score are those surrounding Europe and China (the other two are the Kuroshio Current and Canary Current LMEs; see Figure 7.28 and Annex Table 7-A). These high-impact regions are where past studies have shown cumulative impact to be the highest globally (Micheli *et al.* 2013; Halpern *et al.* 2008), indicating a continuing significant need to improve ecosystem condition. In contrast, nearly all (12 of 14) of the LMEs with the lowest average score are in polar or subarctic regions (the other two are the North Australian Shelf and the New Zealand Shelf). This result also follows patterns seen in previous global assessments (Halpern *et al.* 2008). The average cumulative human impact score of the WPWP places it at the 'medium' risk level. It is important to note, however, that cumulative human impact assessments do not account for future risks, such as the projected change and impact to polar regions from climate change and other human stressors that are projected to lead to a rapid increase in polar LME impact scores in the near future.

Patterns of average cumulative human impact in LMEs elsewhere are more varied. Relatively high impact scores are associated with LMEs that fall within the Canadian Atlantic, Caribbean, Brazil, Southeast Asia, and regions around Australia and Japan. Relatively low impact scores are associated with LMEs in the northern Pacific, north-east of Australia, Gulf of California, and regions around the United States and the Pacific side of South America. Within individual LMEs, finer-scale patterns of high impact ('hotspots') and low impact ('coldspots') mainly follow patterns seen previously (Halpern *et al.* 2008), with the highest per-pixel cumulative impact scores in parts of the North, Norwegian, and South and East China Seas (Halpern *et al.* 2015).

Categories of risk for all LMEs are based on quantiles of scores and thus do not represent thresholds of cumulative impact. For example, the cumulative impact score for the highest-scoring LME within the 'high' risk category (4.246: Sulu-Celebes Sea LME) is only 0.07 lower than the lowest-scoring LME within the 'highest' risk category (4.315: Kuroshio Current LME). LMEs in the lower end of each risk category are thus probably similar in risk to those at the

Figure 7.28 Cumulative human impact risk categories of LMEs and the WPWP. LMEs are ranked by the average cumulative human impact scores across the entire region. LMEs in Europe, Northern Africa, and Southeast Asia are at highest risk.



higher end of the risk category below. Because cumulative human impact assessments produce directly comparable quantitative values, the relative difference between any two LMEs can be measured, rather than comparing their risk categories. For example, the LME with the highest impact score (5.222: East China Sea) is 16 per cent higher than the Mediterranean Sea (4.520), which is in turn just 1 per cent higher than the Black Sea (4.476). All three are in the 'highest' risk category.

Of the individual stressors, the ones relating to climate change are the largest contributors to cumulative impact scores. The highest-scoring stressor for every LME and the WPWP is associated with climate change, and the top three stressors in each LME and the WPWP are almost always those connected with climate change: ocean acidification, changes in sea-surface temperature, and increasing UV radiation. These results match recent reports documenting that climate change is already affecting marine ecosystems worldwide. In particular, the 5th report from the IPCC (IPCC 2014) describes widespread changes already occurring across most taxa and in most parts of the world (also reported in Poloczanska *et al.* 2013). Climate change stressors are the only ones that are truly global, and thus have the potential to impact every square kilometre of every single LME and the WPWP. This global scale drives climate change stressors to consistently have the highest impact scores.

Commercial shipping and commercial fishing, in particular using demersal (seabed) gear, also have relatively high single-stressor impact scores for most LMEs. The impact of demersal fishing (including from bottom trawling and high-bycatch non-destructive gear such as traps and gill-nets) has been well documented elsewhere (Bianchi *et al.* 2000). The relatively low impact of this fishing in some LMEs is probably due either to many of the demersal stocks being overfished and thus currently experiencing lower catch (for example, in the Gulf of Mexico LME) or to fisheries management effectively regulating and limiting these fishing practices (for example in the Gulf of Alaska and California Current LMEs).

The impact of commercial shipping is less well recognized but is beginning to gain attention. Studies show that it can be a significant factor in cumulative impact (Halpern *et al.* 2008), contributing to stressors such as noise pollution, invasive species, ship strikes, and inorganic pollution. These effects are widespread, given the growing and truly global nature of commercial ship trade.

Land-based sources of pollution, including nutrient and organic pollution, have relatively low impacts on LMEs, but this is mainly an issue of scale. The vast amount of land that generates these sources of pollution lies mainly within a few hundred very large watersheds that introduce significant amounts of pollutants into the coastal areas immediately adjacent to their river mouths. However, the resulting pollution concentrations decrease rapidly with increasing distance from the river mouths, and surprisingly little coastal area experiences even modest inputs from land-based pollution (Halpern *et al.* 2009). At smaller scales, however, land-based pollution can dominate cumulative impact scores, most notably in wetland and estuarine coastal ecosystems and coastal areas adjacent to very large watersheds, such as the Mississippi River in the US and the Yellow River in China. Increasing coastal development within many LMEs will probably increase coastal habitat modification and loss and increase the pressure on these habitats from land-based pollution. Thus, the question of which stressors have the largest impact on a region necessarily requires an explicit statement of scale, both spatial and temporal. This report describes current stressors at the scale of entire LMEs and the WPWP; at smaller (or larger) scales, the results will be different.

This issue of scale has important implications for policy and management actions. The results presented here are useful for actions at the scale of entire LMEs, such as allocation of funding among different LMEs, and can be used to identify LMEs most in need of conservation and mitigation resources. Within an LME, however, the results will have more limited relevance, and decisions would benefit from a regional analysis focused on smaller-scale outputs. For example, decisions about where or how to allocate funds among countries within an LME, which stressors to mitigate first for particular locations, or which locations to focus on for restoration activities along a coastline within an LME, all require finer-scale data and analyses.

© S.Heileman

Not all pressures are expected to impact all taxa within an ecosystem. Habitat vulnerability weights capture this fact, as they translate stressor intensity into predicted impact on a habitat (for example, a stressor that affects more species has a greater impact on a habitat than another stressor of the same intensity that affects fewer species). Cumulative human impact assessments can therefore be used to identify the consequences of these stressors for food webs, and combining the stressors into a single index is more likely to capture the full impact on food webs than assessments of single stressors.

The social and economic implications of these results are challenging. Most of the main stressors at the scale of LMEs are driven mainly by global forces that are external to the regions. Climate change is fuelled by global emissions, and commercial shipping by global trade and trade routes. Mitigating these stressors requires global efforts. Countries within a given LME can, and need to, play a role in these solutions, but they cannot manage them alone.

© KM & G Morris/flickr

Results from cumulative human impact assessments capture only half of what needs to be known and understood for measuring the condition of LMEs. CHI assessments measure and indicate human activities, their associated stressors, and the expected impacts on ecosystems (see conceptual framework, Chapter 2). Missing from these assessments is how the changes in ecosystem condition affect the delivery of services to people and how that, in turn, affects governance and management decisions. Most marine ecosystem services that people value highly derive from coastal areas. It is in these areas that land-based pollution, invasive species, small-scale fisheries, and most commercial fisheries are having very large impacts on ecosystems. Connecting CHI assessments to scale of delivery of specific ecosystem services to people (instead of to the entire LME) would probably produce very different results and potentially be much more informative.

All indicators rely on the underlying data that informs them. Uncertainty in cumulative human impact assessments is thus dependent on the quality and certainty of all of the input data, including information on habitat extent and the location and intensity of human stressors. Uncertainty is highest at the finest resolution of assessments permitted by these data (1 km^2), with resulting medium certainty in cumulative impact scores at this resolution. At larger scales, in particular at the scale of an entire LME, certainty is rated as high for overall scores, and especially for the relative quantitative difference in scores between LMEs. A full discussion of assumptions and caveats to cumulative human impact assessments in general is provided elsewhere (Halpern and Fujita 2013). Two particularly important assumptions are that impact on ecosystems linearly tracks changes in stressor intensity, and that individual impacts combine additively to create cumulative impacts. Both assumptions are reasonable starting points given current limited understanding.

Cumulative human impact assessments were also made for open ocean systems, providing an opportunity to compare all regions of the world's ocean directly with the same indicator. Similar cumulative human impact assessments have been made for river systems (Vorosmarty *et al.* 2010), and the connection of CHI assessments in LMEs to watershed transboundary assessments is clear and direct (through land-based pollution inputs into coastal waters). Assessment of cumulative human impact within LMEs is thus a powerful tool for linking the assessment of these three water systems.

Cross-system comparisons can be made because CHI assessments are quantitative and measured in the same universal metric of impact on ecosystems. Because CHI assessments are fully transparent in their methods and process, they can easily be repeated (to check results or to update with new data) and they are more amenable to policy and management decisions. Transparency and repeatability are not only hallmarks of the scientific process, they are essential for decision making if it is to be trusted by all parties involved in and affected by the decisions.

7.7.3 Methodology and analysis

Full details on data sources and processing are provided in extensive supplementary information in Halpern *et al.* (2008; 2015). In summary, data layers were developed as follows:

- Sea-surface temperature and UV radiation layers were based on satellite time-series data, and both were processed to assess the number of values that exceed one standard deviation above the long-term average.
- Ocean acidification and sea-level rise were both modelled globally and processed as the difference between current and historic values.
- The five commercial fishing layers were based on spatially-allocated Food and Agriculture Organization (FAO) catch data assigned to one of the five fishing-gear types.
- Artisanal fishing was modelled using FAO catch data for small-scale fisheries and coastal population and marine habitat distributions.
- Three of the land-based pollution layers were obtained by using land-use land-cover data to model nutrient (fertilizer), organic (pesticides) and inorganic (impervious surface area) inputs into watersheds, and then applying a plume model to estimate outputs into coastal waters.
- Oil rigs and light pollution were derived from processing stable lights and night data (from satellites).
- Invasive species were modelled as a coastal plume of port-volume data, based on the assumption that ballast water is a major source of invasive species.
- Commercial shipping was based on voluntary monitoring data from ships and processed into shipping tracks across the ocean.
- Direct human impact (for example trampling on sensitive ecosystems such as coral reefs) was modelled as a function of distance from coastal populations.
- Table 7.13 summarizes key attributes of each stressor and habitat data layer.

Table 7.13 Summary of data layers used to calculate CHI. Note that not all LMEs have each of the habitat types listed.

Data Type	Layer	Native resolution	Source
Stressors			
Land-based	Nutrient input	1 km² (modelled)	FAO country fertilizer data
	Organic pollution	1 km² (modelled)	FAO country pesticide data
	Inorganic pollution	1 km² (modelled)	Impervious surface area
	Direct human	1 km² (modelled)	Coastal human population
Fishing	Demersal, destructive	half-degree	Sea Around Us
	Demersal, non-destructive, high-bycatch	half-degree	Sea Around Us
	Demersal, non-destructive, low-bycatch	half-degree	Sea Around Us
	Pelagic, high-bycatch	half-degree	Sea Around Us
	Pelagic, low-bycatch	half-degree	Sea Around Us
	Artisanal fishing	1 km² (modelled)	Halpern *et al.* 2008
Climate change	Sea-surface temperature	~16 km²	NOAA
	UV radiation	half-degree	NOAA
	Ocean acidification	half-degree	Halpern *et al.* 2008
	Sea-level rise	quarter-degree	Nicholls and Cazenave, 2010
Ocean-based	Oil rigs	1 km²	Halpern *et al.* 2008
	Shipping	~25 km²	VMS AIS data
	Invasive species	1 km² (modelled)	Port volume
	Ocean-based pollution	1 km² (modelled)	Shipping + port volume
Habitats			
Intertidal	Mangroves	1 km²	WCMC
	Rocky intertidal	1 km² (modelled)	Halpern *et al.* 2008
	Beaches	1 km² (modelled)	Halpern *et al.* 2008
	Salt marsh	1 km² (modelled)	Halpern *et al.* 2008
	Mud flats	1 km² (modelled)	Halpern *et al.* 2008
	Sea-ice edge	1 km² (modelled)	NOAA
Nearshore	Coral reefs	1 km²	WCMC
	Kelp forests	1 km² (modelled)	Halpern *et al.* 2008
	Seagrass	1 km²	Halpern *et al.* 2008
	Rocky reef	1 km² (modelled)	Halpern *et al.* 2008
	Suspension reefs	1 km² (modelled)	Halpern *et al.* 2008
	Shallow soft bottom (0–60 m)	1 km² (modelled)	Halpern *et al.* 2008
Offshore	Seamounts	1 km² (modelled)	Halpern *et al.* 2008
	Hard shelf (60–200 m)	1 km² (modelled)	Halpern *et al.* 2008
	Soft shelf (60–200 m)	1 km² (modelled)	Halpern *et al.* 2008
	Hard slope (200–2 000 m)	1 km² (modelled)	Halpern *et al.* 2008
	Soft slope (200–2 000 m)	1 km² (modelled)	Halpern *et al.* 2008
	Hard deep (>2 000 m)	1 km² (modelled)	Halpern *et al.* 2008
	Soft deep (>2 000 m)	1 km² (modelled)	Halpern *et al.* 2008
	Pelagic surface (0–60 m)	1 km²	Halpern *et al.* 2008
	Deep pelagic (>60 m)	1 km²	Halpern *et al.* 2008

Intensity values for each stressor and presence/absence for each habitat layer are processed to be at 1 km^2 resolution, requiring down-scaling for some layers (finer resolution is modelled for data at coarser native resolution). All stressor layers are normalized to their reference, or maximum, value to allow direct comparison of stressors measured in very different units. Finally, normalized stressor intensity values are multiplied by the habitat vulnerability weight unique for each stressor/habitat combination to create a modelled impact score. These scores are summed by habitat type to create a per-habitat cumulative impact score and averaged across habitats to create a final per-pixel cumulative impact score.

Potential thresholds of cumulative impact, where ecosystem condition changes dramatically with small changes in total human impact, are currently not known. LMEs were therefore classified into risk categories based on quantiles. The ‘highest’ risk category includes the 13 LMEs with the highest scores; the ‘high’ risk category includes the next 13 highest scores, and so on. The ‘low’ and ‘lowest’ risk categories include an extra LME, for a total of 66 LMEs plus the WPWP. Table 7.14 lists the cumulative impact scores that defined these risk categories.

Table 7.14 Summary of CHI values per risk category for global LMEs

Risk category	Range of values (CHI score)	Number of LMEs
Lowest	<2.95	14
Low	≥2.95 and <3.50	14
Medium	≥3.50 and <3.86	13
High	≥3.86 and <4.31	13
Highest	≥4.31	13

ACKNOWLEDGEMENTS

Thanks to John Potapenko for previous work developing land-based pollution models, Cotton Rockwood for previous work developing port volume data used for invasive species and ocean pollution models, and Shaun Walbridge for previous work developing the shipping layer.

References

Bianchi, G., Gislason, H., Graham, K. and others (2000). Impact of fishing on size composition and diversity of demersal fish communities. *ICES Journal of Marine Science* 57, 558-571

Halpern, B.S., Walbridge, S. Selkoe, K.A. and others (2008). A global map of human impact on marine ecosystems. *Science* 319, 948-952

Halpern, B.S., Ebert, C.M., Kappel, C.V. (and others) (2009). Global priority areas for incorporating land-sea connections in marine conservation. *Conservation Letters* 2(4), 189-196

Halpern, B.S., Potapenko, J., Best, B.D. and others (2015). Recent spatial and temporal changes in cumulative human impacts on the world's ocean. *Nature Communications* 6 (7615). doi:10.1038/ncomms8615

Halpern, B.S. and Fujita, R. (2013). Assumptions, challenges, and future directions in cumulative impact analysis. *Ecosphere* 4, 131. http://dx.doi.org/10.1890/ES13-00181.1 (accessed 29 June 2015)

Micheli, F., Halpern, B.S., Walbridge, S. and others (2013). Cumulative human impacts on Mediterranean and Black Sea marine ecosystems. *PLoS One* 8, e79889

Nicholls, R.J. and Cazenave, A. (2010). Sea-level rise and its impact on coastal zones. *Science* 328, 1517-1520. doi: 10.1126/science.1185782

Poloczanska, E.S., Brown, C.J. Sydeman, W.J. and others (2013). Climate change imprints on marine life from long-term observations. *Nature Climate Change* doi: 10.1038/NCLIMATE1958

Vorosmarty, C.J., McIntyre, P.B., Gessner, M.O. and others (2010). Global threats to human water security and river biodiversity. *Nature* 467, 555-561

Annex

Annex Table 7-A Full results of CHI and individual stressor impact scores for each LME and the WPWP

True zero values are indicated by zeros without decimal points; zero values with decimal points are extremely low but non-zero scores

a) LMEs

Cumulative human impact		Climate change				Fishing						Ocean industry				Land-based				
LME Name	CHI	Ocean acidification	Sea-level rise	Sea-surface temperature	UV radiation	Artisanal fishing	Demersal destructive fishing	Demersal non-destructive high-bycatch fishing	Demersal non-destructive low-bycatch fishing	Pelagic high-bycatch fishing	Pelagic low-bycatch fishing	Shipping	Ocean-based pollution	Oil rigs	Invasive species	Inorganic pollution	Light pollution	Nutrient pollution	Organic pollution	Direct human impact
Agulhas Current	3.84	1.09	0.06	1.69	0.64	0.00	0.04	0.01	0.02	0.00	0.01	0.10	0.156	0.00	0.00	0.01	0.00	0.00	0.00	0.01
Aleutian Islands	3.05	0.64	0.03	1.29	0.60	0.00	0.09	0.01	0.02	0	0.00	0.14	0.22	0	0.01	0.00	0.00	0.00	0.00	0.00
Antarctic	0.88	0.40	0.06	0.25	0.14	0	0.00	0	0.01	0	0.00	0.01	0.01	0	0.00	0	0	0	0	0
Arabian Sea	4.12	1.00	0.08	1.65	0.61	0.00	0.08	0.06	0.04	0.02	0.02	0.21	0.312	0.00	0.02	0.01	0.00	0.01	0.00	0.01
Baltic Sea	3.65	0.01	0.71	0.99	0.39	0.00	0.02	0.14	0.11	0	0.05	0.36	0.457	0	0.23	0.06	0.01	0.05	0.01	0.07
Barents Sea	3.14	0.83	0.08	1.15	0.45	0.00	0.17	0.18	0.05	0	0.03	0.09	0.097	0	0.01	0.00	0.00	0.00	0.00	0.00
Bay of Bengal	4.00	0.98	0.11	1.59	0.61	0.00	0.15	0.12	0.07	0.10	0.03	0.08	0.124	0.00	0.01	0.01	0.00	0.01	0.00	0.01
Beaufort Sea	0.93	0.54	0.04	0.23	0.11	0.00	0.00	0.00	0	0	0	0.00	0.006	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Benguela Current	3.70	1.05	0.02	1.54	0.64	0.00	0.04	0.03	0.07	0.00	0.00	0.12	0.170	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Black Sea	4.48	0.96	0.18	1.82	0.53	0.00	0.01	0.01	0.06	0.00	0.00	0.33	0.44	0.00	0.04	0.04	0.00	0.03	0.01	0.02
California Current	2.95	0.97	0.01	0.55	0.70	0.00	0.03	0.02	0.04	0.00	0.01	0.25	0.375	0	0.00	0.00	0.00	0.00	0.00	0.00
Canadian Eastern Arctic-West Greenland	2.52	0.59	0.07	1.13	0.42	0.00	0.15	0.02	0.00	0	0.00	0.05	0.072	0	0.01	0.00	0.00	0.00	0.00	0.00
Canadian High Arctic-North Greenland	0.56	0.43	0.00	0.08	0.05	0.00	0.00	0.00	0.00	0	0	0.00	0.00	0	0	0.00	0	0.00	0.00	0
Canary Current	4.63	1.05	0.07	1.82	0.66	0.00	0.07	0.10	0.12	0.01	0.01	0.29	0.404	0.00	0.01	0.01	0.00	0.00	0.00	0.01
Caribbean Sea	4.21	1.11	0.08	1.82	0.52	0.00	0.03	0.02	0.01	0.00	0.00	0.22	0.332	0.00	0.02	0.01	0.00	0.01	0.00	0.01
Celtic-Biscay Shelf	4.64	0.87	0.14	1.67	0.65	0.00	0.20	0.13	0.06	0	0.04	0.40	0.337	0	0.06	0.02	0.00	0.02	0.00	0.03
Central Arctic	0.74	0.73	0	0.01	0.00	0	0.00	0.00	0.00	0	0	0.00	0.00	0	0	0	0	0	0	0
East Bering Sea	3.10	0.58	0.06	1.13	0.73	0.00	0.22	0.04	0.04	0	0.00	0.13	0.169	0	0.00	0.00	0.00	0.00	0.00	0.00
East Brazil Shelf	4.13	1.04	0.10	1.57	0.60	0.00	0.11	0.05	0.03	0.07	0.01	0.19	0.304	0.00	0.01	0.01	0.00	0.02	0.00	0.00
E.-Cent. Australian Shelf	4.08	1.13	0.05	1.65	0.72	0.00	0.02	0.01	0.01	0.00	0.01	0.18	0.272	0	0.00	0.01	0.00	0.00	0.00	0.01
East China Sea	5.22	0.78	0.25	1.46	0.58	0.00	0.56	0.48	0.17	0.02	0.01	0.42	0.397	0.00	0.03	0.02	0.01	0.02	0.00	0.03
East Siberian Sea	1.02	0.36	0	0.28	0.37	0.00	0.00	0.00	0	0	0	0.00	0.001	0	0.00	0.00	0.00	0.00	0.00	0.00
Faroe Plateau	4.79	1.07	0.02	2.16	0.56	0.00	0.36	0.04	0.02	0	0.01	0.25	0.27	0	0.02	0.00	0.00	0	0	0.01
Greenland Sea	2.65	0.92	0.03	1.13	0.35	0.00	0.05	0.02	0.04	0	0.00	0.05	0.061	0	0.00	0	0.00	0	0	0.00
Guinea Current	4.06	1.04	0.10	1.67	0.57	0.00	0.06	0.06	0.04	0.11	0.01	0.15	0.224	0.01	0.01	0.01	0.00	0.00	0.00	0.00
Gulf of Alaska	2.91	0.80	0.04	0.78	0.70	0.00	0.05	0.01	0.02	0	0.00	0.20	0.276	0.00	0.02	0.00	0.00	0.00	0.00	0.01
Gulf of California	3.23	0.88	0.12	1.37	0.38	0.00	0.07	0.01	0.14	0.00	0.00	0.06	0.096	0	0.01	0.02	0.00	0.01	0.01	0.02
Gulf of Mexico	3.81	0.91	0.22	1.41	0.53	0.00	0.08	0.05	0.04	0.01	0.00	0.19	0.285	0.00	0.02	0.01	0.00	0.02	0.00	0.01
Gulf of Thailand	4.03	0.48	0.66	0.99	0.38	0.00	0.43	0.34	0.16	0.00	0.00	0.19	0.252	0.00	0.04	0.02	0.00	0.04	0.01	0.02
Hudson Bay Complex	2.32	0.32	0.27	1.08	0.58	0.00	0.00	0.00	0.00	0	0.00	0.03	0.03	0	0.00	0.00	0.00	0.00	0.00	0.00

Cumulative human impact		Climate change				Fishing						Ocean industry				Land-based				
LME Name	CHI	Ocean acidification	Sea-level rise	Sea-surface temperature	UV radiation	Artisanal fishing	Demersal destructive fishing	Demersal non-destructive high-bycatch fishing	Demersal non-destructive low-bycatch fishing	Pelagic high-bycatch fishing	Pelagic low-bycatch fishing	Shipping	Ocean-based pollution	Oil rigs	Invasive species	Inorganic pollution	Light pollution	Nutrient pollution	Organic pollution	Direct human impact
Humboldt Current	3.01	0.94	0.04	0.88	0.71	0.00	0.05	0.03	0.10	0.00	0.00	0.09	0.151	0.00	0.00	0.01	0.00	0.00	0.00	0.01
Iberian Coastal	4.57	1.04	0.05	1.48	0.64	0.00	0.14	0.09	0.09	0	0.03	0.41	0.505	0	0.03	0.03	0.00	0.02	0.01	0.02
Iceland Shelf and Sea	4.40	0.95	0.04	1.87	0.47	0.00	0.24	0.20	0.15	0	0.05	0.20	0.21	0	0.01	0.00	0.00	0.00	0.00	0.01
Indonesian Sea	3.75	0.89	0.31	1.17	0.46	0.01	0.26	0.18	0.14	0.00	0.04	0.09	0.138	0.00	0.01	0.02	0.00	0.02	0.00	0.02
Insular Pacific-Hawaiian	3.52	1.20	0.01	1.33	0.67	0.00	0.00	0.00	0.01	0.00	0.00	0.12	0.190	0	0.00	0.00	0.00	0.00	0.00	0.00
Kara Sea	1.56	0.49	0.24	0.50	0.30	0.00	0.00	0.00	0.00	0	0	0.01	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Kuroshio Current	4.32	1.10	0.04	1.53	0.63	0.00	0.11	0.09	0.08	0.01	0.02	0.27	0.394	0	0.02	0.01	0.00	0.01	0.00	0.01
Newfoundland-Labrador Shelf	3.86	0.67	0.10	1.58	0.60	0.00	0.24	0.11	0.04	0	0.02	0.24	0.219	0.00	0.02	0.00	0.00	0.00	0.00	0.01
Laptev Sea	0.63	0.25	0	0.21	0.17	0.00	0	0	0	0	0	0	0.000	0	0.00	0.00	0.00	0.00	0.00	0.00
Mediterranean	4.52	1.06	0.08	1.65	0.54	0.00	0.07	0.07	0.06	0.00	0.01	0.38	0.478	0.00	0.04	0.03	0.00	0.02	0.00	0.02
New Zealand Shelf	2.75	1.00	0.07	0.73	0.51	0.00	0.10	0.03	0.01	0.00	0.00	0.12	0.145	0	0.01	0.01	0.00	0.01	0.00	0.01
North Australian Shelf	2.54	0.53	0.65	0.51	0.51	0.00	0.07	0.03	0.02	0.00	0.01	0.08	0.093	0	0.01	0.00	0.00	0.01	0.00	0.00
North Brazil Shelf	3.81	0.84	0.30	1.61	0.53	0.00	0.07	0.04	0.02	0.03	0.00	0.13	0.197	0.00	0.01	0.01	0.00	0.01	0.00	0.01
North Sea	4.87	0.62	0.36	1.44	0.59	0.00	0.38	0.20	0.10	0	0.09	0.45	0.466	0.00	0.10	0.03	0.01	0.03	0.00	0.03
Northeast Australian Shelf	3.42	0.99	0.26	1.26	0.49	0.00	0.01	0.01	0.03	0.00	0.04	0.12	0.192	0	0.01	0.00	0.00	0.00	0.00	0.00
NE US Continental Shelf	3.73	0.52	0.31	1.13	0.47	0.00	0.28	0.11	0.08	0	0.02	0.31	0.294	0	0.09	0.03	0.01	0.02	0.00	0.05
N Bering-Chukchi Seas	1.92	0.46	0.17	0.71	0.36	0.00	0.11	0.02	0.01	0	0.00	0.03	0.033	0	0.00	0.00	0.00	0.00	0.00	0.00
NW Australian Shelf	3.68	0.93	0.23	1.49	0.55	0.00	0.04	0.02	0.01	0.02	0.00	0.16	0.205	0.00	0.01	0.00	0.00	0.00	0.00	0.00
Norwegian Sea	4.41	1.07	0.02	1.90	0.60	0.00	0.14	0.12	0.06	0	0.08	0.17	0.234	0.00	0.01	0.00	0.00	0.00	0.00	0.01
Oyashio Current	3.21	0.78	0.02	0.91	0.76	0.00	0.07	0.03	0.04	0	0.01	0.22	0.342	0	0.00	0.00	0.00	0.00	0.00	0.00
Pacific Central-American Coastal	3.36	0.97	0.03	1.15	0.64	0.00	0.06	0.02	0.03	0.02	0.01	0.16	0.248	0	0.01	0.01	0.00	0.01	0.00	0.01
Patagonian Shelf	2.97	0.71	0.20	0.97	0.68	0.00	0.22	0.04	0.02	0.00	0.00	0.06	0.060	0.00	0.01	0.00	0.00	0.00	0.00	0.00
Red Sea	3.61	0.94	0.31	1.36	0.26	0.00	0.09	0.05	0.03	0.00	0.00	0.22	0.266	0.00	0.04	0.02	0.00	0.01	0.00	0.02
Scotian Shelf	4.00	0.55	0.23	1.55	0.55	0.00	0.17	0.16	0.08	0	0.05	0.30	0.263	0	0.05	0.01	0.00	0.00	0.00	0.02
Sea of Japan	3.91	0.85	0.05	1.58	0.55	0.00	0.19	0.08	0.09	0	0.00	0.19	0.269	0	0.02	0.01	0.00	0.01	0.00	0.01
Sea of Okhotsk	3.15	0.62	0.07	1.02	0.56	0.00	0.45	0.09	0.10	0	0.00	0.10	0.132	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Somali Coastal Current	3.44	1.04	0.05	1.67	0.52	0.00	0.02	0.02	0.01	0.01	0.00	0.03	0.048	0	0.01	0.01	0.00	0.00	0.00	0.01
South Brazil Shelf	3.89	0.94	0.13	1.46	0.60	0.00	0.08	0.05	0.02	0.01	0.01	0.25	0.270	0.00	0.03	0.01	0.00	0.01	0.00	0.01
South China Sea	4.42	0.89	0.24	1.34	0.51	0.00	0.34	0.32	0.13	0.01	0.03	0.24	0.305	0.00	0.01	0.01	0.00	0.02	0.00	0.01
SW Australian Shelf	3.76	0.93	0.15	1.71	0.68	0.00	0.02	0.02	0.00	0.00	0.00	0.09	0.137	0	0.01	0.00	0.00	0.00	0.00	0.00
SE Australian Shelf	3.53	0.98	0.07	1.49	0.72	0.00	0.01	0.01	0.00	0.00	0.00	0.09	0.131	0.000	0.01	0.00	0.00	0.00	0.00	0.00
SE US Continental Shelf	3.38	0.87	0.22	1.04	0.33	0.00	0.09	0.03	0.03	0.00	0.00	0.28	0.382	0	0.04	0.03	0.00	0.02	0.00	0.02
Sulu-Celebes Sea	4.25	1.05	0.17	1.45	0.47	0.01	0.22	0.30	0.15	0.00	0.05	0.11	0.161	0.00	0.02	0.02	0.00	0.01	0.00	0.04
West Bering Sea	3.44	0.65	0.02	1.69	0.69	0.00	0.08	0.02	0.06	0	0.00	0.09	0.143	0	0.00	0.00	0.00	0.00	0.00	0.00
West-Cent. Australian Shelf	3.87	1.03	0.12	1.55	0.70	0.00	0.01	0.01	0.00	0.03	0.00	0.17	0.241	0	0.01	0.00	0.00	0.00	0.00	0.00
Yellow Sea	4.74	0.38	0.64	0.97	0.44	0.00	0.45	0.60	0.21	0	0.00	0.37	0.437	0.00	0.06	0.05	0.01	0.07	0.01	0.04

b) Western Pacific Warm Pool

Cumulative human impact		Climate change				Fishing						Ocean industry				Land-based				
	CHI	Ocean acidification	Sea-level rise	Sea-surface temperature	UV radiation	Artisanal fishing	Demersal destructive fishing	Demersal non-destructive high-bycatch fishing	Demersal non-destructive low-bycatch fishing	Pelagic high-bycatch fishing	Pelagic low-bycatch fishing	Shipping	Ocean-based pollution	Oil rigs	Invasive species	Inorganic pollution	Light pollution	Nutrient pollution	Organic pollution	Direct human impact
WPWP	3.55	1.13	0.01	1.49	0.68	0.00	0.01	0.03	0.04	0.00	0.05	0.04	0.08	0	0.00	0.00	0.00	0.00	0.00	0.00

Chapter 7.8. Ocean Health Index for the world's large marine ecosystems.

Lead Author

Benjamin Halpern (Bren School of Environmental Science and Management, University of California, Santa Barbara)

Contributing Authors

Melanie Frazier; Benjamin Best; Catherine Longo; Julie Stewart Lowndes (National Center for Ecological Analysis and Synthesis, University of California, Santa Barbara)

Chapter Citation

Halpern, B., Frazier, M., Best, B., Longo, C., Stewart Lowndes, J. (2016). Chapter 7.8: Ocean Health Index for the world's large marine ecosystems . In IOC-UNESCO and UNEP (2016). *Large Marine Ecosystems: Status and Trends*. United Nations Environment Programme, Nairobi, pp 239–249.

7.8 Ocean Health Index for the world's large marine ecosystems

SUMMARY

One of the greatest challenges for resource management, including for LMEs, is to understand the condition of human and natural systems within a region and make informed decisions about the best way to improve that condition. Too often, monitoring, assessments, indicator choice, and decisions are made within a single sector or aimed at a single objective, without adequate consideration of the broader implications of proposed actions. Ecosystem-based management and marine spatial planning aim to overcome these management barriers, but there are relatively few tools to inform and support these comprehensive management approaches. Without a tool to measure overall ecosystem health and track progress towards improving it, one cannot effectively manage towards that objective. Together, the five LME modules capture many of the indicators of a healthy ocean ecosystem, but incompletely and without a transparent and quantitative means to combine the various measures. The Ocean Health Index (OHI) was developed in part to address this need.

Using a common framework, the OHI measures progress towards achievement of ten widely-agreed public goals for healthy oceans, including food provision, carbon storage, coastal livelihoods and economies, and biodiversity. Progress towards each goal is assessed against the optimal and sustainable level that can be achieved. Nearly 80 different global data sets spanning ecological, social, economic, and governance measures are used for the assessments. The Index was calculated for each of 221 exclusive economic zones (EEZs), with the EEZ scores averaged on the basis of overlap with each LME to get LME-specific scores. In cases where more than one LME is within the EEZ of one nation, each of the LMEs received the same score. OHI assessments were completed in 2012, 2013, and 2014. Annual updates are planned.

© Storm Surfers 3D=Red Bull Content Pool/flickr

OHI scores for the 66 LMEs in 2014 ranged from 51 to 81 out of 100, with half of all LMEs scoring between 65 and 75. The lowest-scoring LMEs were those along the equator, the highest were around Australia and in the sub-polar North Atlantic. Comparing annual scores for 2012 to 2014, nearly three-quarters of all LMEs had scores in the latter two years that remained unchanged or improved from the previous year, although several LMEs had significant declines in Index scores over the three-year period. LMEs were divided into five risk categories based on their OHI scores.

Key Messages

1. **Nearly all the LMEs that lie along the equator have low OHI scores and are thus in the 'highest' risk category.** This indicates that priority should be given to improving the health of the ocean in these regions.
    - LMEs in the 'highest' risk category: Agulhas Current; Gulf of California; South China Sea; Sulu-Celebes Sea; Pacific Central-American Coastal; Arabian Sea; Benguela Current; Bay of Bengal; Caribbean Sea; Red Sea; Somali Coastal Current.
2. **Tracking how scores for the ten goals contribute to the OHI score for each LME provides insights into which goals drive overall ocean health and which parameters are in most need of improvement.** Examples:
    - For nearly all LMEs, food provision could be improved by increasing the sustainable harvest of fish and the sustainable production of seafood through mariculture. Achieving these outcomes would have important benefits for food security and local economies.
    - Overall ocean health tends to score lower where coastal habitats are degraded or destroyed. Habitat restoration and protection offers a key way to improve ocean health. Coastal habitats play a key role in protecting coastal communities, storing carbon to help mitigate climate change, and supporting biodiversity.
3. **The use of the OHI together with measures of cumulative human impacts provides added insights on conditions in LMEs and can inform management of transboundary issues.** Examples:
    - High cumulative human impacts and low OHI scores (China and Southeast Asia) indicates heavy human use leading to degraded ocean health; managing to reduce human impacts should improve overall ocean health.
    - High cumulative human impacts and high OHI scores (North and Norwegian Seas) indicates high impact translating into sustainable delivery of ocean health benefits; managing to reduce human impacts would improve ecological conditions but not necessarily overall ocean health.
4. **Improving data-reporting standards for all UN member states would improve assessments of ocean health and improve decision making based on those assessments.** In addition, many aspects of ocean health remain poorly monitored, hindering the tracking of ocean health across space and through time.

7.8.1 Introduction

People value ocean ecosystems for the food they provide, their beauty, the livelihoods they support, and the existence and vast diversity of the species within them. Although the relative importance of each of these benefits varies from person to person, the full set of benefits is nearly universal (MA 2003). The ocean enriches our lives in many ways, but when ocean ecosystems are threatened, the sustainable delivery of these benefits begins to erode (Palumbi *et al.* 2009; Worm *et al.* 2006).

LMEs represent the confluence of these values. Coastal regions are extremely productive, contain the vast majority of marine species, house the coastal habitats that protect our shores and sequester carbon, and are where the majority of people on the planet live, work, and play (Agardy *et al.* 2005). Therefore, to assess the condition, or health, of LMEs fairly, one must measure the status of all benefits provided by coastal marine ecosystems. Measuring any one benefit in isolation at best provides an incomplete picture of ocean health, and potentially produces a misleading picture, given that improvements in one benefit may require trade-offs (and thus lower scores) for others (Lester *et al.* 2013).

Managing for ocean health is inherently a transboundary challenge. Many of the benefits we derive from ocean ecosystems rely on processes that cross national boundaries. The cross-boundary benefits include provision of seafood from fish stocks that straddle EEZ boundaries (Maguire *et al.* 2006), international tourism that extends along coastal areas and supports coastal economies (Honey and Krantz 2007), and the existence of iconic ocean species, such as whales, that migrate across boundaries. LMEs provide a valuable lens for viewing these benefits and the associated issues and challenges. Looking through the LME lens helps to identify opportunities to enhance the sustainable delivery of benefits to people, conserve and protect the underlying processes supporting the benefits, and mitigate threats to these processes.

The Ocean Health Index tracks the current status and expected future condition of these human benefits (expressed as goals and sub-goals) from ocean ecosystems. The Index assesses the cumulative stressors on ecosystem services and tracks the resulting status of the sustainable delivery of services to people (Halpern *et al.* 2012). It also incorporates measures of governance to quantify the potential resilience of the system (Halpern *et al.* 2012). The Index thus directly captures stages 4 (ecosystem state), 5 (change in ecosystem service), and 6 (consequences for people) of the LME assessment conceptual framework (Chapter 2, Figure 2.1), and indirectly captures stages 1a (governance) and 3 (stress), thus spanning both the human and natural systems. A complete picture of LME conditions emerges through the use of the Index in combination with cumulative human impact assessments (Chapter 7.7), which directly measure the connection between stage 3 (stress) and stage 4 (ecosystem state) of the conceptual framework, plus ecosystem service valuations, and more comprehensive governance assessments.

7.8.2 Findings, discussion, and conclusions

OHI scores for LMEs globally ranged from 51 to 81 out of 100, with half of all LMEs scoring between 65 and 75, and an average score of 67.1 (Figure 7.29). Even for the highest-scoring LME (Greenland Sea), there is significant room for improvement. Table 7.15 lists and defines the goals and sub-goals that make up the OHI, and Annex Table 7-B provides the scores for each of these goals and sub-goals, as well as the OHI score, for each LME.

Figure 7.29 Ocean Healath Index score by LME. The OHI measures the status and likely state of ten benefits provided by oceans, on a scale from 0 to 10. Scores less than 100 indicate places for improvement towards sustainable delivery of goals. LMEs in the Arctic and around Australia have the highest scores.

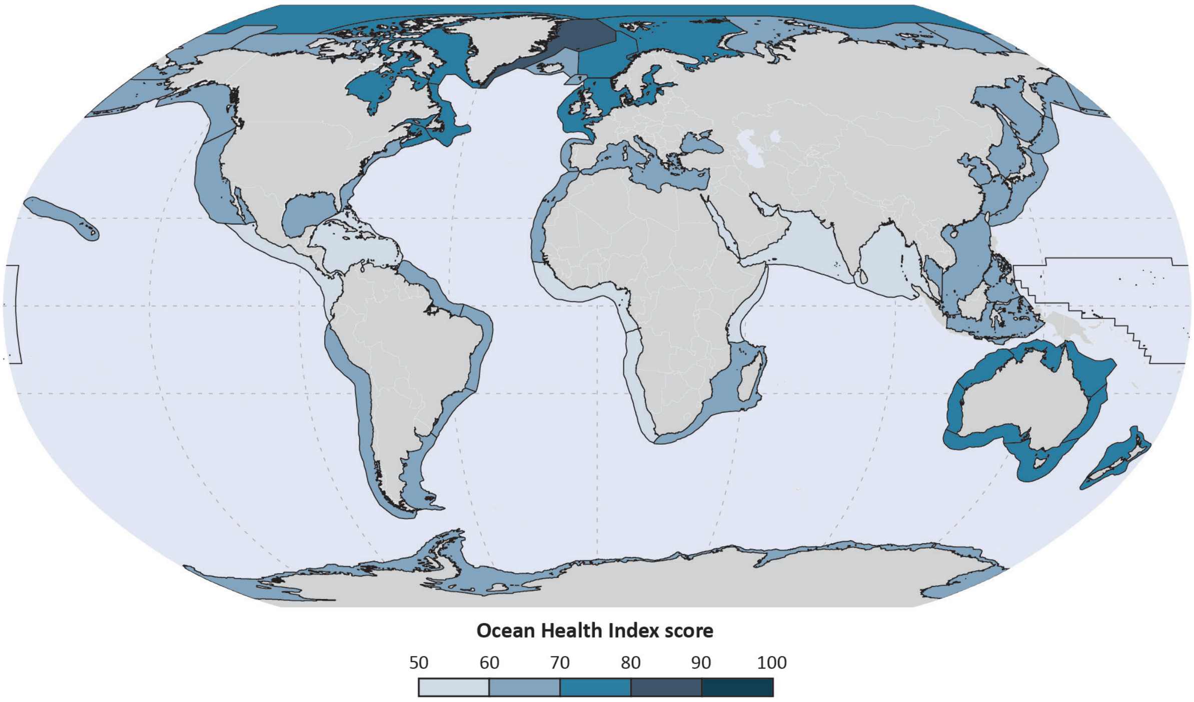
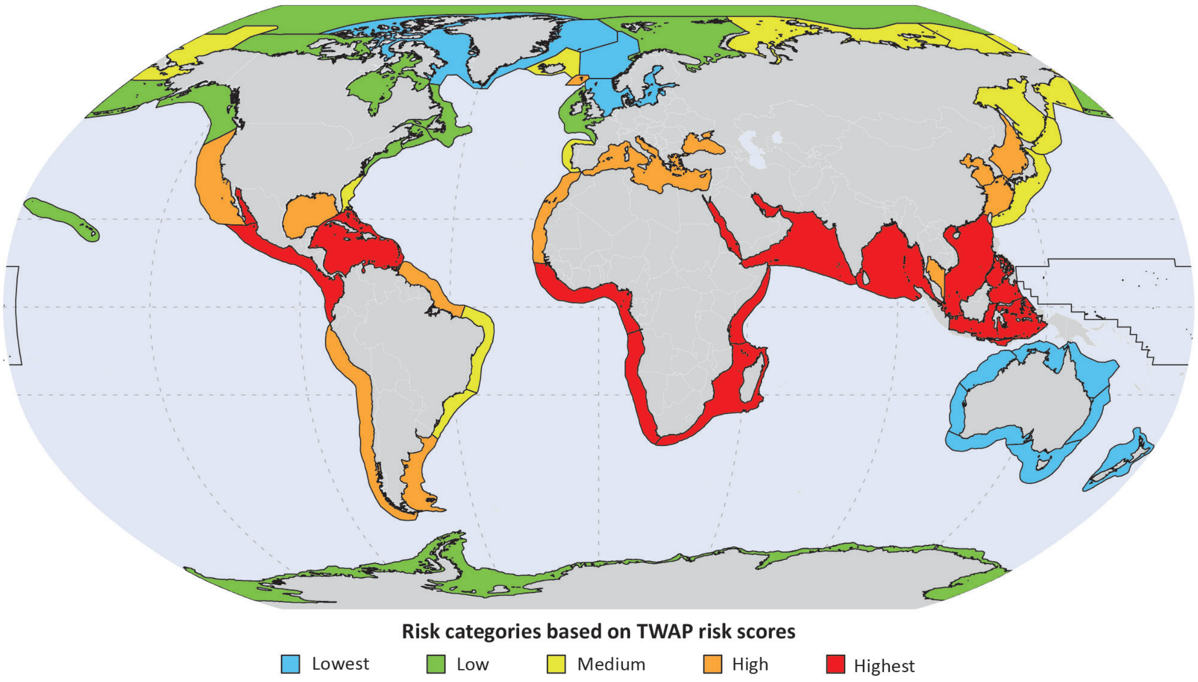


Table 7.15 Definitions of the goals and sub-goals of the Ocean Health Index

Goal	Sub-goal	Definition
Food provision (FP)	Mariculture (MAR)	Production of sustainably cultured seafood
	Fisheries (FIS)	Harvest of sustainably caught wild seafood
Artisanal fishing opportunity (AO)		Opportunity to engage in artisanal-scale fishing for subsistence and/or recreation
Natural products (NP)		Sustainable harvest of natural products, such as shells, algae, and fish oil used for reasons other than food provision
Coastal protection (CP)		Conservation status of natural habitats affording protection of the coast from inundation and erosion
Carbon storage (CS)		Conservation status of natural habitats affording long-lasting carbon storage
Coastal livelihoods and economies (LE)	Coastal livelihoods (LIV)	Jobs and wages from marine-related sectors
	Coastal economies (ECO)	Revenues from marine-related sectors
Tourism and recreation (TR)		Opportunity to enjoy coastal areas for recreation and tourism
Sense of place (SP)	Lasting special places (LSP)	Cultural, spiritual, or aesthetic connection to the environment afforded by coastal and marine places of significance
	Iconic species (ICO)	Cultural, spiritual, or aesthetic connection to the environment afforded by iconic species
Clean waters (CW)		Clean waters that are free from nutrient and chemical pollution, marine debris, and pathogens
Biodiversity (BD)	Species (SPP)	The existence value of biodiversity measured through the conservation status of marine-associated species
	Habitats (HAB)	The existence value of biodiversity measured through the conservation status of habitats

LMEs were divided into five risk categories based on their OHI scores. LMEs were ranked by their scores and divided into five equal groups, from lowest to highest risk, as described in the methodology section. The LMEs with the lowest Index scores, those in the 'highest' risk category, are all located along the equator in Africa, Asia, and the Caribbean (Figure 7.30), emphasizing the need to focus resources on these regions to mitigate further degradation and pursue restoration of ocean health.

Figure 7.30 Ocean Health Index risk category by LME. LMEs in Southeast Asia, the Middle East, Central and Southern Africa, the Caribbean, and Eastern Tropical Pacific have the highest risk.



Patterns for individual goals of the Index (Annex Table 7-B) differ from those seen for overall Index scores. Low scores in food provision tend to correlate with low Index scores, but not always. Some LMEs with the lowest Index scores have the highest food provision scores (for example, Sulu-Celebes Sea). Similar variability exists for natural products and carbon storage goals: scores for these goals show relatively little correlation with overall Index scores. In contrast, overall ocean health within LMEs more closely follows patterns of the goals for coastal protection, tourism and recreation, sense of place, and clean waters. The ability to track if or how individual goals compare and contribute to overall ocean health provides managers, stakeholders, and the general public a key resource for understanding and managing overall ocean health. It offers insights into which goals may be currently driving overall ocean health and which goals scores may be in most need of improvement.

Low goal scores highlight often common-sense but difficult-to-implement solutions for improving conditions. For example, where food provision scores are low, increasing sustainable production of mariculture and improving management of wild-caught stocks to make harvests more sustainable would significantly help to improve scores. Both solutions face difficult political, economic, and social challenges in many places. Similarly, coastal protection, carbon storage, and biodiversity depend strongly on the extent and condition of key habitats. Scores for these goals are low where these habitats have been lost or heavily degraded in the past few decades. Halting this habitat loss and, ideally, restoring significant amounts of habitat area would increase scores across multiple goals.

Most LMEs saw little to no change in overall ocean health between the two most recent assessment years (2013 and 2014), with larger (mostly positive) changes occurring since 2012. Only five LMEs had Index scores change in either direction by more than 2 points between the two most recent years, and only seven LMEs changed by more than 6 points since 2012 (Aleutian Islands, +8 points; East Bering Sea, +8 points; Gulf of Alaska, +7 points; Insular Pacific-Hawaiian, +8 points; Northeast US Continental Shelf, + 8 points; Southeast US Continental Shelf, +7 points; and Beaufort Sea, +6 points). Changes in LME scores were strongly driven by changes in the state of the water (improvements in scores for the clean water goal), which, in turn, were driven to a large extent by annual shifts in the amount of marine debris collected along coastlines worldwide. Thirty LMEs had Index scores decrease in the last year, but only 22 LMEs had scores decrease since 2012.

OHI assessments are comprehensive, but their accuracy depends on the quality of the data used. Data reported to the Food and Agriculture Organization (FAO) by UN member nations (for example on fisheries and natural products) are known to underreport the use of resources and are probably biased, but in ways that are currently unknown (FAO 2014). These data are also commonly revised in subsequent years, so it takes a few years before a given year can be considered ‘final’. Other data sources may vary in quality each year. For example, the marine debris data represent trash collected by volunteers and are influenced by annual differences in effort (OC 2014). Fluctuation in this single data layer has a large effect on the scores for the clean water goal, and ultimately on the overall Index (see discussion above). Finally, some data layers have gaps for certain regions. Gap-filling procedures were used to estimate these missing values (Halpern *et al.* 2015), introducing additional uncertainty.

Caution should be used in drawing strong conclusions or making policy decisions based on differences between risk categories because these categories are simply based on the range of scores divided into groups containing equal numbers of LMEs (quantiles), and, further, because most LMEs had similar scores. This is a particularly important consideration for LMEs in the mid-range of risk categories (‘low’, ‘medium’, and ‘high’). Differences in scores between LMEs in the ‘lowest’ and ‘highest’ risk categories are significant and meaningful. Furthermore, because only two years have been assessed since the 2012 analysis, and only a few regions showed year-to-year changes greater than a few points, it is too early to draw conclusions about trends in ocean health in specific LMEs.

Despite these caveats, results from this assessment offer valuable guidance to managers and policy-makers. First, nearly all aspects of ocean health have room for improvement in all LMEs, but the aspects most in need of improvement across all LMEs would not necessarily be a priority for improving overall ocean health in regions with the lower Index scores. Strategies for improving overall ocean health in LMEs will differ, as they depend on which aspects of ocean health are faring the worst and on the costs and perceived benefits of improving different ocean health aspects, based on the importance people place on each goal. Second, many of the ways that people interact with and benefit from coastal marine ecosystems are at a scale much smaller than the LME, and most actions taken to improve ocean health also happen at these smaller spatial scales (Ruckelshaus *et al.* 2008). Thus, future OHI assessments should be done at the sub-LME scale so that actions at that scale can be as informed and targeted as possible, and so that actions taken at the scale of the whole LME account for potential differences in management actions at smaller scales. Third, and related, the benefits derived from the ocean, and the stressors on these benefits, act at different scales within the LME. Management actions aimed at improving ocean health are most likely to be successful if matched to the scale of the benefit or stressor. For example, many fish stocks span entire LMEs and thus could benefit from LME-scale fisheries management, whereas coastal habitats are patchy and local-scale and thus probably need local or country-level management action to protect and restore habitats. Finally, as noted above, many data gaps remain for many of the LMEs. The comprehensive assessment provided by the OHI offers an efficient way to identify key data gaps by region, thus identifying which regions could benefit from better data collection and reporting to international agencies (for example, FAO).

Differences between results for the OHI and those reported for cumulative human impacts offer important insights into how these two indicators differ and how management can use them in concert to more effectively manage transboundary issues within LMEs. Some LMEs have both high cumulative human impact (poor condition) and low OHI scores, including the LMEs around China and Southeast Asia, indicating that these are regions where heavy human use is leading to widespread degradation of ocean health. These are cases where management aimed at reducing or mitigating cumulative human impact should lead to improvements in ocean health. Other LMEs have high cumulative human impact scores but also high OHI scores, for example in the North and Norwegian seas, suggesting that, in these cases, the high impact is translating into high (and more sustainable) achievement of goals and delivery of benefits. Mitigating cumulative human impacts in these regions will certainly improve ecological conditions (which should help achieve biodiversity and clean waters goals) but may not lead to widespread improvement of ocean health, depending on which actions are taken and which ocean health goals are furthest from being met.

The OHI provides a common framework that can be applied in any context at any scale (Selig *et al.* 2015; Elfes *et al.* 2014; Halpern *et al.* 2014). Because the Index was also used to assess open ocean (high seas) regions within the Transboundary Water Assessment Programme, results can be directly compared between open ocean regions and LMEs. In future, if a similar Index is developed for terrestrial or freshwater systems, comparisons could be made across all ecosystem types.

7.8.3 Methodology and analysis

The OHI measures, on a scale from 0 to 100, the sustainable achievement, now and in the future, of 10 different goals for healthy oceans (Table 7.15). The current status of each aspect is assessed against a reference point (Halpern *et al.* 2012; Samhouri *et al.* 2012) which defines the maximum or optimal sustainable value of the goal, and the overall goal score is determined by combining the current status, recent trend, existing negative cumulative impacts on the goal score, and governance and resilience measures in place (Halpern *et al.* 2012). Reference points for each goal are based on what is possible and sustainable in each country. For example, coastal livelihoods are scaled to the number of people living and working in a country (Samhouri *et al.* 2012). Each goal score is weighted equally when combined to create the single per-region Index score. Although people from different regions (and within regions) probably value different components of ocean health unequally and differently, it was assumed that all goals are of equal importance because no information currently exists on how these values differ regionally. Extensive details on how each parameter is measured and which data are used to calculate the goal scores are provided elsewhere (OHI 2015; Halpern *et al.* 2012 and 2015).

The Index was first calculated for 221 EEZs (Halpern *et al.* 2015). The proportion of overlap of EEZs in each LME was used to calculate an area-weighted average of the EEZ scores to get an LME-specific score. LMEs, therefore, were not directly assessed, but instead were indirectly assessed by combining assessments of their component EEZs. Some countries have multiple LMEs within their EEZ boundaries (for example, US and Australia). In these cases, the LMEs are given the same scores as the EEZ, and are thus identical to each other. Without focused sub-national analyses, differences between these LMEs cannot be determined – but it is highly unlikely they should have the same Index score. Comparisons between these LMEs are therefore not feasible.

Because data and the best available science has improved since the initial assessment by Halpern *et al.* (2012), previous scores were recalculated with new data and methods to allow direct comparison to most recent 2013 and 2014 scores. Year-to-year changes for overall Index and individual goal scores were then calculated simply as the difference between years.

Potential thresholds of OHI scores, where ecosystem condition changes dramatically with small changes in index scores, are currently not known. LMEs were therefore classified into risk categories based on quantiles of the range of observed scores (the 'highest' risk category includes the 13 LMEs with the highest scores, the 'high' risk category includes the next 13 highest scores, and so on). The 'lowest' risk category includes an extra LME, for a total of 66 LMEs. Table 7.16 provides the ranges of Index scores that define these risk categories. It is important to note that the distribution of values is very narrow. The differences in scores among LMEs across all risk categories, but in particular the 'low' through 'high' categories, are relatively small. Caution should be used if decisions are made solely on the basis of risk category assessment.

Table 7.16 Summary of Ocean Health Index values per risk category for all LMEs

Risk category	Range of values (OHI score)	Number of LMEs
Lowest	> 72.5	14
Low	> 68.5 and ≤ 72.5	13
Medium	> 65.25 and ≤ 68.5	13
High	> 62 and ≤ 65.25	13
Highest	≤ 62	13

References

Agardy, T., Alder, J., Dayton, P. (and others) (2005). Chapter 19, Coastal Systems. In: *Ecosystems and Human Well-being*: *Volume 1: Current State and Trends*. (eds. Baker, J., Moreno Casasola, P., Lugo, A. (and others)), 513-549

Elfes, C., Longo, C., Halpern, B.S. (and others) (2014). A regional-scale Ocean Health Index for Brazil. doi: 10.1371/journal.pone.0092589

FAO (2014). *The State of World Fisheries and Aquaculture* 2014. Rome. 223 pages

Halpern, B.S., Longo, C., Hardy, D., (and others) (2012). An index to assess the health and benefits of the global ocean. *Nature* 488, 615-620

Halpern, B.S., Longo, C., Scarborough, C., Hardy, D. and others (2014). Assessing the health of the U.S. west coast with a regional-scale application of the Ocean Health Index. PLoS ONE 9: e98995

Halpern, B.S., Longo, C., Lowndes, J.S.S. and others (2015). Patterns and emerging trends in global ocean health. PLoS ONE. doi:10.1371/journal.pone.0117863

Honey, M. and Krantz, D. (2007). *Global trends in coastal tourism*. Prepared for Marine Program, World Wildlife Fund. Washington DC, USA

Lester, S., Costello, C., Halpern, B.S. and others (2013). Evaluating tradeoffs among ecosystem services to inform marine spatial planning. *Marine Policy* 38, 80-89

MA (2003). *Millennium Ecosystem Assessment, Ecosystems and Human Well-being: A Framework for Assessment*. Island Press, Washington, DC

Maguire, J.-J., Sissenwine, M., Csirke, J. and others (2006). *The state of world highly migratory, straddling and other high seas fishery resources and associated species*. FAO Fisheries Technical Paper 495. Rome, 84 pages

OC (2014). *Turning the tide on trash*. 2014 Report. International Coastal Cleanup. Ocean Conservancy, http://www.oceanconservancy.org/our-work/marine-debris/icc-data-2014.pdf, 28 pages

OHI (2015). OHI-Science: Scientific tools and data for the Ocean Health Index. www.ohi-science.org

Palumbi, S.R., Sandifer, P.A., Allan, J.D. and others (2009). Managing for ocean biodiversity to sustain marine ecosystem services. *Frontiers in Ecology and the Environment* 7, 204-211

Ruckelshaus, M., Klinger, T., Knowlton, N. and DeMaster, D.P. (2008). Marine Ecosystem-based Management in Practice: Scientific and Governance Challenges. *BioScience* 58, 53-63

Samhouri, J.F., Lester, S.E., Selig, E.R. and others (2012). Sea sick? Setting targets to assess ocean health and ecosystem services. *Ecosphere* 3, 41

Selig, E.R., Frazier, M., O'Leary, J.K., Jupiter, S.D. and others (2015). Measuring indicators of ocean health for an island nation: The Ocean Health Index for Fiji. *Ecosystem Services* doi:10.1016/j.ecoser.2014.11.007

Worm, B., Barbier, E.B., Beaumont, N. and others (2006). Impacts of biodiversity loss on ocean ecosystem services. *Science* 314(5800), 787-90

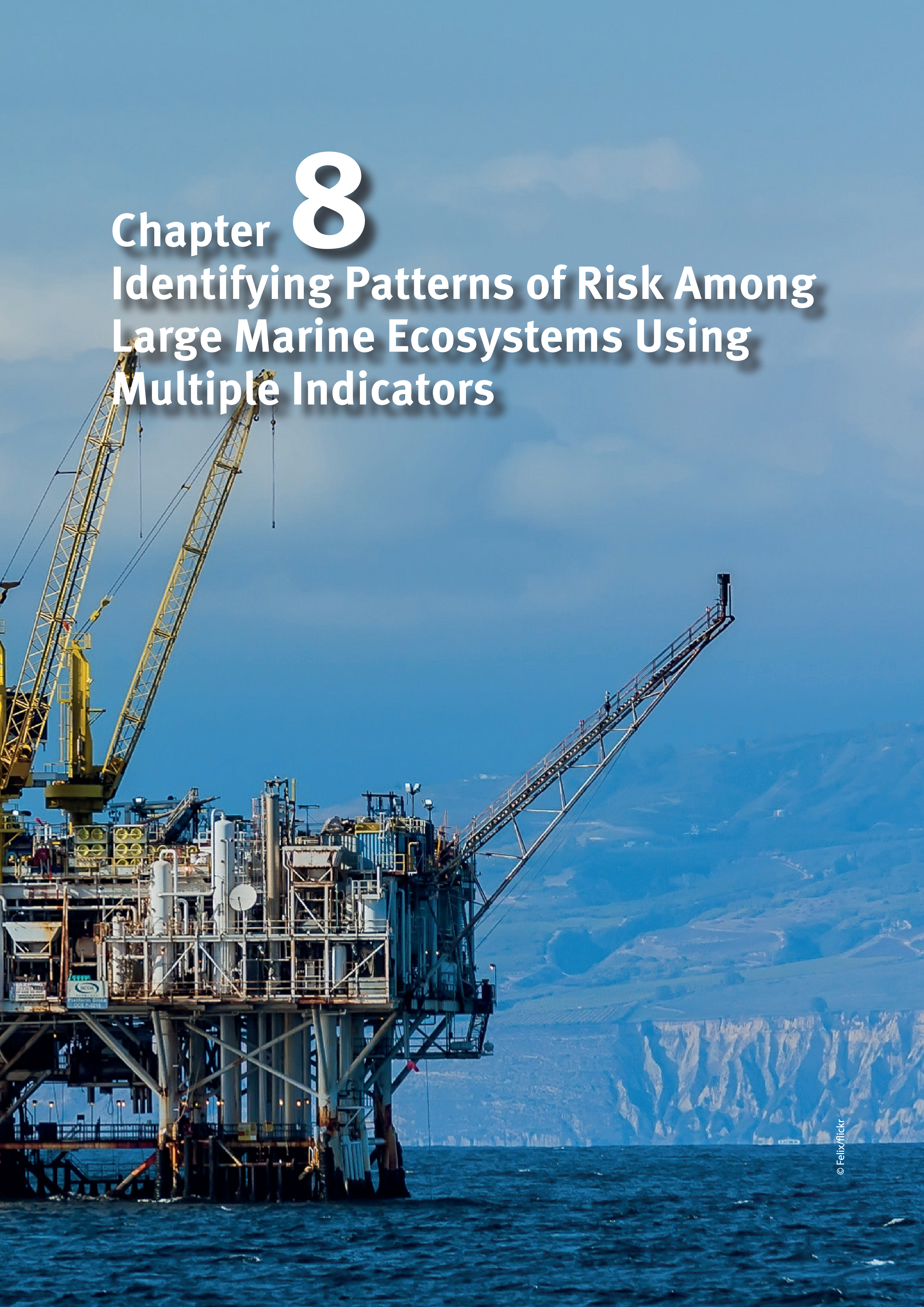
Annex Table 7-B Full results of Ocean Health Index scores and component goal scores for each LME. Index scores are colour-coded by risk category. See Table 7.15 for goal names and abbreviations. Arrows denote the goal index, which is calculated from the sub-goal indices.

Goal		**Food provisioning (FP)**			**AO**	**NP**	**CP**	**CS**	**Livelihoods and economies (LE)**			**TR**	**Sense of place (SP)**			**CW**	**Biodiversity (BD)**		
Sub-goal		**MAR**	**FIS**	↓					**LIV**	**ECO**	↓		**LSP**	**ICO**	↓		**SPP**	**HAB**	↓
LME	*Index*																		
Agulhas Current	61.7	0.4	62.1	61.3	49.8	57.5	50.5	80.8	85.6	98.9	92.3	25.8	46.9	55.5	47.3	64.0	80.2	89.1	84.6
Aleutian Islands	68.9	11.3	53.2	51.5	85.8	44.1	80.1	67.0	55.3	99.9	77.6	45.3	100.0	62.7	81.3	77.0	85.7	73.7	79.7
Antarctic	72.2	–	54.7	54.7	–	29.0	98.6	–	–	82.7	82.7	54.7	1.5	90.4	45.9	100.0	88.4	99.7	93.6
Arabian Sea	58.5	4.6	64.1	62.0	54.5	51.2	52.8	65.6	73.6	95.6	84.6	28.4	38.6	53.4	46.0	56.2	80.6	86.6	83.6
Baltic Sea	74.8	7.4	69.8	66.6	76.6	37.2	94.5	77.6	81.2	98.5	89.9	36.0	99.6	70.4	92.1	83.6	94.1	93.8	93.9
Barents Sea	70.5	44.7	46.5	50.0	80.4	19.9	87.9	100.0	86.0	91.1	88.6	28.8	96.2	68.0	82.1	85.3	87.7	96.8	92.3
Bay of Bengal	57.1	11.4	33.7	32.2	51.1	80.3	49.9	71.6	62.7	94.0	78.4	32.4	40.4	51.3	43.0	54.0	79.8	88.5	84.2
Beaufort Sea	69.8	70.2	58.2	61.2	84.1	50.7	91.8	58.1	74.0	100.0	87.0	28.8	50.2	69.6	59.9	88.0	89.1	87.8	88.5
Benguela Current	57.5	8.3	31.0	31.0	69.9	45.8	19.5	66.0	85.7	76.5	81.1	18.9	77.6	56.6	67.1	76.7	78.3	86.2	82.3
Black Sea	63.4	5.1	70.5	67.1	68.0	26.6	87.3	89.5	81.0	100.0	90.5	19.9	59.1	53.6	56.3	70.3	84.8	94.2	89.5
California Current	65.0	15.6	51.8	49.3	72.1	48.4	57.4	65.4	50.5	100.0	75.2	53.3	100.0	58.2	79.1	69.0	83.7	78.0	80.9
Can. E. Arctic-W. Greenland	75.5	90.5	63.2	65.9	85.9	52.9	96.2	55.0	88.7	100.0	94.3	31.2	61.1	72.2	66.7	91.0	90.1	93.5	91.8
Can. High Arctic-N. Greenland	73.0	90.5	61.6	65.3	84.8	52.9	96.0	55.0	84.8	100.0	92.4	27.3	47.9	72.1	60.0	91.4	90.2	93.1	91.7
Canary Current	63.4	0.5	72.3	72.2	56.2	31.4	35.6	46.4	92.2	89.2	90.7	45.3	71.0	47.1	59.1	64.6	79.0	85.9	82.5
Caribbean Sea	56.7	4.9	33.6	29.8	63.9	31.3	42.1	65.5	74.8	93.8	84.3	40.1	75.3	55.1	65.2	60.5	84.6	75.3	79.9
Celtic-Biscay Shelf	71.0	41.8	71.0	66.8	79.7	70.4	47.4	62.1	69.6	98.6	84.1	52.6	98.7	60.5	79.2	84.8	83.6	82.3	83.0
Central Arctic	71.9	49.0	51.2	53.2	81.1	28.9	94.7	78.2	87.2	99.1	93.2	24.3	73.7	71.8	72.7	87.2	88.5	95.8	92.2
East Bering Sea	68.8	11.0	52.3	50.7	85.3	42.5	80.6	68.3	56.6	99.9	78.2	44.0	99.7	63.1	81.4	77.1	85.7	74.8	80.2
East Brazil Shelf	65.6	4.1	64.6	54.9	62.4	13.6	85.9	93.7	59.7	100.0	79.9	30.2	100.0	55.2	77.6	70.4	81.6	92.5	87.0
East Central Australian Shelf	75.8	11.0	57.6	45.9	90.1	56.2	58.0	91.0	91.3	100.0	95.6	56.5	99.8	73.0	86.4	87.9	86.4	94.4	90.4
East China Sea	64.2	61.4	28.6	49.5	72.5	64.6	67.8	75.6	78.5	99.6	89.1	28.2	60.6	58.2	59.4	50.8	82.1	88.4	85.2
East Siberian Sea	66.5	4.0	31.4	31.3	72.9	4.9	94.3	100.0	86.2	100.0	93.1	11.6	93.3	72.4	82.9	80.8	85.9	99.9	92.9

Goal		**Food provisioning (FP)**			**AO**	**NP**	**CP**	**CS**	**Livelihoods and economies (LE)**			**TR**	**Sense of place (SP)**			**CW**	**Biodiversity (BD)**		
Sub-goal		**MAR**	**FIS**	**↓**					**LIV**	**ECO**	**↓**		**LSP**	**ICO**	**↓**		**SPP**	**HAB**	**↓**
LME	***Index***																		
Faroe Plateau	64.6	98.8	66.1	73.9	88.1	7.8	43.9	55.8	85.7	90.7	88.2	43.1	15.0	64.3	39.7	87.6	82.7	95.0	88.8
Greenland Sea	80.8	97.9	66.8	67.8	88.2	40.3	92.7	–	96.0	94.6	95.3	44.2	99.2	73.7	86.4	89.5	89.6	88.1	88.9
Guinea Current	51.2	0.0	62.9	62.9	49.1	40.9	27.6	47.8	74.1	84.1	79.1	13.7	42.0	57.3	49.6	59.3	77.6	66.3	72.0
Gulf of Alaska	69.4	40.2	55.6	56.3	85.0	47.3	85.8	62.6	64.5	99.9	82.2	37.2	75.5	66.1	70.8	82.4	87.4	80.7	84.0
Gulf of California	61.1	20.0	50.4	47.1	58.5	52.6	34.8	63.8	45.6	100.0	72.8	61.3	100.0	53.8	76.9	61.1	81.8	82.3	82.1
Gulf of Mexico	64.8	15.2	50.5	48.0	72.0	48.3	55.9	66.7	52.1	99.5	75.8	52.3	99.6	58.0	78.8	68.8	83.8	78.2	81.0
Gulf of Thailand	64.9	64.7	48.0	62.4	65.7	68.8	53.5	59.7	70.2	92.0	81.1	56.8	76.3	50.1	63.2	57.0	79.8	81.8	80.8
Hudson Bay Complex	70.1	90.5	59.9	64.6	83.5	52.9	95.9	55.0	80.5	100.0	90.3	23.0	33.0	72.0	52.5	91.7	90.3	92.7	91.5
Humboldt Current	63.2	73.2	74.6	78.7	74.9	17.4	38.7	38.6	94.0	83.0	88.5	26.2	94.6	63.2	78.9	68.2	80.6	82.5	81.6
Iberian Coastal	68.3	15.8	56.6	53.2	71.0	35.5	53.6	54.4	72.7	100.0	86.3	74.9	100.0	56.7	78.4	75.3	81.9	85.4	83.6
Iceland Shelf and Sea	66.9	90.9	60.5	61.1	77.8	38.1	56.6	–	86.0	52.8	69.4	58.5	73.4	65.4	69.4	84.8	85.3	74.5	79.9
Indonesian Sea	61.8	7.4	84.4	76.2	47.5	85.5	58.6	50.2	43.2	99.0	71.1	22.6	85.9	55.3	70.6	59.0	78.8	74.0	76.4
Insular Pacific-Hawaiian	68.9	11.3	53.2	51.5	85.8	44.1	80.1	67.0	55.3	99.9	77.6	45.3	100.0	62.7	81.3	77.0	85.7	73.7	79.7
Kara Sea	66.5	4.0	31.4	31.3	72.9	4.9	94.3	100.0	86.2	100.0	93.1	11.6	93.3	72.4	82.9	80.8	85.9	99.9	92.9
Kuroshio Current	65.8	25.2	29.2	28.5	63.2	40.8	94.6	95.3	57.1	99.4	78.3	22.2	93.6	58.9	76.2	68.7	84.4	96.3	90.3
Laptev Sea	66.5	4.0	31.4	31.3	72.9	4.9	94.3	100.0	86.2	91.9	93.1	11.6	93.3	72.4	82.9	80.8	85.9	99.9	92.9
Mediterranean	64.9	16.2	61.9	51.5	67.5	49.9	46.9	76.0	67.4	99.6	79.6	54.9	66.5	53.5	60.0	75.0	81.3	93.0	87.2
Newfoundland-Labrador Shelf	70.1	90.5	60.0	64.6	83.5	52.9	95.9	55.0	80.7	100.0	90.2	23.2	33.0	72.0	52.5	91.6	90.2	92.8	91.5
New Zealand Shelf	77.6	100.0	48.9	61.3	87.6	76.0	65.7	81.5	100.0	100.0	100.0	61.5	78.9	62.2	70.5	87.3	84.2	85.1	84.6
North Australian Shelf	75.8	11.0	57.5	45.9	90.2	56.1	58.0	91.1	91.2	86.5	95.6	56.5	100.0	73.0	86.5	87.9	86.4	94.5	90.5
North Brazil Shelf	63.2	2.9	39.7	34.6	61.5	15.3	84.5	89.5	64.0	88.7	75.3	29.5	90.9	54.8	72.9	64.5	80.6	92.8	86.7
North Sea	74.8	37.1	67.5	63.9	83.5	58.8	67.5	71.9	80.4	100.0	84.6	60.0	98.8	62.6	80.7	89.1	86.5	87.5	87.0
Northeast Australian Shelf	75.8	11.0	57.6	46.0	90.0	56.3	58.0	91.0	91.3	99.9	95.6	56.5	99.6	72.9	86.3	87.9	86.4	94.4	90.4

Goal		**Food provisioning (FP)**			**AO**	**NP**	**CP**	**CS**	**Livelihoods and economies (LE)**			**TR**	**Sense of place (SP)**			**CW**	**Biodiversity (BD)**		
Sub-goal		**MAR**	**FIS**	↓					**LIV**	**ECO**	↓		**LSP**	**ICO**	↓		**SPP**	**HAB**	↓
LME	***Index***																		
Northeast U.S. Cont. Shelf	69.1	24.7	54.3	53.7	85.4	45.6	82.7	65.0	59.6	100.0	79.7	41.6	88.7	64.3	76.5	79.5	86.5	76.9	81.7
N. Bering-Chukchi Seas	67.6	7.2	41.0	40.3	78.6	22.3	88.0	85.3	72.5	100.0	86.2	26.6	96.3	68.1	82.2	79.1	85.8	88.3	87.0
Northwest Australian Shelf	75.8	11.0	57.5	45.8	90.2	56.1	58.0	91.1	91.2	81.4	95.6	56.5	100.0	73.0	86.5	87.9	86.4	94.5	90.5
Norwegian Sea	74.3	96.9	66.3	72.8	88.5	37.1	76.8	55.8	85.6	100.0	83.5	50.8	89.4	66.8	78.1	90.1	88.7	86.3	87.5
Oyashio Current	66.5	7.7	30.9	30.8	71.2	11.1	94.8	99.3	81.1	99.7	90.5	13.5	94.0	70.1	82.0	78.9	85.7	99.3	92.5
Pacific Central-Amer. Coastal	59.1	20.1	53.8	50.8	59.2	41.6	45.1	54.2	60.6	83.2	80.2	44.3	95.4	54.8	75.1	61.4	82.5	76.6	79.5
Patagonian Shelf	62.3	0.0	43.1	43.1	74.2	50.4	–	–	79.3	82.6	81.2	32.4	59.1	64.6	61.9	65.8	76.5	97.2	86.8
Red Sea	55.4	16.1	67.1	60.8	62.6	20.4	43.6	81.6	73.2	99.9	77.9	17.4	29.8	49.4	39.6	63.5	79.3	94.2	86.7
Scotian Shelf	70.1	90.5	60.0	64.6	83.5	52.9	95.9	55.0	80.6	94.9	90.2	23.1	33.0	72.0	52.5	91.7	90.2	92.8	91.5
Sea of Japan	65.1	21.2	29.4	32.7	67.4	31.6	95.8	97.5	73.1	100.0	84.0	17.4	83.4	65.8	74.6	69.6	83.4	97.9	90.6
Sea of Okhotsk	66.5	4.5	31.3	31.2	72.7	5.7	94.4	99.9	85.6	97.2	92.8	11.9	93.4	72.1	82.7	80.5	85.9	99.8	92.8
Somali Coastal Current	55.1	0.1	70.2	69.9	51.4	44.2	46.3	57.0	95.9	100.0	96.6	9.4	40.1	55.0	47.5	54.9	77.6	69.5	73.6
South Brazil Shelf	65.5	4.1	64.5	55.0	62.5	13.4	85.9	93.7	60.2	83.9	80.1	30.2	99.5	55.2	77.4	70.3	81.5	92.5	87.0
South China Sea	60.4	36.2	50.9	57.2	59.7	78.7	58.4	57.4	64.8	100.0	74.4	31.0	61.5	53.7	57.6	50.3	79.7	79.4	79.6
Southwest Australian Shelf	75.8	11.0	57.5	45.8	90.2	56.1	58.0	91.1	91.2	100.0	95.6	56.5	100.0	73.0	86.5	87.9	86.4	94.5	90.5
Southeast Australian Shelf	75.8	11.0	57.5	45.8	90.2	56.1	58.0	91.1	91.2	99.4	95.6	56.5	100.0	73.0	86.5	87.9	86.4	94.5	90.5
Southeast US Continental Shelf	68.5	9.6	57.5	56.1	83.7	41.2	73.3	67.2	57.5	64.8	78.5	53.7	85.4	62.0	73.7	77.6	86.1	74.2	80.1
Sulu-Celebes Sea	60.1	13.0	86.3	75.1	56.0	87.4	56.3	58.5	44.9	100.0	54.9	26.8	60.9	53.9	57.4	52.0	78.8	75.2	77.0
West Bering Sea	66.6	4.5	32.9	32.7	73.8	7.6	93.3	97.7	84.1	100.0	92.0	14.0	93.8	71.7	82.8	80.5	85.9	98.1	92.0
West Central Australian Shelf	75.8	11.0	57.5	45.8	90.2	56.1	58.0	91.1	91.2	97.0	95.6	56.5	100.0	73.0	86.5	87.9	86.4	94.5	90.5
Yellow Sea	63.9	83.6	27.3	63.0	78.1	82.1	49.8	54.2	92.1	92.1	94.5	31.9	42.3	60.1	51.2	40.3	79.8	84.4	82.1

© Felix/flickr



Chapter 8

Identifying Patterns of Risk Among Large Marine Ecosystems Using Multiple Indicators

© Felix/flickr

Lead Authors

Kristin Kleisner (Sea Around Us, Fisheries Centre, University of British Columbia), Liana Talaue-McManus (Independent consultant, Miami)
(Lead authors contributed equally to the writing and analysis in this chapter).

Contributing Authors

Benjamin Halpern (Bren School of Environmental Science and Management, University of California, Santa Barbara), Peter Kershaw (Centre for Environment, Fisheries and Aquaculture Science, Lowestoft Laboratory; Chair of GESAMP), Vicky Lam (Sea Around Us, Fisheries Centre, University of British Columbia), Kenneth Sherman (National Oceanic and Atmospheric Administration, Northeast Fisheries Science Center).

Other Contributors

B.D. Best, S. Blyth, L. Fanning, M. Frazier, M. Jones, L.C.M. Lebreton, C. Longo, R. Mahon, E. Mayorga, C.McOwen, D. Pauly, S.P. Seitzinger, J.S. Stewart Lowndes

Chapter Citation

Kleisner, K., Talaue-McManus, L., Halpern, B., Kershaw, P., Lam, V., Sherman, K. (2016). Chapter 8: Identifying patterns of risk among large marine ecosystems using multiple indicators. In IOC-UNESCO and UNEP (2016). *Large Marine Ecosystems: Status and Trends. United Nations Environment Programme, Nairobi,* pp 253–287.

Identifying patterns of risk among large marine ecosystems using multiple indicators

SUMMARY

Large marine ecosystems (LMEs) contain the world's most productive and diverse coastal habitats and are subject to pressures from an exponentially growing and increasingly affluent population. LMEs also face challenges from a changing climate. The Transboundary Waters Assessment Programme LMEs component aims to provide a global baseline assessment of the 66 LMEs and to identify those at highest risk of environmental degradation. Previous chapters of this report classify LMEs into risk categories using single indicators or combinations of indicators within one of the five LME modules (Productivity, Fish and Fisheries, Pollution and Ecosystem Health, Socio-economics, and Governance). This chapter applies statistical techniques to identify groups of LMEs based on their similarities across 48 indicators taken from the previous chapters. This large suite of indicators was reduced to a core set of 11 indicators by selecting those that were not strongly correlated with one another and that accounted for the most variance in the data sets. Because the statistical techniques used will only group LMEs and not rank them in any order, an additional scoring analysis was used to assign risk scores and place the LMEs into five risk categories.

The LMEs were first grouped into six clusters based on the 11 selected indicators. The clusters are characterized as follows:

- Cluster 1 – high percentages of rural coastal population, medium to high numbers of collapsed and overexploited fish stocks, and high proportions of fisheries catch from bottom-impacting gear (two subgroups: high-latitude LMEs and LMEs bordering countries with developing economies);
- Cluster 2 – high levels of capacity-enhancing fisheries subsidies;
- Cluster 3 – high rates of increase in marine protected area coverage;
- Cluster 4 – low economic development, high levels of demersal non-destructive low-bycatch fishing, and high concentrations of plastic waste;
- Cluster 5 – moderate to high numbers of collapsed and overexploited fish stocks and very high percentages of catch from bottom-impacting gear;
- Cluster 6 – high levels of shipping activity and the highest levels of demersal non-destructive low-bycatch fishing and pelagic low-bycatch fishing.

Further statistical testing helped visualize the relationships between the LME clusters and the indicators and allowed identification of the dominant indicators. Sixty per cent of the variance in the data set can be explained by 6 of the 11 indicators. Shipping pressure and size of coastal rural populations are the most influential, followed by two fishing indicators: demersal non-destructive low-bycatch fishing, and catch from bottom-impacting gear types. The next most important indicators are extent of capacity-enhancing fishing subsidies, and pollution from plastic debris.

A method for risk scoring is presented as one of several ways that could be used to prioritize LMEs. In this method, the Human Development Index (HDI) is used to measure the socio-economic status of each LME. The assumptions are that LMEs with lower socio-economic development levels will be at higher risk for the same relative levels of environmental degradation, and that socio-economic status may explain the varying capabilities of human populations of LMEs to cope with degraded transboundary waters. The effect of including governance metrics on overall risk was explored in an additional risk-scoring analysis for the 47 inhabited transboundary LMEs. Similar patterns were detected to those found in analyses without governance metrics.

Overall, the analysis presented here is a global comparative assessment intended to provide guidance to the GEF and other policy-makers about groups of LMEs that may need priority intervention. It does not provide fine-scale regional interpretations of LME status, but does allow a broad and general understanding of the environmental and economic status of the LMEs. In addition, the indicators, which are drawn from the LME module assessments, are a subset of the possible indicators that could be used for integrated assessments. Other indicators may provide different risk categorizations of particular LMEs. Finally, each of the indicators used in this analysis is calculated at the LME level and does not necessarily reflect the situation in any individual country's Exclusive Economic Zone (EEZ) within an LME.

Key messages

1. **Socio-economic development has a strong influence in the ranking of LMEs by overall risk.** Based on the 11 indicators used in this analysis:
    - LMEs with developing economies show highest risks from coastal eutrophication and plastic litter density, and moderate to high risks from collapsed and overexploited fish stocks;
    - LMEs along the coasts of developed nations have lower overall risk scores but may be at risk from a combination of high shipping frequencies, high capacity-enhancing fisheries subsidies, high use of bottom-impacting fishing gear, and from pelagic and demersal low-bycatch fishing pressure.
2. **Grouping the LMEs by similarities in multiple indicator values and ranking the LMEs by overall risk scores provides insight into patterns of risk.** Some patterns identified:
    - The clustering of LMEs by similarities in the 11 indicator values does not broadly correspond with the LME risk ranks. The exception is the Australian shelf LMEs, which are all in cluster 3 and all ranked in the 'lowest' risk category;
    - LMEs bordered by developing countries in Africa and Asia (in clusters 1 and 4), are rated as 'highest' risk;
    - LMEs in developed countries with either mainly rural coastal populations or the most-frequented shipping routes (found in clusters 1 and 6) make up the 'medium' risk category;
    - The coastal waters of the US and Canadian LMEs (in clusters 1, 5, and 6) are rated 'low' risk, and the Australian and New Zealand Shelf LMEs are assessed as 'lowest' risk.
3. **Weak points and gaps in the assessment are identified and recommendations provided for improving assessment of transboundary water systems.** The multivariate and risk-scoring techniques used provide complementary approaches to delineating LMEs at risk, through the simultaneous use of multiple indicators that measure biophysical, socio-economic, and governance pressures and states. These analyses constitute a Level 1 assessment for which the use of data sets with global spatial coverage is a priority. A Level 2 assessment, which focuses on transboundary environmental issues, would make use of more finely resolved indicators and evaluations, which could include:
    - spatially explicit and time-varying indicators that address gaps in the conceptual frameworks used in this report and provide an indication of trends in status;
    - metrics that address changes in ecosystem services due to climate and societal pressures and their impact on livelihoods and ecosystems;
    - improvements in the scale and quality of reporting of fisheries data, and improvement of the techniques for evaluating the status and trends of global fisheries biomass;
    - incorporation of economic considerations into metrics for pollution and ecosystem health;
    - assessment of how changes in land use and land cover influence material flows from land to sea, and how they may cause modifications in the structure and functioning of marine food webs;
    - tools and indicators such as poverty maps for coastal and inland areas and regionalized input-output models that track the response of marine industries to changes in climate and governance;
    - finer-scale alternatives to the use of the HDI (a national metric); and
    - evaluation of governance performance to complement the current indicators of government architecture.

8.1 Introduction

One of the two goals of the Transboundary Waters Assessment Programme (TWAP) is to conduct a baseline global assessment of five transboundary water system categories: (1) large marine ecosystems (LMEs), (2) open oceans, (3) groundwater, (4) river basins, and (5) lakes and reservoirs, with the aim of providing guidance to the Global Environment Facility (GEF) and other stakeholders for prioritization of interventions within these systems. With the exception of the open oceans, these assessments are comparative and group the systems into five risk categories (from low to high) based on a suite of indicators.

Previous chapters in this report classify LMEs into risk categories using single indicators or combinations of indicators within one of the five LME modules (Productivity, Fish and Fisheries, Pollution and Ecosystem Health, Socio-economics, and Governance). This chapter applies classification and ordination techniques to multiple indicators to identify groups of LMEs based on their similarities across a suite of multivariate indicators using this classification. Because classification and ordination will only group LMEs and will not provide a priority ranking scheme, an additional scoring analysis is used to place the LMEs into five risk categories. The analysis assumes that among LMEs with similar levels of environmental degradation, those with lower socio-economic development levels measured by the HDI will be at higher risk; and those with higher HDI will be at lower risk. This risk-scoring analysis is then compared with another multivariate approach to assessing and ranking LMEs, the Ocean Health Index (OHI; see Chapter 7.8), to see if the two techniques provide similar results.

Risk in this chapter is defined broadly as the probability of adverse consequences for humans and the environment in relation to the changing states of transboundary waters. Triggers of risk are usually not single but related, and may include biophysical, socio-economic, or governance-related factors in some combination. While a large suite of indicators is available to measure various aspects of ecosystem health, only indicators that clearly distinguish between poor status and good status are used, thereby eliminating the indicators in the Productivity module from this multivariate analysis. Also, since the aim was to cluster all 66 LMEs, the Governance module is excluded from the clustering and ordination analysis because the governance assessment includes only transboundary LMEs. However, the influence of the governance indicators is considered when defining the risk classifications for the transboundary LMEs. Overall, 11 indicators across three modules that gauge the states of Fish and Fisheries, Pollution and Ecosystem Health, and Socio-economics are used to discriminate LME clusters. The nature of these clusters informs the identification of LMEs of potential interest for policy and management interventions. The risk categorization provides an interpretation of the priority status of the LMEs within a human developmental framework. Details of the methodology are given following the results section.

8.1.1 Analytical frameworks for assessing large marine ecosystems

Building on the five LME modules, an overarching conceptual framework was developed to illustrate the links between human vulnerability and natural and anthropogenic stressors, ecosystem services, and consequences for humans (with governance as an overarching concept), so that cause and effect could be better identified, and ecosystem services accommodated (see Figure 2.1). The LME modular approach and the conceptual framework provide a context for the multivariate classification of LMEs into risk categories in this chapter.

Indicators within the Governance and Socio-economic modules describe the features of the human system. Indicators within the Productivity, Fish and Fisheries, and Pollution and Ecosystem Health modules describe the natural ecosystem. This chapter presents the multivariate (multi-indicator) statistical analyses that were used to analyse a set of suitable indicators chosen from 48 indicators for each of the five modules in the LME analytical framework. Details on individual indicators are presented in the respective module chapters of this report. The suite of indicators used in this analysis is subject to its own limitations in terms of scope, data quality, and scale. However, the indicators were selected to be representative across each of the modules for the purpose of providing guidance to the GEF about groups of LMEs that may need priority interventions. The selection of indicators was constrained by the availability of the global data sets needed for a global comparative assessment.

8.2 Results, discussion, and conclusions

8.2.1 Selection of indicators for the multivariate analysis

The indicators used to analyse the biophysical, governance, and socio-economic states of LMEs vary in their ability to indicate risk, and in their geographical coverage. To optimize the discriminatory power of the multivariate analysis, indicators that were strongly directional in indicating 'good' or 'bad' ecosystems states, and that were assessed for at least 60 of the 66 LMEs, were chosen (23 of 48 indicators from Annex Table 8-A). The indicators from this initial selection were examined for significant correlations (Annex Table 8-B). Seven indicators that were not significantly correlated with other indicators across the full suite were retained for the final analysis: pelagic low-bycatch, proportion of collapsed and overexploited stocks, capacity-enhancing subsidies as a fraction of the value of fisheries, proportion of catch from bottom-impacting gear, index of coastal eutrophication potential, plastic debris density, and percentage change in area of marine protected areas (MPAs).

Next, the indicators were examined for their variance within each module (Annex Table 8-C). The indicator that explained the greatest variance for each module was retained: demersal non-destructive low-bycatch fishing (Fish and Fisheries module), shipping pressure (Pollution and Ecosystem Health module), and percentage rural population within 100 km of the coast (Socio-economics module). Additionally, the Night Light Development Index was retained because it is a spatial proxy of economic development and was only strongly correlated with the Human Development Index (HDI). Both these indices represent economic development status, but HDI was correlated with the indicator pelagic high-bycatch fishing, and is therefore less suitable for the clustering and ordination analyses. This elimination of redundant indicators was performed under the assumption that the final selected indicators were statistically representative of the full suite within the multivariate domain. Indicators selected for the multivariate analyses are listed in Table 8.1.

Table 8.1 Indicators selected for the multivariate analysis. The chapter numbers refer to chapters in this volume. All 48 indicators used in thematic analyses (including the 11 indicators in this table), are listed in Annex Table 8-A.

Module	Indicator name	Abbreviation	Source
Fish and Fisherie	Pelagic low-bycatch fishing	*PLB*	Halpern and Frazier (Chapter 7.7)
	Proportion of collapsed and overexploited stocks	*COE*	Pauly and Lam (Chapter 6.l)
	Capacity-enhancing subsidies as a fraction of the value of fisheries	*SUB*	Pauly and Lam (Chapter 6.l)
	Proportion of catch from bottom-impacting gear	*Cat Bot*	Pauly and Lam (Chapter 6.l)
	Demersal non-destructive low-bycatch fishing	*Dem Ndes LB*	Halpern and Frazier (Chapter 7.7)
Pollution and Ecosystem Health	Index of coastal eutrophication potential	*CEut*	Seitzinger and Mayorga (Chapter 7.3)
	Plastic debris density	*Plastic*	Kershaw and Lebreton (Chapter 7.1)
	Percentage change in area of MPAs	*MPA Area*	Jones *et al.* (Chapter 7.6)
	Shipping pressure	*Ship*	Halpern and Frazier (Chapter 7.7)
Socio-economics	Percentage rural population within 100 km of the coast	*Rur Pop*	Talaue-McManus and Estevanez (Chapter 3)
	Night Light Development Index	*NLDI*	Talaue-McManus and Estevanez (Chapter 3)

The indicators were normalized by subtracting the minimum value across all LMEs for a given indicator and dividing by the difference between the maximum and minimum values (thereby rescaling values from 0 to 1). These normalized values were used for all subsequent numerical analyses, including the multivariate techniques and the risk-scoring analyses. De-trending among these indicators was not necessary because the input data are not time-series.

8.2.2 Associating chosen indicators with levels of risk

Risk, as defined earlier, is the probability of adverse consequences on humans and ecosystems triggered by the changing states of transboundary waters. Many of the indicators developed in the previous chapters have a direct relationship with risk. Risks associated with fisheries due to damaging gears, economic subsidies, and collapsing fish stocks are obvious, as are those associated with shipping, coastal eutrophication and floating plastics.

For other indicators, such as for marine protected areas, associated risk may be less direct. The change in extent of MPAs is associated with the value of these areas as recovery zones to buffer ecosystem change, and the assumption is made that buffering, by allowing ecosystem recovery, reduces risk. Management policies would have to include the socio-economic consequences of restricting the extent of economic activities in these zones to obtain optimal net benefits for ecosystems and humans. Marine spatial planning is allowing managers to systematically examine such trade-offs.

Socio-economic metrics, such as percentage of rural population, are often used to indicate the extent to which livelihoods based on natural resources (such as fisheries and agriculture) may underpin a region's economy. A high degree of economic dependence on natural resources may imply high risk when governance is weak and human well-being is compromised. Uneven distribution of spatial economic activity, as measured by the Night Light Development Index, may act as a proxy for multiple types of unevenness, including uneven access to natural resources, markets, and population centres. High unevenness in the NLDI can therefore be associated with high risk.

Socio-economic indicators are used in the TWAP Level 1 assessment methodology to characterize human populations and the manner in which they influence the environmental states of transboundary water systems, including LMEs. Governance responses that aim to mitigate effects of ecosystem change on socio-economic states require integrated and broad policy approaches. Direct policy responses would be improvements in governance architecture (using particular legal or best-practice arrangements) to minimize risks by mitigating adverse impacts. Formal governance arrangements are assessed in this report using three indicators: integration of institutions, completeness of the stages of the policy process, and engagement of countries in governance arrangements (see Fanning *et al.*, this report). Each of the three indicators is assumed to have an inverse relationship with risk, for example, the more complete the policy stages are for an arrangement, the lower the risk.

The aim of establishing associations between the indicators used in this analysis and the levels of risk is to provide guidance to the GEF in identifying LMEs at varying levels of risk. Development of policy options, including economic trade-offs, to reduce these risks, is beyond the scope of this report.

8.2.3 LME classification and ordination

8.2.3.1 Cluster analysis

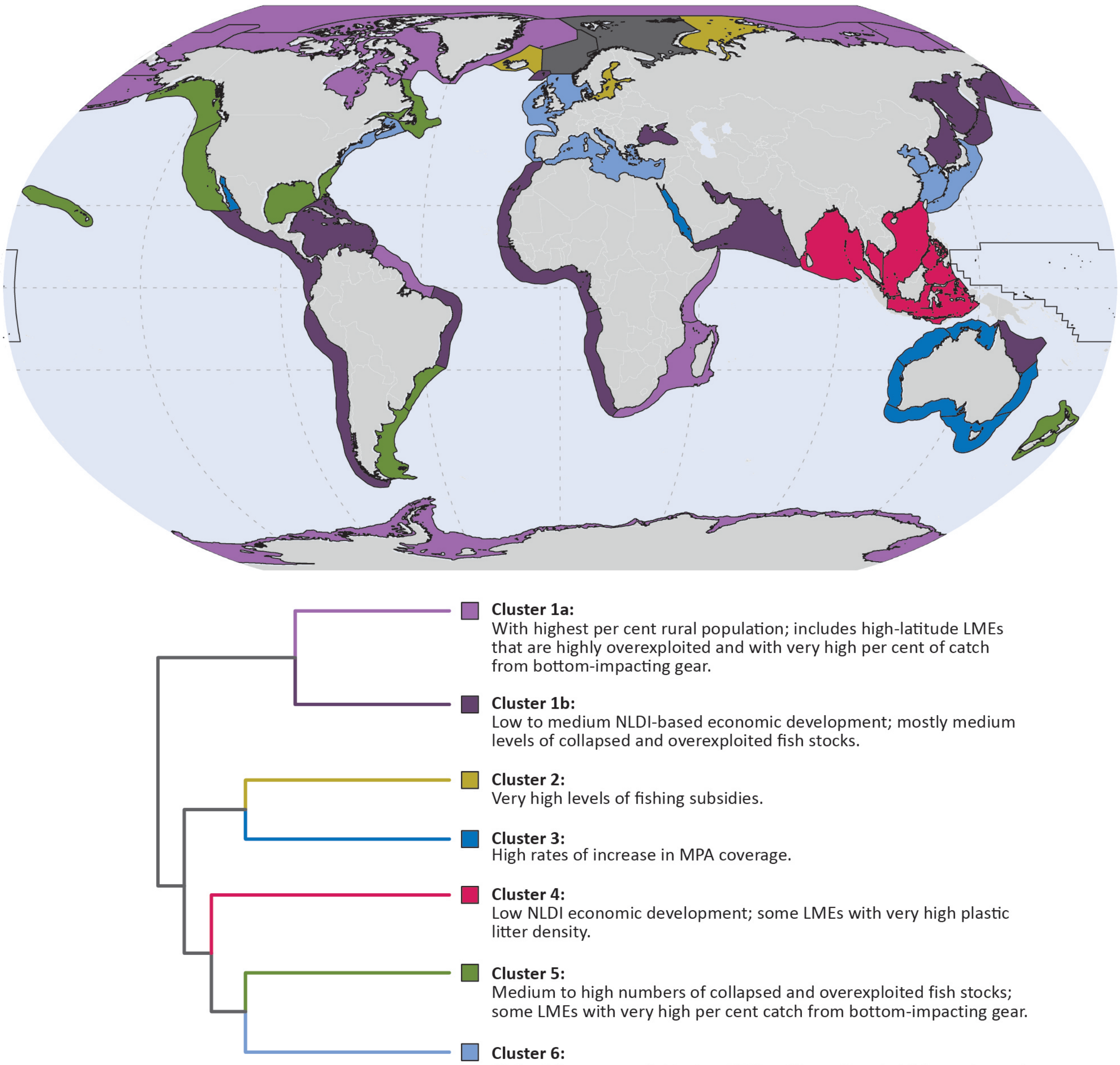
Agglomerative Hierarchical Clustering Analysis (Box 8.1) was used to divide the LMEs into six groups (clusters), as shown in Figure 8.1 (also see Annex Figure 8-A). These clusters maximize differences between, and similarities within, main groups. Note that the groups defined by the clustering and the principal components analyses discussed below do not order or rank the LMEs and cannot be used to define categories that spread over a spectrum from low risk to high risk. Instead, the clusters indicate groups of LMEs that display shared characteristics.

Box 8.1 Overview of statistical techniques

Cluster analysis is a set of multivariate statistical techniques for grouping objects (in this case, LMEs) that are similar. The specific methodology used in this chapter is **Agglomerative Hierarchical Clustering Analysis**. A hierarchy of LME groupings is developed, based on similarities of the values of variables (in this case, the 11 multivariate indicators). This hierarchical arrangement of LMEs is represented graphically in a **dendrogram or tree diagram (**Figure 8.1**)**.

Classification and ordination techniques order objects (LMEs) that are associated with values for multiple variables (indicators). The analysis brings out the patterns in a data set. Similar objects are placed near each other, and objects that are dissimilar are placed further away. **Principal Components Analysis** is the ordination methodology used in this chapter. It develops new sets of variables (principal components (PCs)) based on the variance of the values of the original variables (the 11 indicators). The first PC accounts for as much of the overall variance as possible, the second PC accounts for as much of the remaining variance as possible, and so on. The results can be visualized through a **biplot** (Annex Figure 8-B) which has the top two principal components as x- and y-axes and plots the objects (the LMEs) as positions and the variables (the indicators) as vectors. The biplot shows how the LMEs are positioned in relation to one another and to the indicators.

Figure 8.1 LME clusters and their distinguishing features. Clusters are based on the 11 strongly directional indicators used in the multivariate analysis. LMEs included in the analysis but not in the detailed results are shaded grey.



■ **Cluster 1a:**
With highest per cent rural population; includes high-latitude LMEs that are highly overexploited and with very high per cent of catch from bottom-impacting gear.

■ **Cluster 1b:**
Low to medium NLDI-based economic development; mostly medium levels of collapsed and overexploited fish stocks.

■ **Cluster 2:**
Very high levels of fishing subsidies.

■ **Cluster 3:**
High rates of increase in MPA coverage.

■ **Cluster 4:**
Low NLDI economic development; some LMEs with very high plastic litter density.

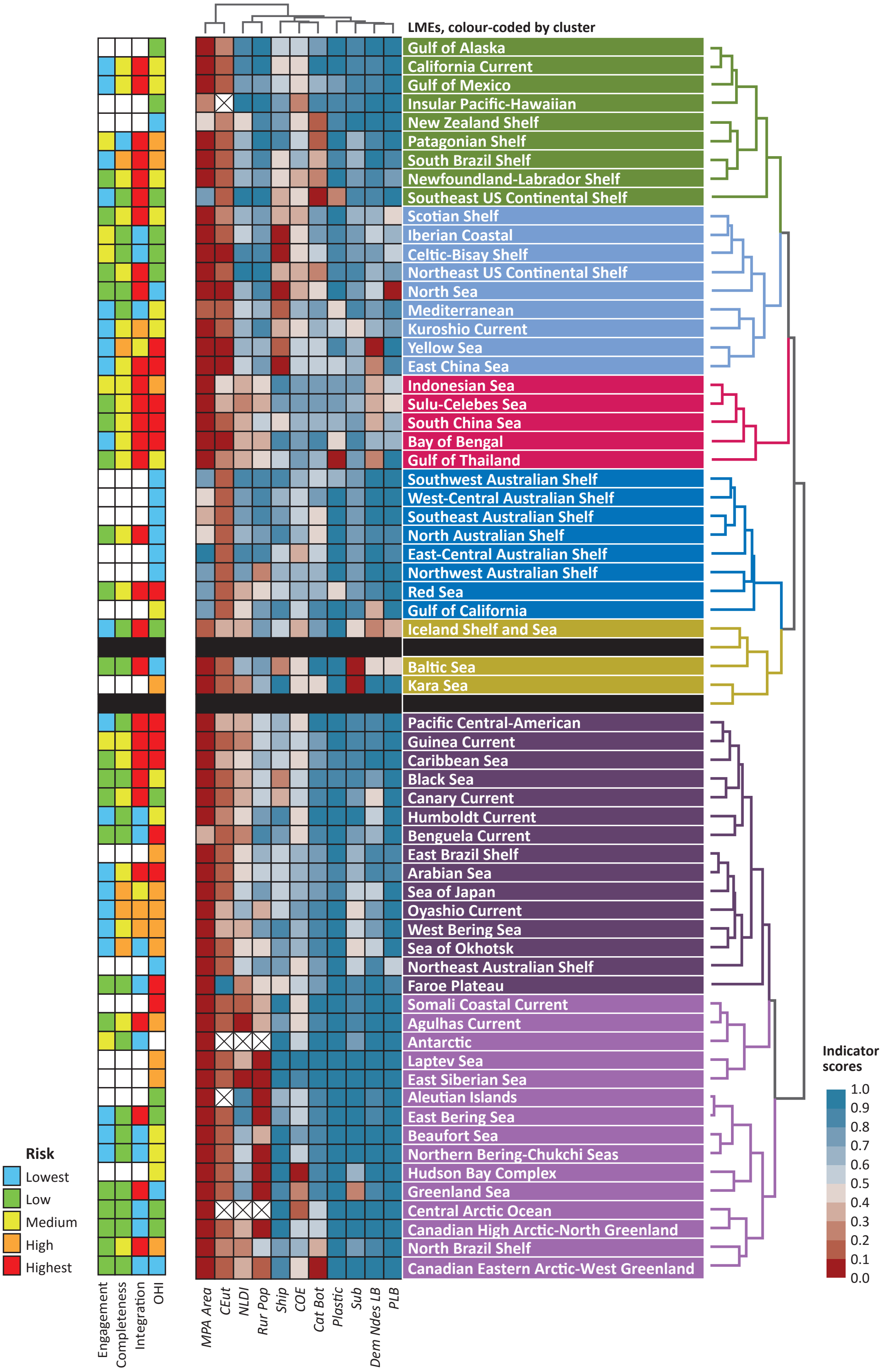
■ **Cluster 5:**
Medium to high numbers of collapsed and overexploited fish stocks; some LMEs with very high per cent catch from bottom-impacting gear.

■ **Cluster 6:**
Highest frequency of shipping; LMEs with medium to high numbers of collapsed and overexploited fish stocks.

The LMEs can also be grouped into these six clusters by plotting them by PCs (see Box 8.1), with PC1 along the x-axis and PC2 along the y-axis, as shown in Annex Figure 8-B. The clusters that result from this analysis, and the influence of each of the 11 indicators on the classification, can also be visualized using a heat map dendrogram (Figure 8.2), which displays not only the LME clusters but also the values of the indicator scores from 0.0 to 1.0. The indicator values are visualized using colour, as is done when showing temperature variations in space using heat maps. Together, these graphics highlight the key features of each LME cluster, described below.

Cluster 1: LMEs in this largest grouping are characterized by high percentages of rural coastal population (*Rur Pop*), medium to high numbers of collapsed and overexploited fish stocks (*COE*), and high proportions of catch from bottom impacting gear (*Cat Bot*). Cluster 1 includes (1a) high-latitude regions such as the High and Central Arctic LMEs, the Hudson Bay Complex and the Antarctic; and (1b) developing-economy regions such as the Agulhas, Somali, and Benguela Currents, and the Arabian and Caribbean Sea LMEs.

Figure 8.2 Heat map of indicator scores, risk categories of governance metrics, and the Ocean Health Index. Governance metrics are engagement, completeness, and integration. Standardized indicator scores used for the heat map are in Annex Table 8-G. LMEs included in the analysis but not in the detailed results are shaded black.



Cluster 2 consists of LMEs significantly influenced by capacity-enhancing fisheries subsidies (*SUB*). They include the Baltic Sea, Iceland Shelf and Sea, and the Kara Sea. While this cluster is characterized by highly subsidized fisheries, this result is not exclusive to this grouping. Highly subsidized fisheries predominate in LMEs in other clusters, notably the Greenland Sea LME in Cluster 1a and the Kuroshio Current LME in Cluster 6.

Cluster 3 is characterized by high rates of increase in MPA coverage (*MPA Area*) over the period 1980 to 2014. This cluster includes six of the seven Australian shelves LMEs (the exception is the Northeast Australia Shelf LME which is in Cluster 1a), the Gulf of California LME, and the Red Sea LME. Some of the LMEs, however, also exhibit less desirable features, including significant numbers of collapsed and overexploited fish stocks (*COE*) in the East-Central Australian Shelf LME, moderate levels of catch from bottom-impacting gear (*Cat Bot*) in the North and Southeast Australian LMEs, and moderate concentrations of plastic litter (*Plastic*) in the Red Sea LME.

Cluster 4 is analogous to Cluster 1b in featuring LMEs with low NLDI-based economic development (*NLDI*). In addition, the coastal waters of the Gulf of Thailand LMEs, and the South China, Indonesian, and Sulu-Celebes Seas LMEs, exhibit high levels of demersal non-destructive low-bycatch fishing (*Dem Ndes LB*). The Bay of Bengal and Gulf of Thailand LMEs are also impacted by high to very high concentrations, respectively, of plastic waste (*Plastic*).

Cluster 5 consists of LMEs with moderate to high numbers of collapsed and overexploited fish stocks (*COE*), such as the Southeast US Continental Shelf and the Insular Pacific-Hawaiian LMEs. The group also includes LMEs with the highest percentage of catch from bottom-impacting gear (*Cat Bot*), notably the Newfoundland-Labrador, South Brazil, New Zealand and Patagonian shelves.

Cluster 6 is made up of LMEs with the highest frequency of shipping activity (*Ship*). They include the North Sea, the East China Sea, the Iberian Coastal, the Celtic-Biscay Shelf, the Mediterranean, and the Yellow Sea, in order of decreasing shipping frequency. The Yellow and East China Seas LMEs also have the highest levels of demersal non-destructive low-bycatch fishing (*Dem Ndes LB*) among the LMEs, and the North Sea LME has the highest levels of pelagic low-bycatch fishing (*PLB*).

The clusters derived by Mahon *et al.* (2010) to characterize the status of 64 LMEs have a different composition of LMEs from the clusters derived in this chapter. The differences can be explained by the selection of indicators used in the two analyses, which differed overall, but in some cases have overlapping information content. For example, development level was represented by Gross Domestic Product in the analysis of Mahon *et al.*, while the Human Development Index was used in this analysis.

8.2.4.2 Ordination using Principal Component Analysis

The first three PCs resulting from the principal components analysis (PCA) (described in Box 8.1), explain 59 per cent of the variance among the 64 inhabited LMEs (Table 8.2). Shipping pressures (*Ship*) and vulnerable rural population within 100 km of the coast (*Rur Pop*), together, significantly weight the first principal component (PC1), which explains 30 per cent of the total variance. Demersal non-destructive low-bycatch fishing (*Dem Ndes LB*) and proportion of catch from bottom-impacting gear (*Cat Bot*), together, contribute significantly to the second principal component (PC2), which accounts for a further 18 per cent of the variance. Finally, capacity-enhancing subsidies (SUB) and plastic debris density significantly influence the third principal component (PC3), which is responsible for an additional 11 per cent of the total variance among LMEs. These major indicators simultaneously affect the resulting LME groupings.

Table 8.2 PCA loadings on each of the eleven principal components and proportion of variance explained by each component. The first, second, and third components explain 59 per cent of the variability. Values highlighted in brown indicate significant positive loadings (≥ 0.4) and values in blue indicate significant negative loadings (≤ -0.4). Indicator abbreviations are defined in Table 8.1.

Indicators	**PC1**	**PC2**	**PC3**	**PC4**	**PC5**	**PC6**	**PC7**	**PC8**	**PC9**	**PC10**	**PC11**
Dem Ndes LB	-0.31	0.48	0.31	0.22	-0.08	0.01	0.12	0.70	-0.07	-0.12	0.05
PLB	-0.27	0.38	-0.22	-0.07	0.01	0.16	-0.73	-0.12	-0.29	0.27	-0.05
Sub	-0.17	0.29	-0.61	0.17	-0.24	0.44	0.38	-0.19	0.14	-0.15	0.14
COE	-0.12	-0.05	-0.27	-0.21	0.17	0.05	0.03	0.29	0.32	0.06	-0.80
Cat Bot	-0.21	-0.42	0.03	-0.44	-0.54	0.27	-0.23	0.28	0.15	-0.14	0.20
Ship	-0.54	0.11	0.24	-0.14	0.35	-0.08	-0.05	-0.30	0.58	-0.10	0.20
CEut	-0.02	-0.11	0.05	0.04	0.06	0.23	0.21	0.16	0.16	0.89	0.21
Plast	-0.17	0.01	0.55	0.15	-0.33	0.37	0.14	-0.41	-0.14	0.05	-0.44
MPA Area	0.02	0.35	0.05	-0.79	0.03	-0.07	0.38	-0.09	-0.30	0.07	0.03
Rur Pop	0.58	0.25	0.21	-0.12	0.24	0.57	-0.20	0.07	0.28	-0.16	0.06
NLDI	0.29	0.38	0.03	0.00	-0.57	-0.43	-0.11	-0.10	0.45	0.18	-0.06
Importance of components	**PC1**	**PC2**	**PC3**	**PC4**	**PC5**	**PC6**	**PC7**	**PC8**	**PC9**	**PC10**	**PC11**
Standard deviation	0.40	0.31	0.25	0.22	0.21	0.19	0.17	0.15	0.13	0.12	0.12
Proportion of variance	0.30	0.18	0.11	0.09	0.08	0.06	0.06	0.04	0.03	0.03	0.02
Cumulative proportion	0.30	0.47	0.59	0.68	0.76	0.82	0.87	0.92	0.95	0.98	1.00

The maps in Figure 8.3 are a spatial representation of the scores of each LME for the first three PCs. LMEs with highly positive values (shown with brown hues on the maps) represent higher scores for each component, which indicates higher risk for the factors that are coloured brown in Table 8.2. LMEs with highly negative values (shown with green-blue hues on the maps) represent lower scores for each component, which indicates higher risk for the factors coloured blue in Table 8.2.

Comparison of the maps in Figure 8.3 with the loadings in Table 8.2 provides an indication of the spatial distribution of key risk factors, as described below.

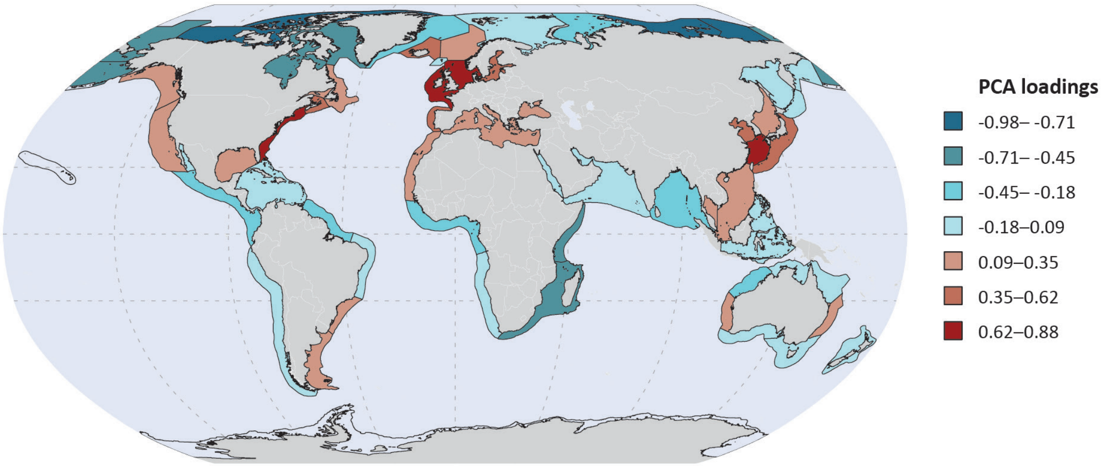
Principal Component 1 separated, generally, along an axis defined by population pressures. LMEs were discriminated on the basis of shipping pressures and pressures due to vulnerable rural populations in coastal areas (see factor loadings for PC1 in Table 8.2). The first component has positive loadings for shipping pressures (*Ship*), and negative loadings for vulnerable rural populations in coastal areas (*Rur Pop*). LMEs that have high positive values for this PC tend to have higher risks associated with shipping pressures (heavy shipping traffic) (Figure 8.3a). Notable examples of LMEs in this category are those in heavily developed regions such as the North Sea, East China Sea, and Northeast US Continental Shelf. At the other end of the component, LMEs that have high negative values for this PC tend to have lower risks from shipping pressures, but higher risks due to vulnerable rural populations in coastal areas, for example, the High Arctic LMEs. Overall, shipping pressures will tend to be heavier in regions with larger populations and large ports, although there will be exceptions to this pattern.

Principal Component 2 can be interpreted as an axis of variation that is defined by pressures due to demersal non-destructive low-bycatch fishing (*Dem Ndes LB*) and catch from bottom-impacting gear types (*Cat Bot*). The second component has positive loadings for *Dem Ndes LB* and negative loadings for *Cat Bot* (see factor loadings for PC2 in Table 8.2). LMEs with high positive scores on this PC tend to be those with high pressures from catches from destructive bottom gears and include the Southeast US and the East Central, Southwest, and Southeast Australian

Figure 8.3 Maps of the three main principal components showing risks related to combinations of indicators. The analysis is for the 64 inhabited LMEs. LMEs included in the analysis but not in the detailed results are shaded grey.

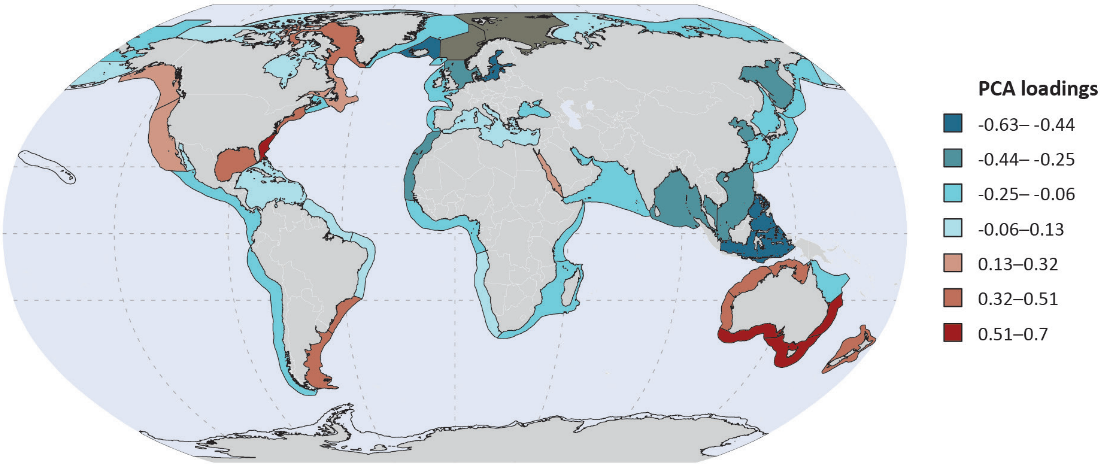
a) Principal component 1

High risk associated with shipping pressure (brown colours) and coastal rural population density (blue colours).



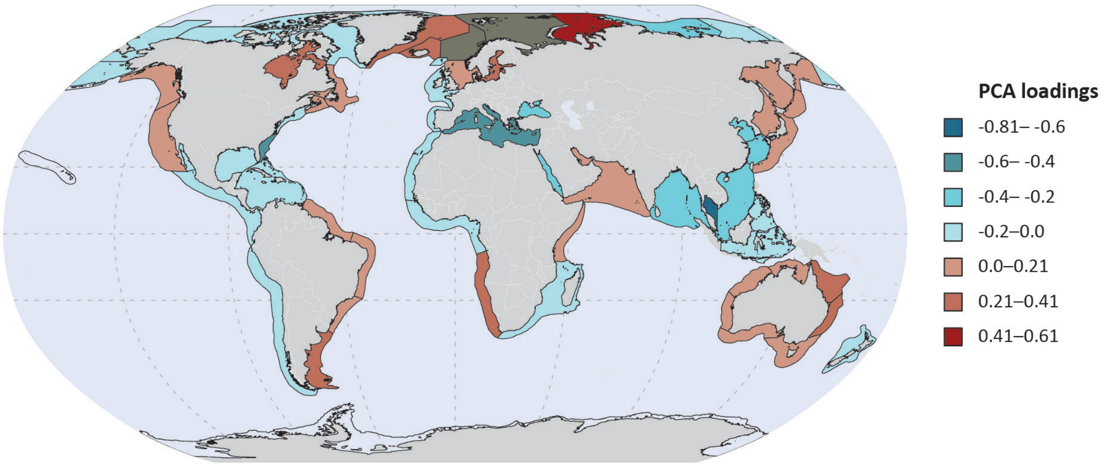
b) Principal component 2

High risk associated with pressures from catch from bottom-impacting gear types (brown colours) and pressures due to demersal non-destructive low bycatch fishing (blue colours).



c) Principal component 3

High risk associated with pressures from capacity-enhancing subsidies (brown colours) and pressures due to pollution from plastic debris (blue colours).



Shelves LMEs (Figure 8.3b). LMEs with high negative scores for this PC tend to be those with more pressure due to demersal non-destructive low-bycatch fishing and include regions in Asia, including the Sulu-Celebes Sea, Indonesian Sea, and South China Sea LMEs, as well as European LMEs such as the Baltic Sea and the Icelandic Shelf and Sea (Figure 8.3b).

Principal Component 3 can be interpreted as an axis of risk defined by pressures due to capacity-enhancing subsidies (*Sub*), which is possibly a proxy for excess fishing pressure, and pollution from plastic debris (*Plastic*). The third PC has positive loadings for *Plastic* and negative loadings for *Sub* (see factor loadings for PC3 in Table 8.2). LMEs that have high positive values for this PC tend to have higher risks associated with capacity-enhancing subsidies. Notable examples of LMEs in this category include regions in the higher latitudes of the northern hemisphere: the Kara Sea, Baltic Sea, and Greenland Sea (Figure 8.3c). At the other end of the component, LMEs that have high negative values for this PC tend to have lower risks from capacity-enhancing subsidies, but higher risks due to plastic debris. Notable examples at this end are the Gulf of Thailand, the Mediterranean, and the Southeast US Continental Shelf LMEs (Figure 8.3c).

The results of the correlation analysis and the PCA identified broad patterns of risk. It is important to realize that, because the dominant indicators for the first three PCs had inverse loadings, interpretation of the risk of LMEs is not directional (LMEs with either very negative or very positive scores exhibit risk in terms of one or the other of the dominant indicators), and therefore one must exercise care in interpreting these results. They are meant to provide guidance on the drivers of risk along the main dimensions of the data available. This analysis integrates the information from all the indicators to provide a concise summary of the dominant gradients of transboundary risk. The maps help to identify broad similarities of risk among LMEs in different parts of the globe, resulting from common causes.

Despite the value of these results, there are several limitations that must be considered in their interpretation. The first is the assumption of a gradient along the PC axes. Along the first three axes discussed here, there are two dominant indicators that have inverse loadings. The assumption is that LMEs with more negative (positive) scores are more closely associated with the negatively (positively) loaded indicator and therefore experience greater pressure from that indicator. However, the LMEs with more positive (negative) scores do not necessarily correspond to LMEs with lower pressure from the negatively (positively) loaded indicator. In addition to this, the PCA requires a complete data set, meaning that any basins with missing values for even a single indicator must be excluded from the analysis.

Overall, the clustering and ordination (PCA) result in descriptive groupings of the LMEs and provide a thorough analysis of the particular pressures influencing certain LMEs within each group. However, the clustering and ordination approaches do not provide a priority ranking of the LMEs. The following section illustrates the scoring analysis used to provide such guidance.

8.2.4 Identifying LMEs of concern by risk scores

Environmental assessments are often used to generate objective means of comparing sites and identifying those that need management interventions. The classification implemented by the clustering and ordination approaches described above highlights shared socio-economic and environmental ecosystem risks among LMEs within and among clusters. As noted above, the PCA arrays LMEs along component axes, each of which represents the combined risk gradients associated with two or more indicators. Classification and ordination both provide excellent bases for comparing LMEs globally, a global comparison being the first goal of the Transboundary Water Assessments Programme. However, multivariate techniques do not provide a linear ranking of assessed units, which is often required by managers as a basis for setting priorities.

The complexity of human–environmental interactions in coastal waters presents challenges to developing a single set of criteria against which to rank LMEs and identify those at relatively high risk. While fully recognizing these challenges and the incompleteness of the current assessment, an illustrative method for risk scoring is presented as one of many ways of prioritizing LMEs. The analysis uses 9 of the 11 selected indicators (excluding two socio-economic indicators) used in the multivariate analysis, but this time with the aim of estimating an overall risk score for each LME. The details of the simple risk-scoring technique are presented in the methods section and summarized as:

$$\text{Risk score}_{\text{LME}} = (1\text{- HDI}) \text{ X Average}(R_{\text{Fisheries}}, R_{\text{Pollution and Ecosystem Health}})$$

where 'R' is the average of the normalized indicator values for each of the modules, and low Human Development Index (HDI) scores indicate high risk.

Note that this equation represents one version of a method for determining a risk score and could be adapted to accommodate indicators from additional modules and other measures of socio-economic development where these are available.

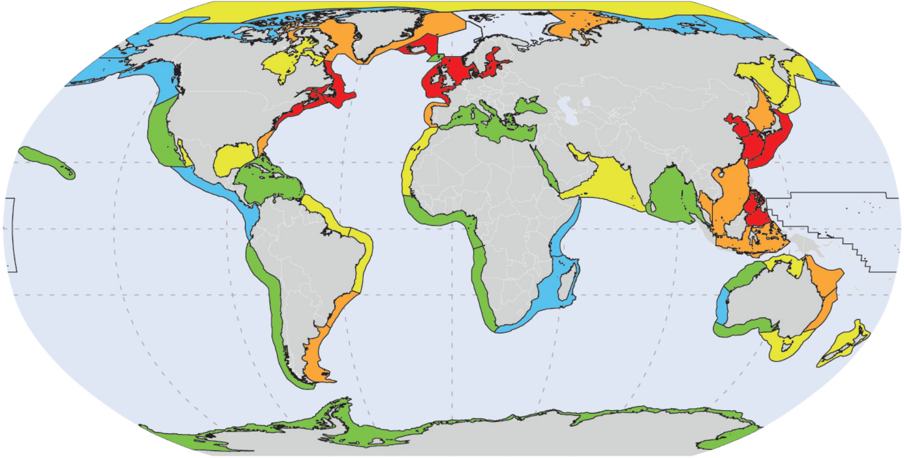
Human development significantly weights the risk scores. The algorithm above uses HDI as a measure of the socio-economic status of an LME and as a calibrating factor in the equation. The approach supports a theory that human responses to environmental phenomena are mediated by social, economic, political, and institutional factors, and that risk is embedded in a social matrix that confers resilience or vulnerability to human societies as they deal with such risks (Adger 2000 and 1999; Bohle *et al*. 1994). The decision to use HDI rather than the socio-economic indicators used in the clustering and ordination (*NLDI* and *Rur Pop*) was made intentionally to take advantage of the strongly directional nature of HDI and its ability to differentiate between developing and developed economies. *NLDI* and *Rur Pop* may at times be confounded. For example, an LME with low population may have high or low developmental status. The HDI, however, separates the LMEs along a single dimension of socio-economic development that integrates metrics of life expectancy, schooling years, and income per capita (HDR 2014). The assumption is that LMEs with lower socio-economic development levels will be at higher risk for the same levels of environmental degradation and that this may explain the limited ability of an LME population to cope with degraded transboundary waters. Within this separation, the LME ranks are nuanced by the combined risks from fisheries and pollution and ecosystem states and pressures.

The scoring system based on this risk score calculation features the HDI as the socio-economic indicator that calibrates the average of the average risks derived from the Fish and Fisheries module and the Pollution and Ecosystem Health module to generate an overall risk score for each of the 64 inhabited LMEs (Annex Table 8-D). These are categorized into five colour-coded groups of equal numbers of LMEs, based on risk relative to the range of values. The LMEs that are most at risk ('highest' category) are those with the lowest HDI (high values for the HDI Gap, measured as 1-HDI) among the tropical developing world and include the Somali Coastal Current, Guinea Current, and Canary Current. These LMEs have low fisheries-related risks, but high risks from pollution and low proportions of MPA Area coverage (*MPA Area*).

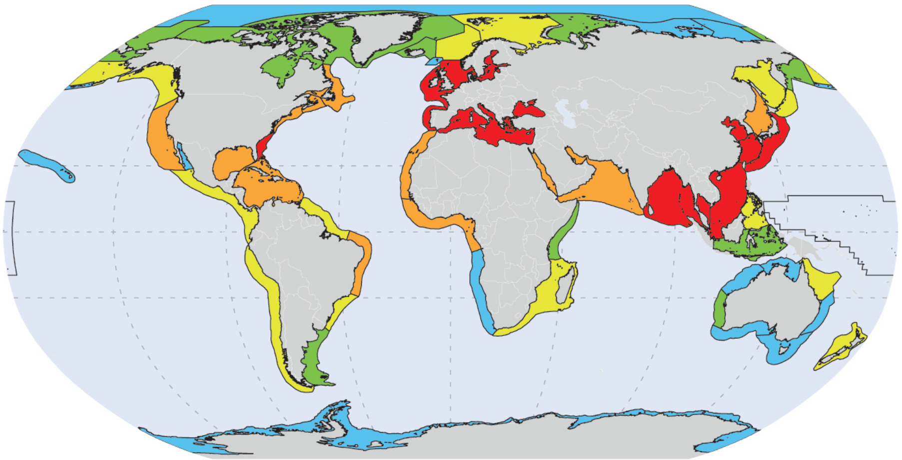
At the other end of the spectrum ('lowest' risk category) are developed LMEs with the lowest overall risk scores. For example, the Beaufort Sea, which has high risk levels because of the absence of an MPA and its high potential for coastal eutrophication, is in the 'lowest' risk category. This LME is ranked 54th out of 64 in terms of overall risk because of its very high human development standing. Another multivariate approach to assessing and ranking LMEs according to risk level, the Ocean Health Index (OHI), ranks it 45th out of 64. TWAP and OHI risk-scoring systems classified 34 of the 64 populated LMEs in the same risk category (53 per cent similarity). Figure 8.4 maps the distribution of risk for the 64 LMEs, based on the module averages of indicators for (a) Fisheries, (b) Pollution and Ecosystem Health, and (c) Socio-economics. Figure 8.5 maps risk based on (a) the combined TWAP risk score and (b) the OHI risk score (from Halpern *et al*., this report, adjusted for 64 LMEs).

Figure 8.4 Risk assessments based on averages of the standardized indicator values for each module. Fish and Fisheries indicators (a) exclude the Barents Sea and Norwegian Sea LMEs. Pollution and Ecosystem Health indicators (b) include all LMEs. Socio-economic indicators (c) exclude the Central Arctic Ocean and Antarctic LMEs, which have no associated coastal **populations.**

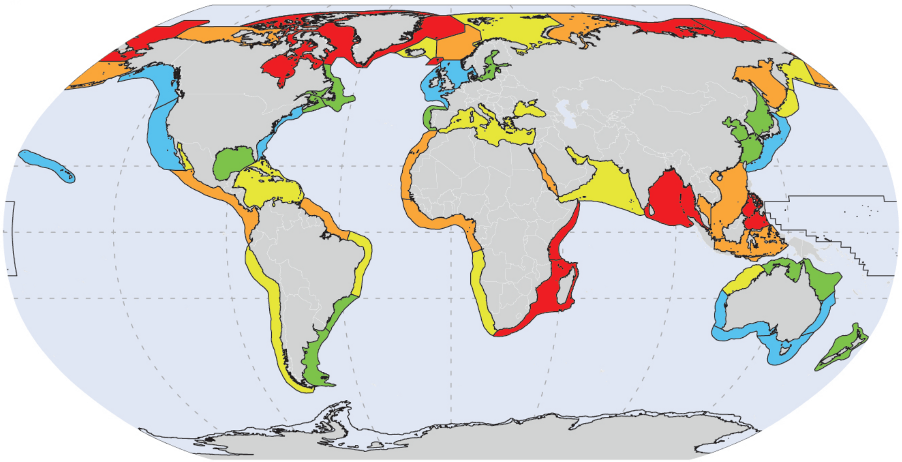
a) Fish and fisheries



b) Pollution and ecosystem health



c) Socio-economics



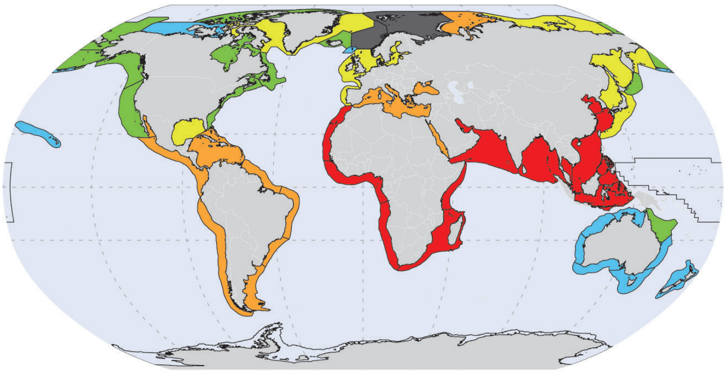
Risk

🟦 Lowest 🟩 Low 🟨 Medium 🟧 High 🟥 Highest

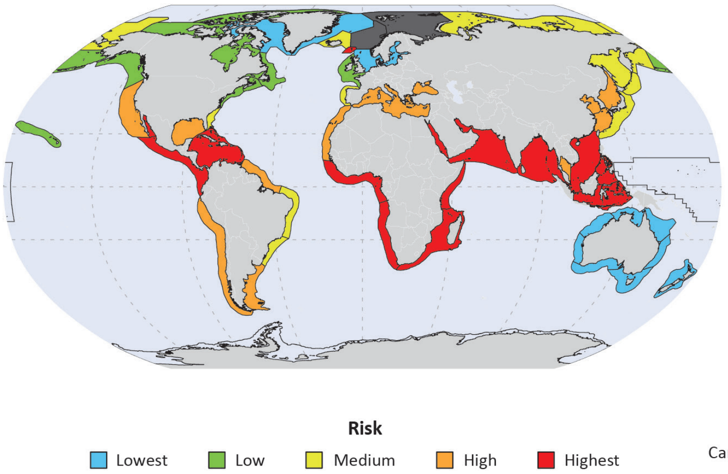
Figure 8.5 TWAP risk scores by LME, averaged across modules, compared with OHI risk scores. The analysis includes the 64 inhabited LMEs. LMEs included in the analysis but not in the detailed results are indicated in grey in the maps and black in the table.

a) TWAP risk scores

Scores are the average of averaged normalized indicator values for (1) the fish and fisheries module and (2) the pollution and ecosystem health module, weighted by the Human Development Index (multiplied by 1-HDI).



b) Ocean Health Index risk scores (1-OHI)



c) LMEs ranked in decreasing order of risk using TWAP risk scores, with corresponding risk rank based on the OHI

	TWAP	OHI
Somali Coastal Current	🟥 1	🟥 2
Canary Current	🟥 2	🟧 18
Guinea Current	🟥 3	🟥 1
Bay of Bengal	🟥 4	🟥 5
Arabian Sea	🟥 5	🟥 7
Agulhas Current	🟥 6	🟥 12
Sulu-Celebes Sea	🟥 7	🟥 9
East China Sea	🟥 8	🟧 20
South China Sea	🟥 9	🟥 10
Gulf of Thailand	🟥 10	🟧 24
Benguela Current	🟥 11	🟥 6
Indonesian Sea	🟥 12	🟥 13
Yellow Sea	🟥 13	🟧 19
Red Sea	🟧 14	🟥 3
South Brazil Shelf	🟧 15	🟥 27
Pacific Central-American	🟧 16	🟥 8
Caribbean Sea	🟧 17	🟥 4
North Brazil Shelf	🟧 18	🟧 15
East Brazil Shelf	🟧 19	🟨 28
Black Sea	🟧 20	🟧 17
Mediterranean	🟧 21	🟧 23
Kara Sea	🟧 22	🟨 31
	⬛	⬛
Humboldt Current	🟧 24	🟧 16
Patagonian Shelf	🟧 25	🟧 14
Gulf of California	🟧 26	🟥 11
West Bering Sea	🟨 27	🟨 35
Iberian Coastal	🟨 28	🟨 38
Baltic Sea	🟨 29	🟦 53
Sea of Okhotsk	🟨 30	🟨 32
East Siberian Sea	🟨 31	🟨 33
Gulf of Mexico	🟨 32	🟧 22
Laptev Sea	🟨 33	🟨 34
Kuroshio Current	🟨 34	🟨 29
Greenland Sea	🟨 35	🟦 64
North Sea	🟨 36	🟦 54
Celtic-Biscay Shelf	🟨 37	🟩 50
Canadian Eastern Arctic-West Greenland	🟨 38	🟦 55
Sea of Japan	🟨 39	🟧 26
Northern Bering-Chukchi Seas	🟩 40	🟨 37
Scotian Shelf	🟩 41	🟩 46
Iceland Shelf and Sea	🟩 42	🟨 36
Oyashio Current	🟩 43	🟨 30
Newfoundland-Labrador Shelf	🟩 44	🟩 47
Southeast US Continental Shelf	🟩 45	🟨 39
Northeast US Continental Shelf	🟩 46	🟩 43
Hudson Bay Complex	🟩 47	🟩 48
California Current	🟩 48	🟧 25
Canadian High Arctic-North Greenland	🟩 49	🟩 51
Gulf of Alaska	🟩 50	🟩 44
East Bering Sea	🟩 51	🟩 40
Northeast Australian Shelf	🟩 52	🟦 56
Insular Pacific-Hawaiian	🟦 53	🟩 41
Beaufort Sea	🟦 54	🟩 45
Aleutian Islands	🟦 55	🟩 42
New Zealand Shelf	🟦 56	🟦 63
	⬛	⬛
Southeast Australian Shelf	🟦 58	🟦 58
North Australian Shelf	🟦 59	🟦 59
West-Central Australian Shelf	🟦 60	🟦 60
Southwest Australian Shelf	🟦 61	🟦 61
East-Central Australian Shelf	🟦 62	🟦 59
Northwest Australian Shelf	🟦 63	🟦 62
Faroe Plateau	🟦 64	🟧 21

TWAP and OHI placed 34 LMEs of 64 populated LMEs in similar risk categories

To explore how governance factors into scoring risk, an additional risk analysis was carried out for the 47 populated and transboundary LMEs. HDI estimates were available for these LMEs, as well as the three metrics of governance architecture that were assessed for transboundary LMEs: engagement, integration, and completeness (Fanning *et al.*, this report). The indicators were renormalized and rescaled because minimum and maximum value guideposts differed from one data set to another. The average of the three governance indicators was included in estimating the average of average module risks:

$$\text{Risk score}_{\text{LME\_TRANSBOUNDARY}} = (1\text{- HDI}) \text{ X Average}(R_{\text{Fisheries}}, R_{\text{Pollution and Ecosystem Health}}, R_{\text{Governance}})$$

where ‘R’ is the average of the normalized indicator values for each of the modules, and low Human Development Index scores (development levels) indicate high risk.

As with the previous risk scoring, the risk ranks were placed into five classes, distributing the number of LMEs evenly among them: ‘highest’ (the ten LMEs with highest risk ranks), ‘high’ (next ten LMEs), ‘medium’ (next nine LMEs), ‘low’ (next nine LMEs) and ‘lowest’ risk (the nine LMEs with the lowest risk ranks). The OHI ranks were adjusted by ranking only the 47 inhabited transboundary LMEs and distributing them evenly among the five risk categories. Annex Table 8-E lists the module scores, the risk scores with and without the Governance module indicators, and the TWAP and OHI risk ranks. Interestingly, the risk ordering of LMEs with only the biophysical (Fish and Fisheries, and Pollution and Ecosystem Health) modules mimicked the HDI Gap (1-HDI) pattern more closely (37 LMEs placed in the same risk class) than when the Governance module average was included (32 LMEs placed in the same risk category). This indicates that the governance metrics of engagement, completeness, and integration did not necessarily co-vary or correlate with HDI metrics on life expectancy, years spent in school, or per capita gross national income (GNI). Nonetheless, the overall imprint of HDI was evident in the way the LMEs were ordered when governance was taken into account.

The comparisons of the TWAP risk ranks with those of the OHI were more nuanced for this transboundary LME data set. As an example, the Baltic Sea LME was ranked as being at higher risk by the TWAP risk scoring method than by the OHI risk score. Looking at the selected indicators by module and index, the Baltic Sea is in the ‘medium’ category on the basis of the HDI, and at ‘highest’ risk for fisheries and governance. The net result is an overall TWAP ‘high’ risk rank of 25th out of 47 LMEs. In contrast, the OHI, with possibly a more comprehensive suite of indicators, ranks the Baltic Sea LME as ‘lowest’ risk (43th out of 47 LMEs). Overall, TWAP (with governance metrics included) and OHI risk-scoring systems classified 21 of 47 populated and transboundary LMEs into the same risk category (45 per cent similarity).

McManus and Estevanez (this report) developed the Contemporary Threat Index which includes the factors used in calculating the TWAP risk scores. In addition, it incorporates socio-economic dependence metrics (fish contribution to animal protein and tourism contribution to coastal country GDP) and measures of property losses and deaths from extreme climate events. The Index was calculated for 62 populated LMEs. A comparison of the TWAP risk scores and the Contemporary Threat Index shows that the same risk scores resulted from calculation of 43 of these 62 LMEs (70 per cent). Calculating risk using the expanded Contemporary Threat Index raised the risk level by one category for 10 LMEs and lowered it for 9 LMEs. The use of HDI as a weighting factor appears to provide robust risk categorization for 70 per cent of the commonly assessed LMEs.

Hoagland and Jin (2008) analysed 64 LMEs and developed a socio-economic index based on HDI and a marine activity index based on five economic activities (marine fishery and aquaculture, tourism, ship building, shipping, and offshore oil). They did not develop an integrated index and so our scores are not directly comparable with the individual indices that they computed. The risk scoring developed here is therefore compared only with the OHI to determine whether a different index provides similar interpretations.

8.2.5 Discerning patterns of risks among LMEs

Grouping and ranking ecosystems are common objectives of environmental assessments. In this TWAP assessment, indicators underpinned by global data sets were used to compare coastal waters by comparing LMEs, using their biophysical, socio-economic, and governance states and pressures. Clustering techniques identified shared properties of LMEs. Ordination reduced the 11 indicators to three major PCA axes, representing six dominant indicators, capturing about 60 per cent of the variance. These results can be used to array LMEs in multidimensional space. Finally, a risk-scoring system using the HDI as a socio-economic calibrating indicator, together with the corresponding biophysical metrics and, where available, governance metrics, illustrates an approach for grouping LMEs into priority risk classes.

The resulting risk groups, based on cluster features or on the TWAP or OHI risk-scoring schemes, provide an interesting comparative snapshot of methods and outputs (Figure 8.5). Clustering of LMEs (Figure 8.1), except for the Australian shelf LMEs (cluster 3), is not conserved in the ordered array of LMEs based on the risk-scoring analysis. This is due mainly to the use of the HDI as a weighting factor, which is based on the assumption that LMEs with lower socio-economic development levels will be at higher risk for the same relative levels of environmental degradation. LMEs bordered by developing countries in Africa and Asia, such as the Somali Coastal Current, the Bay of Bengal, and the Sulu-Celebes Sea (in clusters 1 and 4), are rated as ‘highest’ risk (red). Waters of the Caribbean Sea and Mediterranean LMEs (in clusters 1 and 5) are rated in the high risk category (orange). LMEs with mainly rural coastal areas in developed countries, such as the East Siberian Sea, and LMEs surrounded by developed countries with the most-frequented shipping routes (found in clusters 1 and 6), make up the ‘medium’ risk category (yellow). The coastal waters of the US and Canadian LMEs (in clusters 1, 5, and 6) are rated ‘low’ risk (green), and the Australian and New Zealand Shelf LMEs are assessed as ‘lowest’ risk (blue).

Within the 11-indicator domain used here, LMEs with developing economies show highest risks in terms of coastal eutrophication (*CEut*) and plastic litter density (*Plastic*), and high risks from collapsed and overexploited fish stocks (*COE*). LMEs along the coast of developed nations are impacted by risks from high shipping frequencies (*Ship*), high capacity-enhancing fisheries subsidies (*Sub*), and the high use of bottom-impacting gear (*Cat Bot*), as well as from pelagic and demersal low-bycatch gear (*PLB* and *Dem Ndes LB*). All LMEs, except those around the coast of Australia, the Red Sea, and the Gulf of California, are at risk because of low percentage of established recovery zones, as represented by the indicator for marine protected areas (*MPA Area*).

Comparing the results of the TWAP risk scores with those of the OHI, there is a strong and common influence of socio-economic development in the overall ordering of LMEs. Specific differences in the risk classifications of particular LMEs (such as the Gulf of California, the Sea of Japan, or the Faroe Plateau) can be explained by the differences in the methods used to derive the OHI, that is, in the suite of metrics, indicators, and corresponding weights used in the OHI.

Looking forward, assessment of transboundary water systems could be improved by developing spatially explicit and time-varying indicators that address gaps in the conceptual frameworks used in this report and provide an indication of trends in status. These would include metrics that address changes in ecosystem services due to climate and societal pressures and their impact on livelihoods and ecosystems. In terms of fish and fisheries, improvements in the scale and quality of reporting of fisheries data, and improvements in the techniques available for evaluating the status and trends of global fisheries biomass, will be key for providing more accurate assessments of the health of marine stocks. For pollution and ecosystem health, the biophysical metrics must not be measured in isolation from economic considerations. Embedding pollution models within ecosystem service valuations can produce innovative metrics that can better elucidate and quantify human–environment interactions; this is currently a gap in the conceptual framework of this study. Changes in land use and cover change, including habitat conversion and development along the coast, significantly influence material flows from land to sea and may cause modifications in the structure and functioning of marine food webs. These interactions have not been addressed in this assessment. With respect to socio-economics, indicators such as poverty maps for coastal and inland areas, and regionalized input-output models tracking the response of marine industries (for example, tourism and fisheries) to changes in climate and governance, may allow more resolved discrimination of ecosystem states and pressures. Finer-scale alternatives to the use of the HDI, which is a national metric, may provide more nuanced responses.

An evaluation of governance performance, which could complement the indicators measuring governance architecture, will be necessary to gauge the ability of institutions to learn about, adapt to, and mitigate adverse environmental changes. Such an evaluation would include various scenarios of stakeholder behaviour in affecting policy or altering consumption patterns. Associated studies on economic trade-offs that are required to allow ecosystem recovery and net reduction of risks to humans and ecosystems are needed to inform policy options, which subsequent assessments may include in the logical progression from assessment to policy design. The current analysis is considered a Level 1 assessment, where global spatial coverage in the choice of input data sets was prioritized, thereby limiting the suite of possible indicators to those supported by global data. A Level 2 analysis, with targeted regional foci, more metrics that are more finely resolved in time and space, and that accounts for interactions among variables, may be the next frontier of transboundary water assessment, where the more comprehensive approaches described above may be integrated in the near-term.

8.3 Methodology and analysis

Multivariate (multi-indicator) statistical analyses were carried out to analyse objectively and simultaneously a set of suitable indicators chosen from the 48 that were available for each of the five modules in the LME analytical framework (Annex Table 8-A). In order to identify indicators suitable for inclusion in the multivariate analysis, it was necessary to determine whether each indicator could clearly distinguish between poor and good status. In other words, each indicator had to possess directionality. This resulted in the exclusion of many indicators across the five modules. For example, fisheries catch was eliminated as an indicator for the multivariate analysis because the measure of high or low catch does not allow one to infer whether the fisheries in an LME are in a good or bad state. For the Productivity module, this requirement resulted in the elimination of all the available indicators: chlorophyll *a*, primary productivity, sea surface temperature (O'Reilly and Sherman, this report; Belkin, this report) and UV (Halpern and Frazier, this report), as none was directional. A second criterion was that the indicators must be available for all 66 LMEs. The Governance module indicators included engagement, completeness, and integration (Fanning *et al*., this report), which were only assessed for the 49 trans-boundary LMEs. Therefore, these indicators were not included in the final multivariate analyses. However, the governance indicators, in addition to the excluded productivity indicators, are extremely useful for context and are presented in the module chapters (O'Reilly and Sherman, this report; Fanning *et al*., this report). Also, the governance indicators were used to derive combination scores for the 'medium' to 'highest' risk LMEs.

The sections below describe the steps taken to choose and process the remaining indicators across the Fish and Fisheries, Pollution and Ecosystem Health, and Socio-economics modules, and to determine the nature of the LME groups identified.

8.3.1 Data processing

In order to develop the list of 48 indicators, the Cumulative Human Impacts (CHI) Index (Halpern and Frazier, this report) was disaggregated into individual indicators to avoid double counting with indicators that were already provided by experts in the module chapters. In this way the potential for overlap in information content among indicators was minimized. The individual indicators were assigned to the modules according to best fit. Annex Table 8-A includes the full list of available indicators, including the disaggregated indicators from the CHI index within each module.

As noted above, for indicators to be included in the multivariate statistical analysis, they had to meet two criteria: confer directionality, and have spatial coverage for at least 60 LMEs. Once these criteria were used to eliminate indicators as a first cut, a third criterion was applied: low cross-correlation with other indicators. Therefore, indicators that had directionality and representation across most LMEs, but that were strongly correlated with other variables ($R^2 \geq 0.50$) were excluded from the analysis, under the assumption that the correlated indicator with the highest variance adequately represented the indicator with lower variance (Annex Table 8-B and Annex Table 8-C).

For the Fish and Fisheries module, eight indicators were directional: five (demersal destructive fishing, demersal non-destructive high bycatch fishing, demersal non-destructive low-bycatch fishing (*Dem Ndes LB*), pelagic high-bycatch fishing, and pelagic low-bycatch fishing (*PLB*)) from Halpern *et al*. (this report), and three (proportion of collapsed and overexploited stocks (*COE*), proportion of catch from bottom-impacting gear (*Cat Bot*), and capacity-enhancing subsidies as a fraction of the value of fisheries (*Sub*)) assessed by Pauly and Lam (this report). Of these, four were selected because they had low correlations with all other indicators (Annex Table 8-B): (1) *PLB*, (2) *COE*, (3) *Cat Bot*, and (4) *Sub*. Based on the variance explained between the remaining Fish and Fisheries module indicators, the indicator with the highest variance (Annex Table 8-C) was selected as the final indicator for this module: (5) *Dem Ndes LB*.

Ten directional indicators were considered for the Pollution and Ecosystem Health module. These included indicators of nutrient loadings: total nitrogen loading and the Index of Coastal Eutrophication Potential (*CEut*) from Seitzinger and Mayorga (this report); land-based inorganic urban run-off, invasives, light pollution, oil rigs, land-based organic pesticides, and shipping pressure (*Ship*) from Halpern *et al.* (this report); an indicator of plastic debris density (*Plastic*) from Kershaw and Lebreton (this report); and percentage change in area of MPAs (*MPA Area*) from Jones and Blyth (this report). Of these indicators, *CEut*, *Plastic*, and *MPA Area* were retained in the analysis because they did not have significant correlations with any of the other indicators (Annex Table 8-B). Of the remaining directional pollution and ecosystem health indicators, *Ship* was included as it explained the greatest variance (Annex Table 8-C).

The Socio-economics module included population density within 100 km of the coast, vulnerable population at 10 m elevation within 100 km of the coast, percentage rural population within 100 km of the coast (*Rur Pop*), Human Development Index (HDI), and the Night Light Development Index (*NLDI*) (Talaue-McManus and Estevanez, this report). Of these indicators, *NLDI* was included in the final analysis because it was strongly correlated with HDI, but not with any other indicators. It was retained, therefore, as a proxy for development (Annex Table 8-B). Additionally, *Rur Pop* was included because it explained the greatest variance among the Socio-economics module indicators (Annex Table 8-C).

Overall, a total of 11 indicators were selected for inclusion in the multivariate analysis. These included five indicators for fish and fisheries, four for pollution and ecosystem health, and two for socio-economics (summarized in Table 8.1; indicator scores in Annex Table 8-F). These indicators exhibit strong directionality in their information content, with low to high values indicating a gradient of environmental or socio-economic ecosystem state. The indicators were standardized by subtracting the minimum value of a given indicator for all LMEs and dividing by the difference between the maximum and minimum values. De-trending among these indicators was not necessary because the input data were not time-series. The scores for each indicator were then scaled so that 0 is low (worst) and 1 is high (best). These standardized and rescaled indicator values are shown in Annex Table 8-G. The multivariate analyses were run on all 66 LMEs.

8.3.2 Analytical methods

8.3.2.1 Cluster Analysis

Agglomerative Hierarchical Clustering Analysis (HCA) with complete linkage was used to distinguish LME groups based on the 11 indicators. HCA requires the use of a dissimilarity matrix to define the cluster. For this analysis the Bray-Curtis measure was used (Bray and Curtis 1957), where zero is complete similarity and one is complete dissimilarity. In Agglomerative HCA, two LMEs with the shortest distance (determined by Euclidean distance measures) are joined by a node or branch of a tree, with the length of the branch equal to the distance between the joined observations (Johnson 1967). This process is repeated on all remaining observations until only a single observation remains. Complete linkage clustering was used where the distance between individual clusters is the maximum of all pairwise distances between the observations contained in each cluster. Six clusters of LMEs were determined to be optimal, and therefore *k* was set to six. For this analysis, the variable that was clustered was the LME, and the indicators were used as the clustering metrics. Hierarchical clustering was run using the *AGNES* function in R 2.13.1 (R Core Team 2013). The dendrogram illustrates the linkages and clusters of LMEs (Annex Figure 8-A; Figure 8.1).

8.3.2.2 Ordination via Principal Component Analysis

For comparative purposes, principal components analysis (PCA) was used to evaluate the LME groupings. PCA is a statistical method for multivariate data that orthogonally transforms a set of observations of possibly correlated variables into a set of values of linearly uncorrelated variables called principal components (PCs). The number of components is equal to the number of original variables. The transformation confers the greatest variance on the first PC, and each succeeding component has the highest variance possible under the constraint that it is orthogonal to the preceding components. One can identify indicators that are most influential by examining the first several PCs. Biplots illustrate the relationship between the LME clusters and the indicator axes (Annex Figure 8-B) and provide a multivariate visualization of the results. A heat map with LMEs clustered according to the hierarchical clustering routine (Figure 8.2) is used to illustrate the large amount of multi-dimensional data and identify clusters of rows with similar values (through coding with colour gradients). The multivariate analysis helps to indicate the major drivers (indicators) that distinguish between the LMEs and provide an indication of pressures on the LMEs along different axes (PCA component maps, Figure 8.3). It is important to realize that the clustering and PCA will provide direction in terms of the types of pressures that LMEs within the groupings face, but will not linearly rank the LMEs. Therefore, in order to provide a linear risk classification, we also examine risks based on the selected multivariate indicators within each of the modules (Figure 8.4).

8.3.3 Identifying LMEs of concern using risk scores

To optimize the spatial LME coverage of the risk-scoring analysis, two LME data subsets were analysed for risk. One data subset includes all 64 inhabited LMEs, excluding only the uninhabited Central Arctic and Antarctic LMEs. The other data subset is made up of 47 inhabited transboundary LMEs for which governance architecture indicators (engagement, integration, and completeness) are available in addition to the 11 indicators selected for multivariate analysis

The level of human development, as measured by the HDI, was chosen as the socio-economic indicator for the risk-scoring analysis. Although any of the measures of socio-economic development could be used, the HDI was selected as the measure for sorting the LMEs into risk-priority groupings on the basis of the assumption that LMEs with lower socio-economic development levels will be at higher risk for the same levels of environmental degradation. The HDI was computed and aggregated at the LME scale as the geometric average (over the period 2009 to 2013) of its three underlying metrics: life expectancy, average of expected and actual years in school, and the per capita GNI. The decision to use *HDI* rather than the socio-economic indicators used in the clustering and ordination (*NLDI* and *Rur Pop*) was made intentionally to take advantage of the strongly directional nature of HDI and its ability to differentiate between developing and developed economies. HDI separates the LMEs along a single dimension of socio-economic development. Within this separation, the LME ranks are influenced by the combined risks from fisheries and pollution and ecosystem states and pressures.

It should be noted that the normalized risk scores all have the property of directionality: higher values equate to higher risk. HDI was subtracted from one (1-HDI) so that high normalized values equate to low human development, and therefore indicate high risk.

To obtain overall risk values for each of the 64 inhabited LMEs, the average normalized values for indicators from the Fish and Fisheries module and the Pollution and Ecosystem Health module were averaged and then multiplied by the metric of socio-economic development, the HDI Gap (1-HDI). The resulting risk scores were used to rank the LMEs (Figure 8.5).

In the analysis of the 47 inhabited transboundary LMEs, the three indicators of governance architecture (engagement, integration, and completeness) were also subtracted from one so that higher scores indicate higher risk. For this analysis, the averages of the indicators within the Fish and Fisheries module, the Pollution and Ecosystem Health module, and the Governance module, were averaged and multiplied by the metric of socio-economic development, the HDI Gap (1-HDI) to obtain the overall LME risk scores (Annex Table 8-E). All indicators were renormalized, as the minimum and maximum values differed for this data subset compared to those used in the 64-LME data subset analysis described above.

References

Adger, W.N. (1999). Social vulnerability to climate change and extremes in coastal Vietnam. *World Development* 27, 249-269. Adger, W.N. (2000). Social and ecological resilience: are they related? *Progress in Human Geography* 24, 347-364. Belkin, I. M. Sea surface temperature trends in large marine ecosystems (this report)

Bohle, H.G., Downing, T.E. and Watts, M.J. (1994). Climate change and social vulnerability. *Global Environmental Change* 4(1) 37-48

Bray, J.R. and Curtis, J.T. (1957). An ordination of the upland forest communities of southern Wisconsin. *Ecological Monographs* 27, 326-349

HDR (Human Development Report). (2014). UNDP, New York

Fanning, L., Mahon, R., Baldwin, K. and Douglas, S. Governance: Assessment of governance arrangements for transboundary LMEs (this report)

Halpern, B. and Frazier, M. Cumulative human impacts in the world's large marine ecosystems (this report)

Halpern, B., Frazier, M., Best, B., Longo, C. and Stewart Lowndes, J. Ocean Health Index for the world's large marine ecosystems (this report)

Hoagland, P., and Jin, D. (2008). Accounting for marine economic activities in large marine ecosystems. *Ocean and Coastal Management* 51, 246-58

IOC-UNESCO and NOAA. Assessment methodology (this report)

Johnson, S.C. (1967). Hierarchical clustering schemes. *Psychometrika* 32, 241-254

Kershaw, P. and Lebreton, L. Floating plastic debris (this report)

Mahon, R., Fanning, L., McConney, P. and Pollnac, R. (2010). Governance characteristics of large marine ecosystems. *Marine Policy* 34, 919-927

Mcowen, C., Jones, M. and Blyth, S. Change in protected area coverage within large marine ecosystems (this report)

O'Reilly, J.E. and Sherman, K. Trends in primary productivity and chlorophyll *a* (this report)

Pauly, D. and Lam, V. The status of fisheries in large marine ecosystems, 1950-2010 (this report)

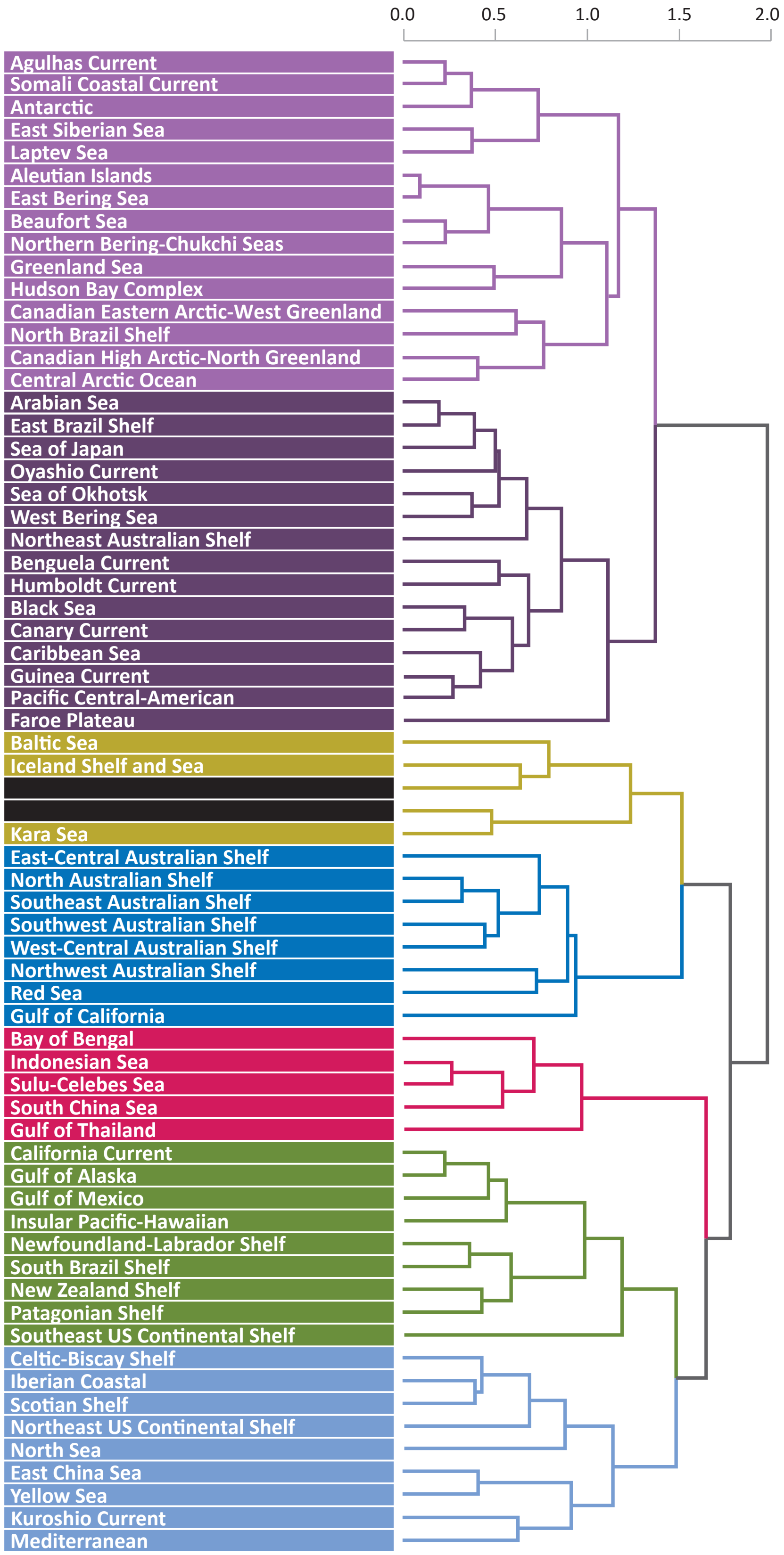
R Core Team (2013). R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria

Seitzinger, S. and Mayorga, E. Nutrient inputs in large marine ecosystems (this report)

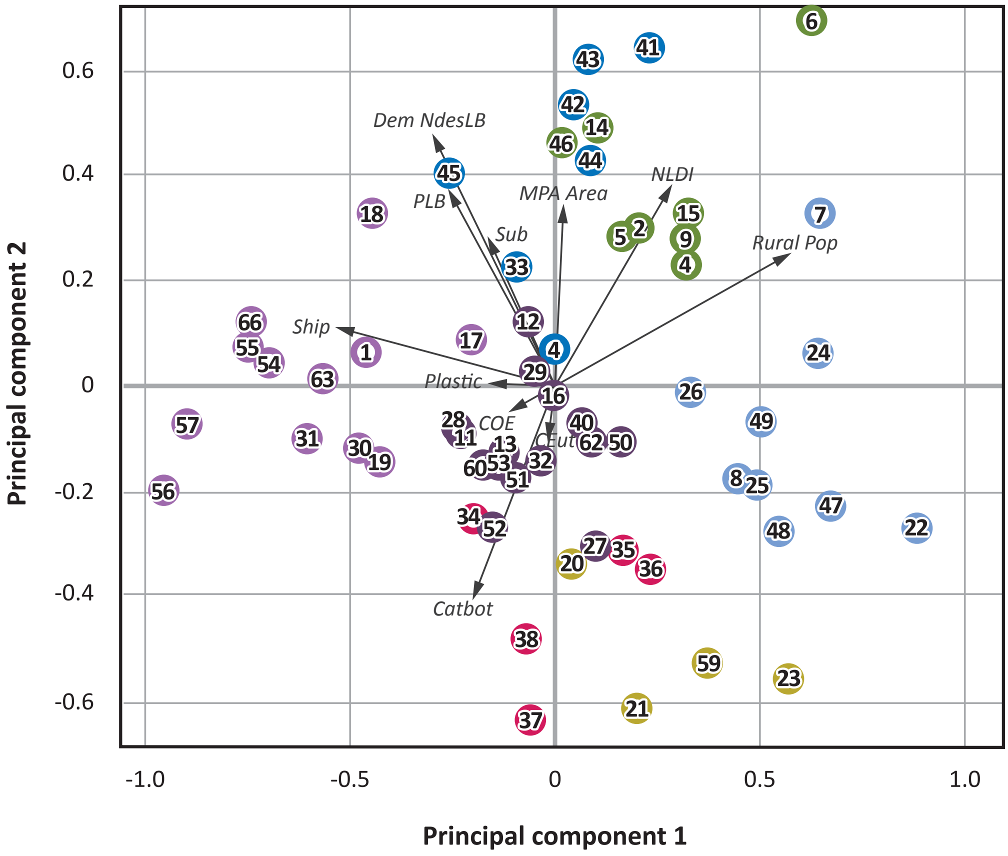
Talaue-McManus, L. and Estevanez, M. Examining socio-economic bases of risk and vulnerability among coastal inhabitants of large marine ecosystems (this report)

8.4 Annex

Annex Figure 8-A Dendrogram illustrating the six clusters. The scale indicates the degree of similarity. LMEs included in the analysis but not in the detailed results are shaded black.



Annex Figure 8-B PCA biplot illustrating LME clusters in relation to the 11 indicator axes. The vectors are the 11 multivariate indicators; full names and sources for the indicators are in Table 8.1. Numbers are LME numbers.



Annex Table 8-A Forty-eight indicators used in assessing LMEs. The 48 indicators were evaluated as to their suitability for the multivariate analyses (directionality, availability, low correlations, and high variance). The evaluation resulted in the selection of the 11 indicators in the top row.

Productivity	Fish and Fisheries	Pollution and Ecosystem Health	Socio-economics	Governance
Used in multivariate analysis				
None	Proportion of collapsed and over-exploited stocks (*COE*) Catch from bottom-impacting gear (*Cat Bot*) Demersal non-destructive low-bycatch (*Dem Ndes LB*)1 Pelagic low-bycatch (*PLB*)[1] Capacity enhancing subsidies as a fraction of the value of fisheries (*Sub*)	Coastal eutrophication potential (*CEut*) Plastic debris density (*Plastic*) Change in MPA coverage (*MPA Area*) Shipping (*Ship*)[1]	Rural population within the 100 km coastal zone (*Rur Pop*) Night Light Development Index (*NLDI*)	None* * However, governance architecture indicators (below) were used in scoring transboundary LMEs (see text)
Used in thematic analysis (including indicators listed above)				
Chlorophyll *a* Primary productivity Sea surface temperature (Impacts) UV[1]	Annual catch Marine trophic index Fishing in balance index Fishing effort Ecological footprint Demersal destructive fishing (*Dem Des*)[1] Demersal non-destructive high-bycatch fishing (*Dem Ndes HB*)[1] Pelagic high-bycatch fishing (*PHB*)[1]	Nutrients (N (*Nit*), P, Si) Land-based inorganic (*LB InOr*)[1] POPs in plastic pellets Reefs at risk index Mangrove extent Coral reef extent Delta vulnerability index Invasives (*Inv*)[1] Light pollution (*Li Poll*)[1] Ocean acidification[1] Oil rigs (*Oil Rig*)[1] Land-based nutrients[1] Land-based organic (*LB Or*)[1]	Coastal population within the 100 km coastal zone (*Coas Pop*) Fisheries revenues Tourism revenues Vulnerable population to natural coastal disasters (*Vul Pop*) Human Development Index (*HDI*) Regional sea level change Tropical cyclone landfalls Night Light Development Index (*NLDI*)	Governance architecture Completeness Engagement Integration

Annex Table 8-B Correlation matrix. Indicators that did not have correlations of greater than 0.5 (bolded values in the table) with any other indicators were retained in the analysis (*PLB, Sub, COE, CatBot, CEut, Plastic,* and *MPA Area*).

Annex Table 8-C illustrates how the variance of the remaining indicators was used to make the final selections. Indicator abbreviations are defined in Annex Table 8-A.

	Fish and Fisheries								Pollution and Ecosystem Health										Socio-economics				
	Dem Des	Dem Ndes HB	Dem Ndes LB	PHB	PLB	Sub	COE	Cat Bot	LB InOr	Inv	Li Poll	Oil Rig	LB Or	Ship	Nit	CEut	Plastic	MPA Area	Coast Pop	Vuln Pop	Rur Pop	HDI	NLDI
Dem Des	1.00																						
Dem Ndes HB	**0.82**	1.00																					
Dem Ndes LB	**0.73**	**0.86**	1.00																				
PHB	-0.08	-0.02	-0.09	1.00																			
PLB	0.25	0.30	0.35	-0.02	1.00																		
Sub	0.13	0.22	0.21	-0.08	0.39	1.00																	
COE	-0.10	-0.06	-0.01	-0.24	0.25	0.19	1.00																
Cat Bot	0.25	0.15	-0.10	-0.07	-0.03	-0.03	0.11	1.00															
LB InOr	0.20	0.47	0.47	-0.07	0.20	0.08	0.13	0.10	1.00														
Inv	0.08	0.26	0.28	-0.12	0.39	0.27	0.28	0.02	**0.80**	1.00													
Li Poll	0.31	**0.50**	0.44	-0.15	0.32	0.19	0.30	0.16	**0.87**	**0.87**	1.00												
OilRig	-0.09	-0.04	-0.09	**0.69**	-0.06	-0.09	-0.07	-0.06	-0.05	-0.05	-0.11	1.00											
LB Or	0.32	**0.54**	0.49	-0.12	0.03	-0.02	0.13	0.14	**0.85**	0.52	**0.69**	-0.08	1.00										
Ship	0.31	0.42	0.43	-0.12	0.32	0.12	0.38	0.16	**0.71**	0.58	**0.81**	-0.05	**0.65**	1.00									
Nit	0.11	0.13	0.02	**0.68**	0.01	-0.06	-0.25	0.13	0.01	-0.08	-0.05	0.13	-0.00	-0.04	1.00								
CEut	0.05	0.03	-0.14	0.24	-0.27	-0.02	0.11	0.20	0.24	0.23	0.33	0.07	0.25	0.25	0.24	1.00							
Plastic	0.29	0.33	0.27	0.15	-0.03	-0.08	-0.33	0.30	0.37	0.12	0.28	-0.05	0.28	0.28	0.22	0.15	1.00						
MPA Area	0.15	0.12	0.14	0.10	0.09	0.06	0.17	-0.08	0.06	0.04	0.05	-0.00	0.20	0.06	0.14	-0.05	-0.17	1.00					
Coas Pop	**0.59**	**0.75**	**0.61**	0.30	0.15	-0.11	-0.09	0.17	0.43	0.16	0.46	0.07	0.46	**0.50**	0.39	0.24	0.46	0.16	1.00				
Vuln Pop	0.03	0.20	0.09	**0.55**	-0.04	0.03	-0.23	0.25	0.02	0.01	-0.06	0.46	-0.09	-0.15	0.49	0.18	0.20	-0.04	0.28	1.00			
Rur Pop	-0.13	-0.15	-0.25	0.07	-0.20	0.00	-0.46	-0.39	-0.31	-0.31	-0.40	-0.01	-0.29	**-0.52**	0.01	-0.09	-0.14	0.09	-0.21	-0.05	1.00		
HDI	-0.06	0.09	0.12	**0.51**	-0.21	-0.25	-0.25	-0.25	0.04	-0.18	-0.19	0.43	-0.04	-0.09	0.36	0.07	0.14	-0.14	0.25	**0.53**	0.06	1.00	
NLDI	0.16	0.03	-0.04	-0.25	-0.01	-0.11	0.19	0.39	0.25	0.33	0.44	-0.23	0.28	0.41	-0.23	0.27	0.15	0.13	0.14	-0.35	-0.22	**-0.67**	1.00

Annex Table 8-C Variance matrix. Indicators that had the highest variance (bolded values on the diagonal) within each module were retained in the multivariate analysis (Dem Ndes LB, Ship, and Rur Pop). In addition, within the Socio-economics module, NLDI and HDI were correlated, and NLDI was retained due to fewer correlations with other indicators (see Annex Table 8-B). Indicator abbreviations are defined in Table 8.1

	Fish and Fisheries				Pollution and Ecosystem Health							Socio-economics				
	Dem Des	Dem Ndes HB	Dem Ndes LB	PHB	LB InOr	Inv	Li Poll	Oil Rig	LB Or	Ship	Nit	Coast Pop	Vuln Pop	Rur Pop	HDI	NLDI
Dem Des	0.055															
Dem Ndes HB	0.038	0.038														
Dem Ndes LB	0.042	0.039	0.060													
PHB	-0.002	0.000	-0.003	0.040												
LB InOr	0.018	0.022	0.030	-0.001	0.047											
Inv	0.008	0.010	0.013	-0.003	0.026	0.023										
Li Poll	0.022	0.022	0.026	-0.006	0.040	0.029	0.049									
Oil Rig	-0.001	0.000	-0.001	0.017	0.000	0.000	-0.002	0.017								
LB Or	0.017	0.020	0.027	-0.003	0.035	0.015	0.026	-0.001	0.035							
Ship	0.026	0.024	0.029	-0.002	0.038	0.024	0.044	0.000	0.028	**0.068**						
Nit	0.008	0.007	0.005	0.021	0.003	-0.001	0.000	0.004	0.002	0.001	0.034					
Coast Pop	0.029	0.029	0.030	0.012	0.022	0.007	0.022	0.003	0.018	0.028	0.015	0.042				
Vuln Pop	0.002	0.003	0.002	0.006	0.001	0.001	0.001	0.004	-0.001	0.001	0.005	0.004	0.004			
Rur Pop	-0.007	-0.004	-0.011	0.003	-0.014	-0.011	-0.020	0.000	-0.010	-0.036	0.003	-0.011	-0.004	**0.080**		
HDI	0.005	0.010	0.018	0.023	0.010	-0.003	-0.005	0.015	0.006	-0.002	0.019	0.017	0.006	0.013	0.068	
NLDI	0.002	-0.003	-0.008	-0.008	0.005	0.008	0.016	-0.006	0.005	0.022	-0.011	0.003	-0.001	-0.028	-0.041	0.054

Annex Table 8-D Average scores of selected indicators, by module, calculation of the TWAP risk score, and comparison of risk ranks based on the LME TWAP risk score and the Ocean Health Index. The analysis is based on 64 out of 66 LMEs. The average socio-economics score was not used in the risk score calculation, but is included here to compare with the HDI Gap (1-HDI). Both TWAP and OHI risk ranks and average module scores were divided into five equal groups and colour-coded as follows: blue (n = 12) lowest risk, green (n = 13) low risk, yellow (n = 13) medium risk, orange (n = 13) high risk, and red (n = 13) highest risk. The OHI risk ranks are from Halpern et al., this report, adjusted for 64 LMEs.

LME	Average fisheries scores (FISH)	Average pollution and ecosystem scores (ECO)	Average socio-economic scores	HDI Gap (1-HDI)	TWAP risk score = (1-HDI) * Average (FISH, ECO)	TWAP risk rank	OHI risk rank
Somali Coastal Current	0.1453	0.4786	0.7579	1.0000	0.3120	1	2
Canary Current	0.2903	0.6397	0.5451	0.5987	0.2784	2	18
Guinea Current	0.2017	0.5479	0.6193	0.7423	0.2782	3	1
Bay of Bengal	0.2441	0.6899	0.6297	0.5644	0.2636	4	5
Arabian Sea	0.2654	0.6153	0.5213	0.5416	0.2385	5	7
Agulhas Current	0.1899	0.5236	0.7833	0.6509	0.2322	6	12
Sulu-Celebes Sea	0.4297	0.5218	0.7194	0.4780	0.2270	7	9
East China Sea	0.4500	0.8203	0.3384	0.3426	0.2176	8	20
South China Sea	0.3804	0.6801	0.5417	0.4078	0.2162	9	10
Gulf of Thailand	0.3228	0.8058	0.5753	0.3801	0.2145	10	24
Benguela Current	0.2433	0.4586	0.4599	0.6101	0.2141	11	6
Indonesian Sea	0.3701	0.4750	0.6265	0.4486	0.1896	12	13
Yellow Sea	0.4518	0.7106	0.3510	0.3230	0.1877	13	19
Red Sea	0.2025	0.5437	0.6122	0.4927	0.1838	14	3
South Brazil Shelf	0.3206	0.6135	0.2372	0.3442	0.1608	15	27
Pacific Central-American	0.1882	0.5120	0.5557	0.4192	0.1468	16	8
Caribbean Sea	0.1988	0.5712	0.4549	0.3785	0.1457	17	4
North Brazil Shelf	0.2836	0.5194	0.6242	0.3573	0.1434	18	15
East Brazil Shelf	0.2632	0.5606	0.4470	0.3442	0.1418	19	28
Black Sea	0.2191	0.6956	0.5093	0.3100	0.1418	20	17
Mediterranean	0.2263	0.7866	0.3964	0.2773	0.1405	21	23
Kara Sea	0.3921	0.4701	0.5667	0.2741	0.1182	22	31
Barents Sea	–	0.5212	0.5269	0.2137	0.1114	23	49
Humboldt Current	0.2212	0.5017	0.4277	0.2985	0.1079	24	16
Patagonian Shelf	0.3588	0.4972	0.2324	0.2463	0.1054	25	14
Gulf of California	0.2981	0.3235	0.3852	0.3266	0.1015	26	11
West Bering Sea	0.2486	0.4655	0.4656	0.2741	0.0978	27	35
Iberian Coastal	0.3724	0.7312	0.3338	0.1713	0.0945	28	38
Baltic Sea	0.5089	0.6799	0.3203	0.1370	0.0814	29	53
Sea of Okhotsk	0.2945	0.5166	0.5331	0.1762	0.0716	30	32
East Siberian Sea	0.0421	0.4626	1.0000	0.2741	0.0692	31	33
Gulf of Mexico	0.2460	0.6225	0.2322	0.1533	0.0666	32	22
Laptev Sea	0.0077	0.4612	0.8422	0.2741	0.0643	33	34
Kuroshio Current	0.4071	0.7178	0.2206	0.1036	0.0583	34	29
Greenland Sea	0.3593	0.4985	0.6361	0.1321	0.0567	35	64
North Sea	0.5712	0.7430	0.2271	0.0816	0.0536	36	54
Celtic-Biscay Shelf	0.3944	0.7341	0.1541	0.0946	0.0534	37	50

LME	Average fisheries scores (FISH)	Average pollution and ecosystem scores (ECO)	Average socio-economic scores	HDI Gap (1-HDI)	TWAP risk score = (1-HDI) * Average (FISH, ECO)	TWAP risk rank	OHI risk rank
Canadian Eastern Arctic-West Greenland	0.3272	0.5009	0.7484	0.1240	0.0513	38	55
Sea of Japan	0.3151	0.6013	0.3498	0.1109	0.0508	39	26
Northern Bering-Chukchi Seas	0.1262	0.4771	0.7057	0.1533	0.0463	40	37
Scotian Shelf	0.4333	0.6100	0.2844	0.0832	0.0434	41	46
Iceland Shelf and Sea	0.5436	0.4766	0.4510	0.0848	0.0433	42	36
Oyashio Current	0.2483	0.5343	0.5059	0.1093	0.0428	43	30
Newfoundland-Labrador Shelf	0.3984	0.6027	0.2791	0.0832	0.0416	44	47
Southeast US Continental Shelf	0.3530	0.7858	0.0326	0.0669	0.0381	45	39
Northeast US Continental Shelf	0.4369	0.6629	0.0659	0.0669	0.0368	46	43
Hudson Bay Complex	0.2930	0.4799	0.6686	0.0832	0.0322	47	48
California Current	0.2013	0.6063	0.0479	0.0767	0.0310	48	25
Canadian High Arctic-North Greenland	0.1904	0.4738	0.8399	0.0832	0.0276	49	51
Gulf of Alaska	0.1897	0.5427	0.0857	0.0734	0.0269	50	44
East Bering Sea	0.1584	0.5261	0.5784	0.0669	0.0229	51	40
Northeast Australian Shelf	0.3680	0.5147	0.3827	0.0489	0.0216	52	56
Insular Pacific-Hawaiian	0.2277	0.4040	0.0142	0.0669	0.0211	53	41
Beaufort Sea	0.0747	0.4672	0.6747	0.0767	0.0208	54	45
Aleutian Islands	0.1386	0.4403	0.5784	0.0669	0.0193	55	42
New Zealand Shelf	0.2863	0.5121	0.3728	0.0473	0.0189	56	63
Norwegian Sea	–	0.5058	0.5459	0.0163	0.0082	57	52
Southeast Australian Shelf	0.2557	0.4463	0.2037	0.0131	0.0046	58	58
North Australian Shelf	0.2680	0.4077	0.3351	0.0131	0.0044	59	59
West-Central Australian Shelf	0.1917	0.4711	0.1859	0.0131	0.0043	60	60
Southwest Australian Shelf	0.2159	0.4171	0.1812	0.0131	0.0041	61	61
East-Central Australian Shelf	0.2999	0.3295	0.1714	0.0131	0.0041	62	57
Northwest Australian Shelf	0.1994	0.3810	0.4992	0.0131	0.0038	63	62
Faroe Plateau	0.2075	0.3901	0.6292	0.0000	0.0000	64	21

Annex Table 8-E TWAP risk score calculations and risk rank comparisons for the 47 inhabited transboundary LMEs. This analysis includes Fish and Fisheries, Pollution and Ecosystem Health, and Governance module indicators for determining TWAP LME risk ranks. Both TWAP and OHI risk ranks were divided into five equal groups and colour-coded as follows: blue (n = 9) lowest risk; green (n = 9) low risk; yellow (n = 9) medium risk; orange (n = 10) high risk; and red (n = 10) highest risk. The OHI risk ranks are from Halpern et al., this report, adjusted for 47 LMEs.

LME	Average fisheries scores (FISH)	Average pollution and ecosystem scores (ECO)	Average governance scores (1-GOV)	Average socio-economic scores	(1-HDI)	Risk score = (1-HDI)* AVE (FISH, ECO)	Risk score = (1-HDI)* AVE (FISH, ECO, (1-GOV))	TWAP risk rank	OHI risk rank
Guinea Current	0.1806	0.5450	0.5758	0.5791	1.0000	0.3628	0.4338	1	1
Canary Current	0.2797	0.6394	0.6199	0.0455	0.8066	0.3707	0.4138	2	16
Agulhas Current	0.1808	0.5212	0.7120	0.2377	0.8769	0.3078	0.4133	3	10
Bay of Bengal	0.2024	0.6892	0.5813	0.0260	0.7604	0.3390	0.3733	4	4
Arabian Sea	0.2338	0.6143	0.6231	0.0624	0.7297	0.3094	0.3578	5	6
Sulu-Celebes Sea	0.3905	0.5152	0.6801	0.2938	0.6440	0.2916	0.3404	6	8
South China Sea	0.3531	0.6715	0.7001	0.2892	0.5495	0.2815	0.3159	7	9
Indonesian Sea	0.3318	0.4695	0.7589	0.5818	0.6044	0.2422	0.3143	8	11
Gulf of Thailand	0.2809	0.8052	0.6551	0.4735	0.5121	0.2781	0.2972	9	22
East China Sea	0.4374	0.8201	0.6500	0.4495	0.4615	0.2902	0.2935	10	18
Red Sea	0.1712	0.4738	0.6673	0.2456	0.6637	0.2140	0.2903	11	2
Yellow Sea	0.4353	0.7105	0.5808	0.2474	0.4352	0.2493	0.2504	12	17
South Brazil Shelf	0.2941	0.6051	0.6282	0.6572	0.4637	0.2085	0.2361	13	25
Benguela Current	0.2358	0.4267	0.1842	0.7764	0.8220	0.2723	0.2320	14	5
Caribbean Sea	0.1935	0.5680	0.5973	0.6427	0.5099	0.1941	0.2309	15	3
Pacific Central-American	0.1799	0.5098	0.4963	0.5574	0.5648	0.1948	0.2233	16	7
North Brazil Shelf	0.2578	0.5174	0.5794	0.5716	0.4813	0.1866	0.2173	17	13
Black Sea	0.2093	0.6953	0.4898	0.2352	0.4176	0.1889	0.1941	18	15
Patagonian Shelf	0.3461	0.4965	0.5167	0.3319	0.3319	0.1398	0.1504	19	12
Barents Sea	–	0.5205	0.5013	0.1535	0.2879	0.1499	0.1471	20	39
Mediterranean	0.1949	0.7758	0.1185	0.3474	0.3736	0.1813	0.1356	21	21
West Bering Sea	0.2229	0.4639	0.3744	0.4126	0.3692	0.1268	0.1306	22	29
Humboldt Current	0.2195	0.5011	0.1598	0.5715	0.4022	0.1449	0.1180	23	14
Iberian Coastal	0.3745	0.7311	0.3846	0.6521	0.2308	0.1276	0.1146	24	32
Baltic Sea	0.5079	0.6792	0.6663	0.4927	0.1846	0.1096	0.1141	25	43
Gulf of Mexico	0.2365	0.6163	0.5316	0.8228	0.2066	0.0881	0.0953	26	20
Sea of Okhotsk	0.2612	0.5161	0.3154	0.5429	0.2374	0.0923	0.0865	27	28
Greenland Sea	0.3747	0.4980	0.5013	0.6385	0.1780	0.0777	0.0815	28	47
Sea of Japan	0.2933	0.6009	0.5750	0.6548	0.1495	0.0668	0.0732	29	24
Kuroshio Current	0.4012	0.7169	0.4000	0.5999	0.1396	0.0780	0.0706	30	26
North Sea	0.5737	0.7425	0.5836	0.5667	0.1099	0.0723	0.0696	31	44
Scotian Shelf	0.4405	0.6069	0.7634	0.7516	0.1121	0.0587	0.0677	32	38
Newfoundland-Labrador Shelf	0.3982	0.6018	0.7634	0.6854	0.1121	0.0560	0.0659	33	37
Oyashio Current	0.2143	0.5341	0.5667	0.3481	0.1473	0.0551	0.0645	34	27
Celtic-Biscay Shelf	0.3892	0.7340	0.2957	0.3518	0.1275	0.0716	0.0603	35	40
Canadian Eastern Arctic-West Greenland	0.3277	0.5003	0.1841	0.3616	0.1670	0.0691	0.0563	36	45
Northeast US Continental Shelf	0.4502	0.6590	0.6949	0.7193	0.0901	0.0500	0.0542	37	35
Iceland Shelf and Sea	0.5464	0.4603	0.3828	0.3650	0.1143	0.0575	0.0529	38	30
Southeast US Continental Shelf	0.3438	0.7782	0.4881	0.5192	0.0901	0.0506	0.0484	39	33
California Current	0.1941	0.6043	0.6051	0.5531	0.1033	0.0412	0.0483	40	23
Northern Bering-Chukchi Seas	0.1069	0.4765	0.0833	0.4910	0.2066	0.0603	0.0459	41	31
East Bering Sea	0.1437	0.5246	0.4198	0.2284	0.0901	0.0301	0.0327	42	34
Canadian High Arctic-North Greenland	0.1796	0.4732	0.1820	0.6541	0.1121	0.0366	0.0312	43	41

LME	Average fisheries scores (FISH)	Average pollution and ecosystem scores (ECO)	Average governance scores (1-GOV)	Average socio-economic scores	(1-HDI)	Risk score = (1-HDI)* AVE (FISH, ECO)	Risk score = (1-HDI)* AVE (FISH, ECO, (1-GOV))	TWAP risk rank	OHI risk rank
Beaufort Sea	0.0318	0.4666	0.0962	0.4762	0.1033	0.0257	0.0205	44	36
Norwegian Sea	–	0.5053	0.4413	0.6595	0.0220	0.0111	0.0104	45	42
North Australian Shelf	0.2334	0.3672	0.6209	0.5331	0.0176	0.0053	0.0072	46	46
Faroe Plateau	0.1904	0.3899	0.2035	0.8672	0.0000	0.0000	0.0000	47	19

Annex Table 8-F Raw unstandardized values for the 11 chosen indicators. In terms of directionality, (1-x) refers to an indicator where higher values indicate a worse status and (x) refers to an indicator where high values indicate a better state.

Direction	1-x	1-x	x	1-x	1-x	1-x	1-x	1-x	x	1-x	1-x
LME	**Dem Ndes LB**	**PLB**	**Sub**	**COE**	**Cat Bot**	**Ship**	**CEut**	**Plast**	**MPA Area**	**Rural Pop**	**NLDI**
Agulhas Current	0.0169	0.0054	0.1061	0.5079	0.1324	0.1011	-0.32	197.76	14.49	0.6579	0.9223
Aleutian Islands	0.0212	0.0004	0.0000	0.4459	0.1077	0.1448	–	8.34	1.80	1.0000	0.6022
Antarctic	0.0108	0.0022	0.2172	0.4517	0.0099	0.0057	–	0.33	0.00	–	–
Arabian Sea	0.0405	0.0181	0.3082	0.3212	0.1711	0.2078	0.86	868.58	5.01	0.4916	0.7749
Baltic Sea	0.1085	0.0451	0.7525	0.5727	0.0234	0.3555	0.46	431.58	4.88	0.2944	0.6921
Barents Sea	–	–	–	–	–	0.0929	-0.58	153.37	1.84	0.3330	0.8484
Bay of Bengal	0.0712	0.0289	0.1422	0.2355	0.1163	0.0777	11.51	3905.93	1.45	0.6362	0.8030
Beaufort Sea	0.0000	0.0000	0.0298	0.2250	0.0938	0.0026	-0.12	3.94	0.18	0.9969	0.6842
Benguela Current	0.0666	0.0008	0.1888	0.5209	0.1100	0.1234	1.55	28.18	226.68	0.1608	0.8670
Black Sea	0.0570	0.0029	0.1197	0.5014	0.1137	0.3342	1.40	1056.08	1.49	0.4269	0.7929
California Current	0.0392	0.0052	0.1245	0.5222	0.0750	0.2481	-0.97	253.22	12.87	0.0345	0.5766
Canadian Eastern Arctic-West Greenland	0.0031	0.0002	0.0639	0.6022	0.6572	0.0538	1.45	24.10	0.85	0.8091	0.8274
Canadian High Arctic-North Greenland	0.0000	0.0000	0.0000	0.5000	0.3259	0.0012	1.78	50.03	0.07	1.0000	0.8213
Canary Current	0.1178	0.0064	0.1745	0.4948	0.0915	0.2895	0.02	334.20	0.82	0.4482	0.8137
Caribbean Sea	0.0145	0.0010	0.0899	0.5413	0.1956	0.2248	-14.37	791.16	21.14	0.4211	0.7499
Celtic-Biscay Shelf	0.0611	0.0418	0.1745	0.5465	0.3221	0.4029	4.67	804.66	1.26	0.2058	0.5913
Central Arctic Ocean	0.0000	0.0000	0.0000	0.8500	0.3219	0.0013	–	54.32	0.00	–	–
East Bering Sea	0.0374	0.0014	0.0000	0.4611	0.1115	0.1256	-2.38	3.48	8.29	1.0000	0.6022
East Brazil Shelf	0.0301	0.0137	0.3066	0.3689	0.1999	0.1924	-0.72	154.84	45.36	0.3843	0.7592
East China Sea	0.0128	0.0128	0.2216	0.6086	0.2964	0.1811	-1.60	457.10	692.95	0.1850	0.6148
East Siberian Sea	0.1652	0.0114	0.3114	0.4839	0.3351	0.4247	5.98	2667.94	1.39	0.2964	0.7064
East-Central Australian Shelf	0.0000	0.0000	0.0000	0.2000	0.0250	0.0007	0.28	16.55	14.55	1.0000	0.9554
Faroe Plateau	0.0174	0.0119	0.0905	0.4437	0.1980	0.2464	-73.46	78.21	0.00	0.5357	0.8462
Greenland Sea	0.0381	0.0019	0.5697	0.7117	0.1348	0.0453	0.44	158.90	0.00	1.0000	0.6505
Guinea Current	0.0368	0.0084	0.1029	0.4083	0.1563	0.1497	-1.19	230.11	18.57	0.4698	0.8665
Gulf of Alaska	0.0192	0.0011	0.1471	0.4757	0.1446	0.1999	-10.84	18.25	9.55	0.0699	0.5929
Gulf of California	0.1444	0.0039	0.1403	0.4591	0.1038	0.0645	-1.02	131.52	500.00	0.2938	0.7467
Gulf of Mexico	0.0425	0.0007	0.1082	0.5082	0.2746	0.1918	1.01	1644.87	42.59	0.2406	0.6416
Gulf of Thailand	0.1623	0.0043	0.1665	0.2388	0.2551	0.1907	-5.44	6634.23	1.67	0.5400	0.7992
Hudson Bay Complex	0.0000	0.0000	0.2903	1.0000	0.0876	0.0292	-0.70	2.99	1.24	0.9880	0.6830
Humboldt Current	0.1004	0.0024	0.0278	0.5670	0.0179	0.0918	-5.60	39.19	1.35	0.3081	0.7761
Iberian Coastal	0.0902	0.0264	0.2437	0.6024	0.1744	0.4079	1.25	917.79	0.95	0.2829	0.7084
Iceland Shelf and Sea	0.1530	0.0539	0.4401	0.6085	0.1716	0.1990	-20.99	73.76	114.57	0.2879	0.8044
Indonesian Sea	0.1412	0.0398	0.1822	0.2663	0.1797	0.0917	-29.25	1515.27	36.42	0.5812	0.8242
Insular Pacific-Hawaiian	0.0056	0.0011	0.1610	0.7400	0.1257	0.1184	–	975.40	137.55	0.0619	0.5365

Direction	1-x	1-x	x	1-x	1-x	1-x	1-x	1-x	x	1-x	1-x
LME	**Dem Ndes LB**	**PLB**	**Sub**	**COE**	**Cat Bot**	**Ship**	**CEut**	**Plast**	**MPA Area**	**Rural Pop**	**NLDI**
Kara Sea	0.0000	0.0000	0.7297	0.5417	0.3637	0.0121	-0.26	43.99	9.82	0.4012	0.8522
Kuroshio Current	0.0764	0.0185	0.4806	0.5375	0.2403	0.2704	-2.28	2912.02	5.29	0.1735	0.6610
Laptev Sea	0.0371	0.0219	0.1701	0.5978	0.5333	0.2428	0.36	49.52	4.32	0.2441	0.6794
Mediterranean	0.0000	0.0000	0.0000	0.0000	0.0442	0.0000	0.17	16.20	16.50	1.0000	0.8232
New Zealand Shelf	0.0559	0.0114	0.1387	0.3233	0.1820	0.3816	0.53	3563.87	77.34	0.3539	0.7300
Newfoundland-Labrador Shelf	0.0095	0.0004	0.0169	0.5369	0.5800	0.1158	-11.68	698.10	28.90	0.1980	0.7779
North Australian Shelf	0.0228	0.0134	0.2194	0.3024	0.3621	0.0827	-1.03	65.50	287.88	0.2971	0.7033
North Brazil Shelf	0.0224	0.0025	0.2401	0.3775	0.4312	0.1259	-6.07	136.93	11.37	0.4744	0.8686
North Sea	0.1005	0.0887	0.1942	0.6117	0.3756	0.4488	3.76	467.90	4.69	0.1807	0.6633
Northeast Australian Shelf	0.0308	0.0401	0.3647	0.5155	0.2023	0.1195	-0.83	251.51	69.26	0.3182	0.7340
Northeast US Continental Shelf	0.0810	0.0228	0.0970	0.7049	0.5067	0.3118	0.83	812.32	27.34	0.0893	0.5679
Northern Bering-Chukchi Seas	0.0146	0.0000	0.0000	0.4229	0.1120	0.0255	-1.11	3.29	0.03	1.0000	0.7088
Northwest Australian Shelf	0.0099	0.0019	0.2117	0.3110	0.2588	0.1604	-0.07	164.27	500.00	0.7926	0.6258
Norwegian Sea	–	–	–	–	–	0.1684	-22.58	336.80	0.91	0.4614	0.8086
Oyashio Current	0.0433	0.0060	0.4185	0.2996	0.1172	0.2222	-20.92	162.52	0.19	0.6209	0.7059
Pacific Central-American	0.0349	0.0071	0.0915	0.5125	0.0645	0.1588	-15.81	236.04	13.43	0.4735	0.8116
Patagonian Shelf	0.0444	0.0547	0.0000	–	–	0.0437	–	0.00	33.00	–	–
Red Sea	0.0210	0.0002	0.2511	0.4920	0.6225	0.0562	0.15	4.07	1.94	0.0952	0.7049
Scotian Shelf	0.0252	0.0006	0.2021	0.3261	0.2280	0.2165	1.31	3543.58	500.00	0.5780	0.8136
Sea of Japan	0.0754	0.0471	0.2915	0.6461	0.2004	0.3016	-5.93	33.01	21.54	0.2667	0.6740
Sea of Okhotsk	0.0868	0.0044	0.3828	0.4035	0.1763	0.1904	-2.43	968.25	0.41	0.2828	0.7218
Somali Coastal Current	0.1036	0.0005	0.4214	0.3060	0.1151	0.1005	-1.84	8.49	0.83	0.5460	0.7612
South Brazil Shelf	0.0072	0.0024	0.0787	0.5328	0.0413	0.0250	-1.90	198.97	9.10	0.6379	0.9097
South China Sea	0.0163	0.0110	0.2859	0.3727	0.4760	0.2515	-1.70	892.96	59.04	0.1607	0.6805
Southeast Australian Shelf	0.1329	0.0301	0.2185	0.3589	0.2222	0.2436	-3.57	2929.16	59.81	0.4689	0.8019
Southeast US Continental Shelf	0.0041	0.0010	0.2180	0.3709	0.2946	0.0907	0.06	2078.05	493.06	0.2047	0.6145
Southwest Australian Shelf	0.0026	0.0006	0.2189	0.4779	0.3641	0.0935	-0.57	602.84	257.35	0.1706	0.6481
Sulu-Celebes Sea	0.0276	0.0004	0.0849	0.5236	0.6998	0.2812	-3.03	5071.81	53.21	0.0848	0.5420
West Bering Sea	0.1454	0.0502	0.3078	0.2741	0.1709	0.1116	-20.81	1873.21	43.87	0.6737	0.8619
West-Central Australian Shelf	0.0605	0.0000	0.3830	0.3682	0.0924	0.0875	-15.81	4.45	8.12	0.3117	0.8063
Yellow Sea	0.0034	0.0014	0.2177	0.4285	0.1722	0.1696	0.07	492.59	300.00	0.1877	0.6258

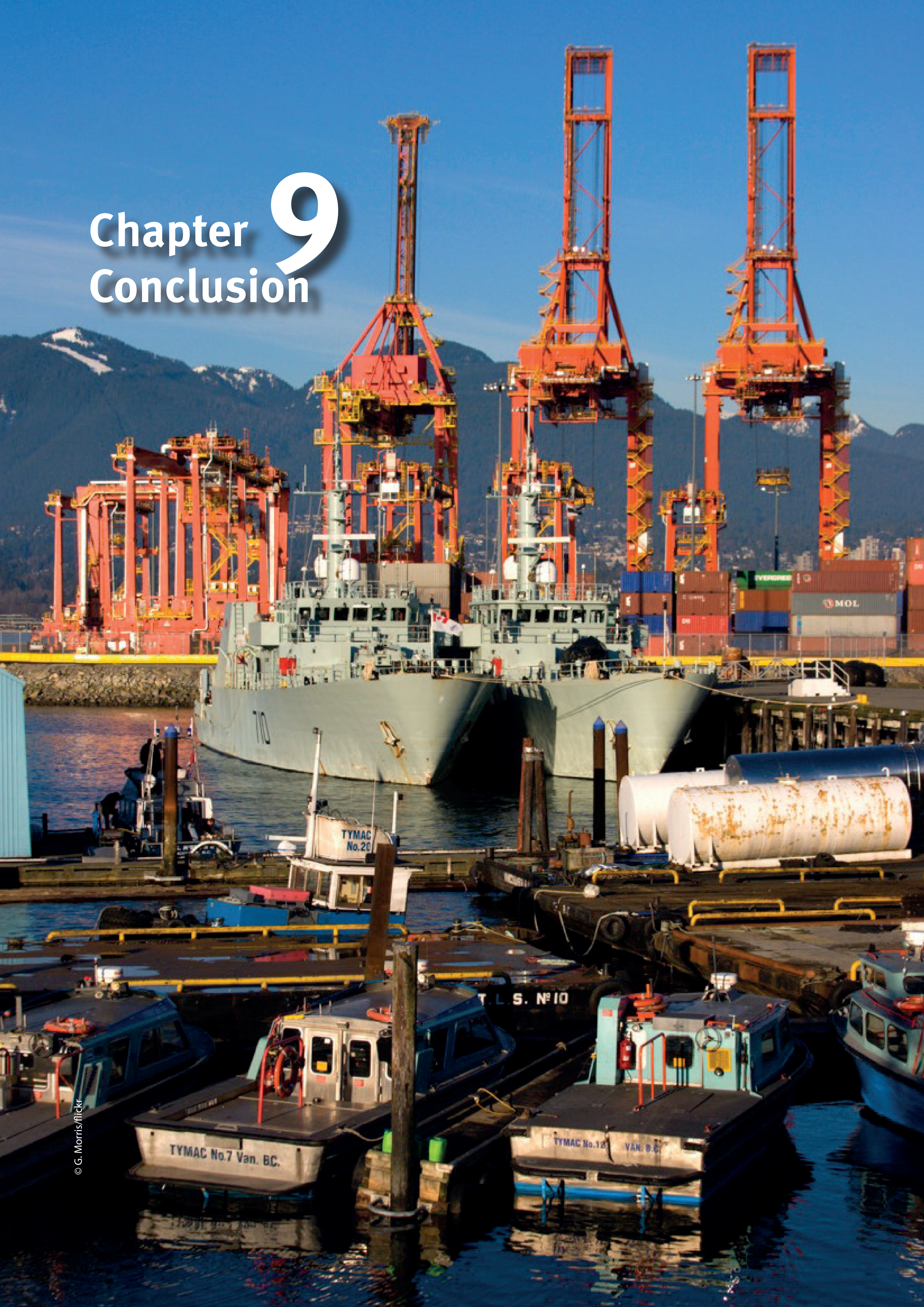
Annex Table 8-G Standardized and rescaled values for the 11 chosen indicators. Direction: a standardized value of '1' indicates the best condition, and a value of '0' indicates the worst state, relative to the indicator (variable).

Direction	1-x	1-x	1-x	1-x	1-x	1-x	1-x	1-x	x	1-x	x
LME	**Dem Ndes LB**	**PLB**	**Sub**	**COE**	**Cat Bot**	**Ship**	**CEut**	**Plast**	**MPA Area**	**Rural Pop**	**NLDI**
Agulhas Current	0.9196	0.9391	0.8675	0.4921	0.8223	0.7746	0.1393	0.9702	0.0209	0.3543	0.0790
Aleutian Islands	0.8995	0.9951	1	0.5541	0.8581	0.6774	–	0.9987	0.0026	0	0.8432
Antarctic	0.9486	0.9757	0.7287	0.5483	1	0.9873	–	1	0	–	–
Arabian Sea	0.8078	0.7962	0.6149	0.6788	0.7662	0.5369	0.1254	0.8691	0.0072	0.5266	0.4309
Baltic Sea	0.4848	0.4919	0.0598	0.4273	0.9803	0.2079	0.1301	0.9349	0.0070	0.7308	0.6286
Barents Sea	–	–	–	–	–	0.7930	0.1423	0.9769	0.0027	0.6908	0.2554
Bay of Bengal	0.6620	0.6749	0.8224	0.7645	0.8457	0.8270	0	0.4112	0.0021	0.3768	0.3638
Beaufort Sea	1	1	0.9628	0.7750	0.8783	0.9942	0.1369	0.9994	0.0003	0.0032	0.6474
Benguela Current	0.6840	0.9913	0.7641	0.4791	0.8548	0.7251	0.1173	0.9958	0.3271	0.8692	0.2110
Black Sea	0.7292	0.9668	0.8504	0.4986	0.8495	0.2552	0.1191	0.8408	0.0022	0.5936	0.3879
California Current	0.8139	0.9412	0.8444	0.4778	0.9055	0.4471	0.1469	0.9618	0.0186	1	0.9043
Canadian Eastern Arctic-West Greenland	0.9852	0.9983	0.9201	0.3978	0.0617	0.8801	0.1185	0.9964	0.0012	0.1977	0.3056
Canadian High Arctic-North Greenland	0.9998	1	1	0.5000	0.5419	0.9973	0.1146	0.9925	0.0001	0	0.3201
Canary Current	0.4408	0.9284	0.7820	0.5052	0.8816	0.3549	0.1352	0.9496	0.0012	0.5715	0.3383
Caribbean Sea	0.9313	0.9888	0.8877	0.4587	0.7308	0.4991	0.3046	0.8807	0.0305	0.5996	0.4906
Celtic-Biscay Shelf	0.7100	0.5288	0.7820	0.4535	0.5474	0.1022	0.0805	0.8787	0.0018	0.8226	0.8692
Central Arctic Ocean	1	1	1	0.1500	0.5476	0.9971	–	0.9918	0	–	–
East Bering Sea	0.8225	0.9840	1	0.5389	0.8527	0.7202	0.1635	0.9995	0.0120	0	0.8432
East Brazil Shelf	0.8570	0.8457	0.6170	0.6311	0.7246	0.5712	0.1440	0.9767	0.0655	0.6377	0.4684
East China Sea	0.9391	0.8556	0.7231	0.3914	0.5847	0.5963	0.1543	0.9311	1	0.8441	0.8131
East Siberian Sea	0.2159	0.8720	0.6109	0.5161	0.5286	0.0536	0.0651	0.5979	0.0020	0.7287	0.5944
East-Central Australian Shelf	1	1	1	0.8000	0.9780	0.9983	0.1322	0.9975	0.0210	0	0
Faroe Plateau	0.9172	0.8661	0.8870	0.5563	0.7273	0.4509	1	0.9882	0	0.4809	0.2607

Direction	**1-x**	**1-x**	**1-x**	**1-x**	**1-x**	**1-x**	**1-x**	**1-x**	**x**	**1-x**	**x**
LME	**Dem Ndes LB**	**PLB**	**Sub**	**COE**	**Cat Bot**	**Ship**	**CEut**	**Plast**	**MPA Area**	**Rural Pop**	**NLDI**
Greenland Sea	0.8194	0.9788	0.2883	0.2883	0.8190	0.8990	0.1304	0.9760	0	0	0.7279
Guinea Current	0.8255	0.9057	0.8714	0.5917	0.7877	0.6664	0.1495	0.9653	0.0268	0.5491	0.2122
Gulf of Alaska	0.9089	0.9880	0.8163	0.5243	0.8047	0.5545	0.2630	0.9972	0.0138	0.9633	0.8654
Gulf of California	0.3143	0.9556	0.8248	0.5409	0.8639	0.8563	0.1475	0.9802	0.7216	0.7314	0.4982
Gulf of Mexico	0.7982	0.9916	0.8649	0.4918	0.6162	0.5726	0.1236	0.7521	0.0615	0.7865	0.7491
Gulf of Thailand	0.2293	0.9516	0.7920	0.7612	0.6446	0.5750	0.1995	0	0.0024	0.4764	0.3729
Hudson Bay Complex	0.9999	1	0.6373	0	0.8873	0.9349	0.1437	0.9995	0.0018	0.0124	0.6503
Humboldt Current	0.5234	0.9725	0.9653	0.4330	0.9884	0.7954	0.2014	0.9941	0.0020	0.7166	0.4280
Iberian Coastal	0.5716	0.7026	0.6955	0.3976	0.7615	0.0910	0.1207	0.8617	0.0014	0.7427	0.5896
Iceland Shelf and Sea	0.2735	0.3924	0.4502	0.3915	0.7655	0.5566	0.3825	0.9889	0.1653	0.7375	0.3605
Indonesian Sea	0.3296	0.5512	0.7724	0.7337	0.7538	0.7957	0.4797	0.7716	0.0526	0.4338	0.3132
Insular Pacific-Hawaiian	0.9734	0.9874	0.7988	0.2600	0.8321	0.7362	–	0.8530	0.1985	0.9716	1
Kara Sea	0.9999	1	0.0884	0.4583	0.4872	0.9730	0.1385	0.9934	0.0142	0.6202	0.2464
Kuroshio Current	0.6372	0.7911	0.3996	0.4625	0.6660	0.3976	0.1623	0.5611	0.0076	0.8560	0.7028
Laptev Sea	0.8239	0.7528	0.7874	0.4022	0.2413	0.4590	0.1312	0.9925	0.0062	0.7829	0.6589
Mediterranean	1	1	1	1	0.9502	1	0.1335	0.9976	0.0238	0	0.3156
New Zealand Shelf	0.7345	0.8712	0.8268	0.6767	0.7505	0.1498	0.1292	0.4628	0.1116	0.6692	0.5381
Newfoundland-Labrador Shelf	0.9551	0.9958	0.9789	0.4631	0.1735	0.7419	0.2729	0.8948	0.0417	0.8307	0.4237
North Australian Shelf	0.8918	0.8495	0.7259	0.6976	0.4894	0.8157	0.1476	0.9901	0.4154	0.7280	0.6018
North Brazil Shelf	0.8936	0.9721	0.7000	0.6225	0.3893	0.7195	0.2069	0.9794	0.0164	0.5444	0.2072
North Sea	0.5230	0	0.7574	0.3883	0.4699	0	0.0912	0.9295	0.0068	0.8486	0.6973
Northeast Australian Shelf	0.8536	0.5482	0.5443	0.4845	0.7210	0.7336	0.1453	0.9621	0.0999	0.7062	0.5285
Northeast US Continental Shelf	0.6153	0.7430	0.8789	0.2951	0.2798	0.3052	0.1257	0.8776	0.0395	0.9432	0.9250

Direction	**1-x**	**1-x**	**1-x**	**1-x**	**1-x**	**1-x**	**1-x**	**1-x**	**x**	**1-x**	**x**
LME	**Dem Ndes LB**	**PLB**	**Sub**	**COE**	**Cat Bot**	**Ship**	**CEut**	**Plast**	**MPA Area**	**Rural Pop**	**NLDI**
Northern Bering-Chukchi Seas	0.9305	0.9995	1	0.5771	0.8520	0.9433	0.1485	0.9995	0	0	0.5887
Northwest Australian Shelf	0.9531	0.9787	0.7355	0.6890	0.6392	0.6425	0.1363	0.9752	0.7216	0.2148	0.7868
Norwegian Sea	–	–	–	–	–	0.6247	0.4012	0.9492	0.0013	0.5578	0.3504
Oyashio Current	0.7943	0.9322	0.4771	0.7004	0.8444	0.5049	0.3816	0.9755	0.0003	0.3926	0.5956
Pacific Central-American	0.8344	0.9198	0.8857	0.4875	0.9208	0.6462	0.3216	0.9644	0.0194	0.5453	0.3433
Patagonian Shelf	0.9005	0.9982	0.6863	0.5080	0.1119	0.8747	0.1338	0.9994	0.0028	0.9371	0.5980
Red Sea	0.8805	0.9938	0.7476	0.6739	0.6838	0.5176	0.1201	0.4659	0.7216	0.4371	0.3385
Scotian Shelf	0.6422	0.4694	0.6359	0.3539	0.7239	0.3281	0.2053	0.9950	0.0311	0.7595	0.6718
Sea of Japan	0.5882	0.9503	0.5217	0.5965	0.7587	0.5758	0.1641	0.8541	0.0006	0.7428	0.5577
Sea of Okhotsk	0.5082	0.9945	0.4735	0.6940	0.8474	0.7760	0.1571	0.9987	0.0012	0.4702	0.4636
Somali Coastal Current	0.9656	0.9734	0.9016	0.4672	0.9544	0.9442	0.1578	0.9700	0.0131	0.3750	0.1091
South Brazil Shelf	0.9226	0.8758	0.6428	0.6273	0.3244	0.4395	0.1555	0.8654	0.0852	0.8693	0.6562
South China Sea	0.3691	0.6603	0.7271	0.6411	0.6922	0.4573	0.1775	0.5585	0.0863	0.5501	0.3664
Southeast Australian Shelf	0.9807	0.9891	0.7276	0.6291	0.5873	0.7980	0.1348	0.6868	0.7115	0.8237	0.8138
Southeast US Continental Shelf	0.9876	0.9930	0.7265	0.5221	0.4865	0.7917	0.1422	0.9091	0.3714	0.8590	0.7336
Southwest Australian Shelf	0.8688	0.9959	0.8939	0.4764	0	0.3733	0.1711	0.2355	0.0768	0.9479	0.9869
Sulu-Celebes Sea	0.3098	0.4338	0.6155	0.7259	0.7666	0.7513	0.3804	0.7176	0.0633	0.3380	0.2232
West Bering Sea	0.7130	1	0.5215	0.6318	0.8803	0.8051	0.3216	0.9993	0.0117	0.7129	0.3559
West-Central Australian Shelf	0.9839	0.9844	0.7280	0.5715	0.7647	0.6220	0.1347	0.9258	0.4329	0.8413	0.7868
Yellow Sea	0	0.9618	0.6768	0.5481	0.5478	0.1684	0.1003	0.8868	0.0016	0.6496	0.6484

Chapter 9
Conclusion



© G. Morris/flickr

Conclusion

9.1 Meeting Transboundary Waters Assessment Programme (TWAP) objectives

The first objective of the current TWAP project was to undertake the first global assessment of transboundary waterbodies through a formalized consortium of partners to assist the Global Environment Facility (GEF) and other international organizations to improve priority setting for funding allocations. The assessment of the world's 66 LMEs and the Western Pacific Warm Pool (WPWP) presented in the preceding chapters of this report fulfil the first TWAP objective. This consists of a Level 1 global baseline comparative assessment and a limited Level 2 assessment at the sub-LME scale in the Bay of Bengal LME, the latter focusing on nutrients. The Level 1 assessment is based on averages at the scale of the entire LME and does not reflect the situation at smaller scales, such as the scale of an individual country's exclusive economic zone (EEZ). This assessment aimed to answer a number of key questions to help identify LMEs that are most at risk of degradation from human and natural causes and/or have the greatest dependence on ecosystem goods and services. It provides a scientific foundation that will contribute to improved strategic focus and cost-effectiveness of investments of GEF and other international stakeholders. In addition, the global baseline developed will allow improved reviews of the state of LMEs and the WPWP in the future.

The second objective was to formalize the partnership with key institutions aimed at incorporating transboundary considerations into regular assessment programmes, resulting in periodic assessments of transboundary groundwater, lake/reservoirs, river basins, large marine ecosystems (LMEs), and open ocean areas. The working group of institutional partners and experts that was established by IOC-UNESCO to conduct the current assessment forms the basis for a partnership to contribute to future LME assessments. Details are presented in a separate document on Sustaining Mechanisms (see onesharedocean.org).

9.2 Main conclusions

Conclusions drawn from the preceding chapters are presented according to the five LME modules representing the human and natural systems, as illustrated in the conceptual framework (Figure 2.1).

HUMAN SYSTEM

9.2.1 Socio-economics

Assessment of socio-economics of LMEs aimed to identify where human dependence on LMEs goods and services is greatest and to describe patterns of risk to coastal communities from a combination of ecological degradation and current climate-related extreme events, taking into account socio-economic dependence and capacity to adapt to change. Coastal population, contribution of fish protein to total animal protein, and tourism contribution to GDP, are used together as a metric of dependence. The Indonesian Sea LME has the highest dependence, followed by the Gulf of Thailand and the Bay of Bengal LMEs. Climate-related extreme events and changing ecosystem states are further burdens that coastal communities already at risk from socio-economic factors may face. Taking into account the combined current effects of socio-economic dependence, capacity to adapt, ecological conditions, and threats from climate-related extreme events, the LMEs where coastal populations are at highest risk are all in developing regions across the world. Most at risk are the Bay of Bengal, Canary Current, and Gulf of Thailand LMEs. Reducing vulnerability of coastal populations must be addressed without sacrificing ecosystem health, and vice-versa.

9.2.2 Governance

Formal transboundary governance arrangements relevant to fisheries, pollution, and biodiversity and habitat modification in the 49 multi-country LMEs and the WPWP were assessed. There is considerable room for improvement in the design of transboundary governance arrangements for LMEs. Current and new agreements should have appropriate mechanisms for all stages of the policy cycle. Fisheries arrangements need improvement in institutional collaboration for implementation. Few pollution arrangements include provisions for repercussions for lack of compliance, and accountability is limited for most biodiversity arrangements. Lack of data and information provisions is a serious shortcoming at the LME level for many biodiversity arrangements. For ecosystem-based management to be effectively implemented in LMEs, greater effort is needed to strengthen collaboration among organizations involved in transboundary governance and to create overarching integrating mechanisms. The Mediterranean LME has the lowest overall risk level related to governance arrangements, mainly because it has a functioning overarching integrating mechanism to address transboundary issues. The LMEs with the highest risk level are all in developing regions.

NATURAL SYSTEM

Indicators cover drivers of change in LME condition, anthropogenic stress (or pressure) on the ecosystem, and environmental state. Primary productivity, chlorophyll, and sea surface temperature (SST) indicators are representative of natural LME variability and are not associated with risk levels. In addition, three composite indicators or indices were assessed: Reefs at Risk Index, Cumulative Human Impacts (CHI) Index, and Ocean Health Index (OHI). Most indicators were assessed for current conditions. Projections to 2030 and 2050 were made for nutrients, the Reefs at Risk Index, and fish catch potential as affected by global warming.

9.2.3 Productivity

Primary productivity, chlorophyll *a* and SST indicators give no clear indication of 'good' or 'bad' ecosystem state. Changes can be beneficial or detrimental, depending on the context. From a global ocean perspective, coastal waters within LME boundaries have the highest primary productivity. All but two LMEs have warmed since 1957, with the East China Sea LME showing the largest increase in SST. The Southeast US Continental Shelf and the Barents Sea LMEs were the only two LMEs to cool during this period. There is no consistent link between SST trends and environmental risks. Precautionary management actions, however, are needed in the light of the uncertainties about the effects of climate warming in LMEs.

9.2.4 Fish and Fisheries

9.2.4.1 Fisheries status

Nine catch-based indicators were assessed from time-series data from 1950 to 2010 for all LMEs except the Barents Sea and Norwegian Sea LMEs, and the WPWP. Of these, three are drivers or pressures: ratio of capacity-enhancing subsidies to the value of landed catch (a measure of potential overharvest), fishing effort, and catch from bottom-impacting gear (a measure of potential habitat destruction). Five indicators relate to ecosystem state: ecological footprint (measured as primary production required to sustain fisheries landings), Marine Trophic Index (MTI), Fishing-in-Balance (FiB) Index, percentage of collapsed or overexploited stocks, and catch biomass of exploited stocks. Conclusions based on assessment of these indicators:

- The drivers and sources of pressure and degree of risk to the ecosystem from fisheries vary among the LMEs. This suggests that management approaches need to be tailored according to the dominant drivers and sources of pressure in individual LMEs.
- LMEs with the highest average scores across all the indicators except change in catch potential are the Bay of Bengal LME with the highest score, followed by the Sulu-Celebes Sea and Indonesian Sea LMEs (due to high rate of increase of effective fishing effort). Among the LMEs with the lowest average scores are the

Beaufort Sea, East Siberian Sea, and Laptev Sea (marine regions with limited fishing activity), East Central Australian Shelf, and Benguela Current LMEs. The WPWP shows similar trends to the mean LME trends for some indicators, but has experienced greater increases in certain indicators, including fishing effort.
- Although the number of collapsed stocks in LMEs is increasing, the number of rebuilding stocks is also increasing in certain countries, an encouraging sign.
- Warming seas will substantially reduce the fish catch potential in many LMEs by the 2050s. The East Siberian Sea and Indonesian Sea LMEs are projected to be the most affected. The catch potential for the WPWP is projected to drop by 7 per cent.
- Because of poor data coverage for fisheries and other statistics at the national scale, the indicators derived may not represent any specific country or policy. Catch data accounting for small-scale fisheries (artisanal, subsistence, and recreational) at the national level are needed to improve the quality of the indicators.

9.2.4.2 Fish production potential

A first application of a new approach to estimating fishery production potential suggest that fisheries exploitation rates should not exceed 25 per cent of available production in order to be sustainable. In some systems even lower rates are warranted. If these potential yields are to be realized, an overall species diversification of the complex of harvested species will have to be attained and exploitation rates on overfished species reduced.

9.2.5 Pollution

Land-based, and to some extent sea-based human activities are the major drivers of pollution by plastics, persistent organic pollutants (POPs), and nutrients.

Modelled estimates of the abundance of floating micro- and macro-plastics showed that many of the LMEs with the highest relative abundances of both size classes of plastics are located in east-Southeast Asia, with the Gulf of Thailand having the highest values for both. Other LMEs with high levels of floating plastics are the Southeast US Continental Shelf, Mediterranean, and Red Sea LMEs. Further observations, combined with more sophisticated modelling approaches, are needed to increase the level of confidence in future assessments.

POPs were detected in all 37 LMEs for which empirical data were available. This included remote islands, showing the widespread distribution of these substances in the marine environment. A number of hotspots were identified within LMEs in both developing and developed regions. Time-series sampling of POPs is needed to detect trends, to evaluate the effectiveness of regulation, and to identify emerging pollution sources so that mitigation actions can be taken.

Coastal eutrophication in LMEs is associated with high nutrient loads (nitrogen, phosphorus, and silica) to coastal areas from large urban populations and intense agricultural production with high fertilizer use and/or large numbers of livestock. Although the majority of LMEs are at low risk for coastal eutrophication, 16 per cent are at ‘high’ or ‘highest’ risk, including the Gulf of Mexico and several LMEs in Western Europe and southern and eastern Asia. In many watersheds around the world, river nutrient loads are projected to increase due to increase in human activities. Based on current trends, the proportion of LMEs in the ‘high’ to ‘highest’ risk category for coastal eutrophication is also projected to increase substantially by 2030 and 2050. LMEs with the highest risk of eutrophication in both 2000 and 2050 include the Bay of Bengal and Black Sea LMEs. Only two LMEs (Iberian Coastal and Northeast US Continental Shelf) are projected to lower their coastal eutrophication risk by 2050.

As illustrated by a study of the Bay of Bengal LME, there can be considerable variation in the nutrient loads and sources, as well as in eutrophication potential among the various river basins within an LME. In order to develop appropriate nutrient reduction strategies for an LME, information on the relative contribution and location of nutrient sources within river basins and across the LME is needed.

Many LMEs, especially those with large coastal human populations, show high levels of risks related to some or all of these substances (plastic debris, POPs, and nutrient inputs from watersheds). These LMEs include South China Sea, Bay of Bengal, East China Sea, Indonesian Sea, Mediterranean, Kuroshio Current, Black Sea, Gulf of Mexico, and Yellow Sea.

9.2.6 Ecosystem health

Ecosystem health assessment focuses on composite indicators or indices (Reefs at Risk, Cumulative Human Impacts in LMEs, and the Ocean Health Index), a baseline measure of mangrove extent, and a single response indicator: change in marine protected area (MPA) coverage.

9.2.6.1 Habitats

Mangroves are rare and productive tropical coastal systems that are experiencing extensive loss and degradation from deforestation, land clearing and sea-level rise. About 20 per cent of the global mangrove area was lost between 1980 and 2005 and decline continues at an estimated 1 per cent per year. Pressures on these endangered ecosystems are both local and global in nature, with coastal development being the most widespread cause of mangrove loss. This assessment shows that the relative impact of different drivers of mangrove loss is highest, and increasing, in Southeast Asia.

Coral reefs are under threat from human activities, with overfishing and destructive fishing practices being of greater threat than coastal development and marine pollution. Reefs are also threatened by rising sea temperatures and ocean acidification. By 2030, more than 50 per cent of coral reefs are projected to be at ‘high’ to ‘critical’ risk from ocean warming and acidification, increasing to almost 80 per cent by 2050. Conditions may be particularly severe in the Gulf of California and Kuroshio Current LMEs.

Implementing measures such as MPAs may enhance ecosystem resilience in the face of increasing global threats. There has been a 15-fold increase in global MPA extent since 1983. This increase indicates progress towards Aichi Target 11 of the Convention on Biological Diversity’s target to conserve 10 per cent of the world’s coastal and marine areas by 2020.

9.2.6.2 Cumulative Human Impacts (CHI) Index

In general, LMEs adjacent to heavily populated coastlines, particularly in developed countries that encompass large watersheds, have the highest CHI Index scores. The most heavily impacted LMEs are adjacent to China (for example, South China Sea, East China Sea, Yellow Sea, and Kuroshio Current) and Europe (for example, Norwegian Sea, North Sea, Iberian Coastal, and Mediterranean). Stressors associated with climate change, most notably ocean acidification and increasing sea surface temperatures, are the top stressors for nearly every LME. At smaller scales, however, particularly along coastlines, many other stressors, such as land-based pollution and fishing, play a dominant role. Efforts to manage marine ecosystems at the LME scale will require coordination not only among countries bordering the LME, but also among sectors. The latter is critical for successful management because the key stressors are global in nature, and are therefore beyond the scope of what can be identified and addressed through single-sector management.

9.2.6.3 Ocean Health Index (OHI)

The OHI measures progress towards achievement of ten widely-held public goals for healthy oceans. These include goals related to food provision, carbon storage, coastal livelihoods and economies, and biodiversity. Tracking how scores for the ten goals contribute to the OHI score for each LME provides insight into which goals drive overall ocean health and which parameters are in most need of improvement. The LMEs with the lowest OHI scores are those along the equator, which suggests that priority should be given to improving LME health in tropical regions. The highest scoring LMEs are around Australia and in the sub-polar North Atlantic. Ocean health tends to score lower where coastal habitats are degraded or destroyed. Habitat restoration and protection is therefore a key strategy for improving ocean health. The use of the OHI together with the CHI Index can inform management of transboundary issues. Managing to reduce human impacts should improve overall LME health. Improving data-reporting standards for all UN member states will improve assessments of ocean health and in turn improve decision making.

9.3 Patterns of risk among LMEs based on multiple indicators

Single indicators or indices provide valuable information on LME condition and drivers of change and are important for identifying LMEs at risk for the selected issue or issues. However, triggers of risk are usually multiple factors, which may be some combination of biophysical, socio-economic, or governance-related factors. The complexity of human–environmental interactions in coastal waters presents challenges in developing a single set of criteria against which to rank and prioritize LMEs. For this assessment, the Human Development Index (HDI) was used as a weighting factor in determining an overall risk score for each LME.

LMEs at 'highest' overall risk are fringed by developing countries in Africa and Asia, while those at 'high' risk include the Mediterranean LME and LMEs in South and Central America. LMEs with largely rural coastal areas of developed countries, such as the East Siberian Sea or LMEs surrounded by developed countries with frequented shipping routes are at 'medium' risk. The coastal waters of the US and Canadian LMEs are at 'low' risk, and the Australian and New Zealand Shelf LMEs are in the 'lowest' risk category. Results relate to the scale of the entire LME and do not reflect on any individual country's management of its coastal waters. Patterns may change as more spatial data specific to the LMEs become available and depend on the weighting factors used.

9.4 Overall conclusion

This first global comparative assessment of LMEs provides a valuable snapshot of LME condition with respect to a number of priority issues identified in Transboundary Diagnostic Analyses conducted as part of GEF LME projects – for example, unsustainable fishing, pollution, habitat destruction, and climate change. The patterns of risk among LMEs (based on single as well as multiple indicators for both the human and natural systems) have highlighted those LMEs at highest potential risk of degradation and the contributing factors, as well as where human dependence on LMEs services and vulnerability to LME degradation and natural phenomena are greatest.

Exploring human–environment interactions in the assessment, with a focus on human dependence on ecosystem services and vulnerability to environmental degradation and climate-related natural phenomena, reveals patterns that are relevant for management and provides a multidimensional basis for determining risk. Management and response options can be tailored to suit the specific socio-economic and environmental conditions in each LME.

Assessment results based on single indicators and indices, as well as on multivariate indicators, are fairly consistent. They show that, in general, LMEs in developing regions (GEF-eligible) are at highest potential risk. However, LMEs are impacted to different degrees by each issue assessed, and the factors accounting for high risk vary across LMEs. These factors are largely anthropogenic and local and regional in scale. But global threats (warming seas and acidification) are projected to play an increasing role in determining LME condition, as seen in changes in fish catch potential under future warming, Reefs at Risk with warming and acidification, and the CHI Index. Furthermore, in a business-as-usual scenario, risk levels in a number of LMEs are projected to rise in the future due to factors such as increasing nutrient inputs from watersheds and increasing coastal populations. While this assessment focuses attention on LMEs at relatively high risk, low and medium risk LMEs should not be ignored, as appropriate actions will be necessary to ensure that the risk levels in them do not increase.

Because this was a global comparative assessment across all LMEs, it was not possible to examine cause and effect, which is likely to vary among and within LMEs. Detailed assessments, including at the sub-LME scale, are needed to link cause and effect in the conceptual framework for specific issues. More conclusive results can be obtained with improved data, including data at the sub-LME scale. While this assessment presents an approach for prioritization of LMEs based on multiple indicators, other types of indices can be created from the indicators based on stakeholder priorities and user-defined weightings.

9.5 Target audience

While the GEF Secretariat is the main target audience for this assessment, there are other major potential beneficiaries of both the assessment and its methodology, including GEF LME projects (specifically for the transboundary diagnostic analysis and strategic action programme processes), and LME commissions or similar regional bodies. This assessment will also provide the LME community of practitioners with a robust, tested, and harmonized assessment methodology and results that can be used to engage local stakeholders responsible for management of marine resources. The assessment provides a valuable baseline for future assessments using the suite of indicators, especially as most are regularly monitored or assessed at spatial scales that are amenable to aggregation at LME or other scales. This baseline and the assessment methodology can make a significant contribution to other marine assessment processes such as the World Ocean Assessment and the Regional Seas state of the coast reporting.

The LME assessment has been completed at an opportune time with respect to the UN's new post-2015 development agenda and its Sustainable Development Goal (SDG) 14 that calls for nations to *"conserve and sustainably use the oceans, seas and marine resources for sustainable development."* A number of the key targets are well-aligned with those of LMEs, including the need to reduce marine pollution of all kinds (including nutrients), to sustainably manage and protect marine and coastal ecosystems, and to support sustainable development of fisheries. This assessment and future LME assessments support the monitoring of progress towards SDG 14.

The TWAP LME assessment results and data are freely available on the LMEs data portal (onesharedocean.org). The majority of the data sets used to assess the indicators consist of global, gridded data that can be scaled to other geographical units such as Regional Seas, countries, or smaller scales. These 'raw' data sets are available from the respective TWAP LME partners.

9.6 Future TWAP LME assessments

The second objective of the current TWAP project was to formalize a partnership with key institutions aimed at incorporating transboundary considerations into regular assessment programmes, resulting in periodic assessments of transboundary water bodies. The current consortium of institutional partners and individual experts is the foundation for a formal partnership for future LME assessments, and partners have expressed their interest in contributing to such assessments. Other partners will be identified as necessary for the next assessment. The potential mechanisms for sustaining the TWAP LME assessment are described the TWAP LMEs Sustaining Mechanisms document.

Future assessments will require improvements in data, with a focus on better quality and filling temporal and spatial gaps. In addition, ground-truthing is needed to validate remotely-sensed data used in the assessment. As indicated in the individual chapters, confidence levels in the assessment depend to a large extent on the availability or quality of the data underpinning the indicators or models. Maintaining and sustaining the current data portal as new data and information become available will also be critical in facilitating and improving future assessments. Adequate resources will be required to ensure that the portal continues to be populated with the most recent available data.

In addition to the Level 1 global comparative assessment, the original TWAP LME assessment methodology included Level 2 assessments at the sub-LME scale. Because of funding constraints, however, only a limited assessment was conducted of nutrient inputs in the Bay of Bengal LME. In order to develop appropriate management strategies for an LME, information at the sub-LME scale may be needed, depending on the issue to be addressed. The socio-economics assessment also highlighted the importance of using finer-scale geo-referenced indicators of social and economic attributes as they relate to environmental change.

Future TWAP LME assessments should incorporate Level 2 assessments and include more in-depth analysis to identify cause and effect and to ground-truth the results of the current global assessment. Additional indicators can also be assessed in the Level 2 assessment, depending on the priority issues and data availability. Future assessments should also include an evaluation of the performance of governance arrangements for transboundary issues.

The TWAP LME assessment will greatly benefit from strengthening the capacity at national and regional levels for conducting assessments and for applying the results to develop management strategies for addressing transboundary issues in LMEs. Mechanisms to facilitate capacity strengthening include the GEF LME-Learn project and the LME community of practitioners. In addition, closer engagement with relevant regional stakeholders will be an important exercise to ensure that the assessment meets their needs for information to manage their respective LMEs and promote their acceptance and uptake of the assessment results.

Finally, and very importantly, the sustainability of TWAP LME assessments will depend to a large extent on the availability of adequate financial resources. The current assessment was conducted with U$400 000 support from the GEF. While this was a relatively small sum for a global comparative assessment of all LMEs, it was through this and several times this amount of co-financing from partners, as well as partners' continued interest and commitment, that such a comprehensive assessment has been realized. Potential mechanisms for financing future assessments are discussed in the Sustainability Mechanisms document.

Glossary

Sources: (1) as defined or used in this report; (2) GEO 5 glossary (UNEP 2012); additional sources as noted.

Adaptation (socio-economic and in relation to climate change)	Adjustment in natural or human systems to a new or changing environment, including anticipatory and reactive adaptation, private and public adaptation, and autonomous and planned adaptation. (2) Making changes in order to reduce the vulnerability of a community, society, or system to the negative effects of climate change or make the most of potential positive effects. It includes building skills and knowledge as well as making practical changes such as strengthening coastal infrastructure, adjusting farming systems, and improving water management. (SPREP 2012)
Adaptive capacity	The potential or ability of a system, region, or community to adapt to the effects or impacts of a particular set of changes. Enhancement of adaptive capacity is a practical means of coping with changes and uncertainties, reducing vulnerabilities, and promoting sustainable development. (2)
Adaptive management	A systematic management paradigm that assumes natural resource management policies and actions are not static, but are adjusted based on the combination of new scientific and socioeconomic information. (2)
Algal bloom	A large, often considered excessive, growth of algae on or near the surface of water (lakes or sea), occurring naturally or as a result of an oversupply of nutrients from organic pollution. (UNEP WCMC 2015)
Areas Beyond National Jurisdiction (ABNJ)	The United Nations Convention on the Law of the Sea (UNCLOS) provides that the areas beyond the limits of national jurisdiction include the water column beyond the Exclusive Economic Zone (EEZ), or beyond the Territorial Sea where no EEZ has been declared and the seabed which lies beyond the limits of the continental shelf. (UNEP WCMC 2015)
Arrangement (governance)	The formal documentation and the institutional structures that have been put in place to implement an agreement. (1)
Assessment (environmental)	The entire process of undertaking an objective evaluation and analysis of information designed to support environmental decision making. It applies the judgement of experts to existing knowledge to provide scientifically credible answers to policy-relevant questions, quantifying where possible the level of confidence. It reduces complexity but adds value by summarizing, synthesizing, and building scenarios, and identifies consensus by sorting out what is known and widely accepted from what is not known or not agreed. It sensitizes the scientific community to policy needs and the policy community to the scientific basis for action. (2)
Bacteria (marine)	Bacteria (microscopic one-celled organisms) that feed on nano-picoplankton. (1)
Benthic	Bottom-dwelling; living on or under the sediments or other substrate. (UNEP WCMC 2015)
Benthivores	Marine organisms that feed on benthos. (1)
Billion	10^9 (1 000 000 000)
Binding agreement	An agreement, such as a treaty, which gives rise to an obligation under international law. As contrasted, for example, with a declaratory resolution, a voluntary code of conduct or a political commitment. (UNITAR 2005)
Biodiversity (a contraction of biological diversity)	The variety of life on Earth, including diversity at the genetic level, among species and among ecosystems and habitats. It includes diversity in abundance, distribution, and behaviour. (2)
Biomass	Organic material, above and below ground and in water, both living and dead. (2)
Bleaching (of coral reefs)	A phenomenon occurring when corals under stress expel their mutualistic microscopic algae, called zooxanthellae. This results in a severe decrease or even total loss of photosynthetic pigments. Since most reef-building corals have white calcium carbonate skeletons, these then show through the corals' tissue and the coral reef appears bleached. (2)
Bottom-impacting fishing gear	Fishing gear types that can damage marine benthic habitat, including dredges and bottom trawls. (1)
Bycatch (fisheries)	Species taken incidentally in a fishery; bycatch species may be of lesser value than the target species, and are often discarded. Some bycatch species are of commercial value and are retained for sale. Bycatch often consists of the juveniles of commercial species, and their loss has a deleterious impact on the overall yield obtained from a certain area. (Froese and Pauly 2015)
Capacity	The combination of all the strengths, attributes and resources available within a community, society or organization that can be used to achieve agreed goals. (UNISDR 2007)
Catchment (area)	The area of land from which precipitation drains into a river, basin, or reservoir. (2)
Chlorophyll	The green pigment involved in photosynthesis. (1)
Climate change	A change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods. (UNFCCC 2014)

Cluster analysis (statistics)	A set of multivariate statistical techniques for grouping objects that are similar. (1)
Confidence level (statistical)	Probability that the provided estimates will be correct (that is, that the estimate or range of estimates will in fact contain the true value of the parameter). (Statcan 2013)
Correlation (statistical)	A statistical measure of the relationship between measurable variates or ranks often expressed as a percent. (1) In a negative correlation, the two variables tend to go in opposite directions. As one variable increases, the other variable decreases. Therefore, it can also be called an inverse relationship. In a positive correlation, the two variables tend to move in the same direction. When one variable increases, the other variable also increases. (Statcan 2013)
Data set	Any grouping of data which has a common theme or similar attributes. (Statcan 2013)
DDT (dichlorodiphenyltrichloro-ethane)	Includes DDT, a synthetic organochlorine insecticide, and its metabolites (degradation products), DDD and DDE. One of the persistent organic pollutants listed for control under the Stockholm Convention on Persistent Organic Pollutants. (1)
Dead zone	A part of a water body so low in oxygen that normal life cannot survive. The low-oxygen conditions usually result from eutrophication caused by fertilizer run-off from land. (2)
Demersal (fish and fisheries)	Desmersal fish live and feed on or near the seabed. (1)
Disaster	A serious disruption of the functioning of a community or a society involving widespread human, material, economic or environmental losses and impacts, which exceeds the ability of the affected community or society to cope using its own resources. (UNISDR 2007)
Drainage basin (also called watershed, river basin or catchment)	Land area where precipitation runs off into streams, rivers, lakes, and reservoirs. It is a land feature that can be identified by tracing a line along the highest elevations between different areas, often a ridge. (2)
Driver	The overarching socio-economic forces that exert pressures on the state of the environment. (2)
Ecological footprint	A measure of the area of biologically productive land and water an individual, population or activity uses to produce all the resources it consumes and to absorb the corresponding waste (such as carbon dioxide emissions from fossil fuel use), using prevailing technology and resource management practices. (2)
Ecosystem	A dynamic complex of plant, animal, and micro-organism communities and their non-living environment, interacting as a functional unit. (2) The boundaries of what could be called an ecosystem are somewhat arbitrary, depending on the focus of interest or study. Thus the extent of an ecosystem may range from very small spatial scales to, ultimately, the entire Earth. (SPREP 2012)
Ecosystem health	The degree to which ecological factors and their interactions are reasonably complete and function for continued resilience, productivity, and renewal of the ecosystem. (2)
Ecosystem resilience	The level of disturbance that an ecosystem can withstand without crossing a threshold to become a different structure or deliver different outputs. Resilience depends on ecological dynamics as well as human organizational and institutional capacity to understand, manage, and respond to these dynamics. (2)
Ecosystem services (or ecosystem goods and services)	The benefits of ecosystems. These include provisioning services, such as food and water; regulating services, such as flood and disease control; cultural services, such as spiritual, recreational, and cultural benefits; and supporting services, such as nutrient cycling, that maintain the conditions for life on Earth. (2)
Ecosystem-based management	An approach to maintaining or restoring the composition, structure, function and delivery of services of natural and modified ecosystems for the goal of achieving sustainability. It is based on an adaptive, collaboratively developed vision of desired future conditions that integrates ecological, socioeconomic, and institutional perspectives, applied within a geographic framework, and defined primarily by natural ecological boundaries. (2)
Environmental degradation	The reduction of the capacity of the environment to meet social objectives and needs. Potential effects are varied and may contribute to an increase in vulnerability and the frequency and intensity of natural hazards. Some examples: land degradation, deforestation, desertification, wild land fires, loss of biodiversity, land, water and air pollution, climate change, sea-level rise, and ozone depletion. (SPREP 2012).
Eutrophication	The degradation of water or land quality due to enrichment by nutrients, primarily nitrogen and phosphorous, which results in excessive plant (principally algae) growth and decay. Eutrophication of a lake normally contributes to its slow evolution into a bog or marsh and ultimately to dry land. Eutrophication may be accelerated by human activities that speed up the aging process. (2)
Exclusive economic zone (EEZ)	A marine zone prescribed by the Convention on the Law of the Sea. A state has special rights for exploration and use of marine resources within its EEZ. (2)
Food chain	An abstraction describing the network of feeding relationships in a community as a series of links of trophic levels, such as primary producers, herbivores, and primary carnivores. (Froese and Pauly 2015)

Food security	The World Food Summit of 1996 defined food security as existing "*when all people at all times have access to sufficient, safe, nutritious food to maintain a healthy and active life*". (WHO 2015)
Food web	Network of food chains in an ecosystem. (Froese and Pauly 2015)
Geographic Information System (GIS)	A computer-based tool used for collection and analysis of geographic data. Increasingly used for hazard and vulnerability mapping and analysis, as well as for the application of disaster risk management measures. (SPREP 2012)
Global warming	Increase in surface air temperature, referred to as the global temperature, induced by emissions of greenhouse gases into the air. (2)
Governance	The act, process, or power of governing for the organization of society/ies. For example, there is governance through the state, the market, or through civil society groups and local organizations. Governance is exercised through institutions: laws, property-rights systems, and forms of social organization. (2)
Greenhouse gas	The atmospheric gases responsible for causing global warming and climate change. The major greenhouse gases are carbon dioxide, methane, and nitrous oxide. (UNFCCC 2014)
Gross domestic product (GDP)	The value of all final goods and services produced in a country in one year. GDP can be measured by adding up all of an economy's incomes – wages, interest, profits, and rents – or expenditures – consumption, investment, government purchases, and net exports (exports minus imports). (2)
Ground-truthing	A process by which the content of satellite images, aerial photographs – or maps based on them – is compared with the reality on the ground through site visits and field surveys. It is used to verify the accuracy of the images or the way they have been interpreted to produce maps. (2)
Hazard	A potentially damaging physical event, phenomenon, or human activity that may cause the loss of life or injury, property damage, social and economic disruption, or environmental degradation. (2)
HCHs (hexachlorocyclohexane isomers)	Organochlorine insecticides used from the 1950s to the 1970s in many countries and as late as the 2000s in some countries. One of the persistent organic pollutants listed for control under the Stockholm Convention on Persistent Organic Pollutants. (1)
Human well-being	The extent to which individuals have the ability to live the kinds of lives they have reason to value; the opportunities people have to pursue their aspirations. Basic components of human well-being include security, meeting material needs, health and social relations. (2)
Hydrographic fronts	Boundaries between water masses with different physical properties. (1)
Hypoxia	Lack of oxygen. In the context of eutrophication and algal blooms, hypoxia is the result of a process that uses up dissolved oxygen in the water. (2)
Implementation	Actions (legislation or regulations, judicial decrees, or other actions) that governments take to translate international accords into domestic law and policy. (UNFCCC 2014)
Index	A measure that combines two or more indicators, often with weighting factors to adjust for the relative importance of the indicators. (1)
Indicator	Information based on measured data used to represent a particular attribute, characteristic, or property of a system. (UNEP WCMC 2015)
Invasive species	A species whose introduction and/or spread threatens biological diversity. (UNEP WCMC 2015)
Landing (fisheries)	Weight of what is landed at a landing site. May be different from the catch (which includes the discards). Landing value: Value of a product at the landing point (location at which boats land their catch), not taking account of any transportation or handling costs. (FAO 2015)
Large marine ecosystem (LME)	Relatively large areas (200 000 km^2 or more) encompassing coastal areas extending from river basins and estuaries to the seaward boundaries of continental shelves and to the outer margins of major coastal currents or enclosed/semi-enclosed seas. (1)
Mangrove	Highly productive tropical coastal system consisting mainly of trees and shrubs that are adapted to marine and estuarine conditions. (1)
Marine protected area (MPA)	A geographically defined marine area that is designated or regulated and managed to achieve specific conservation objectives. (2)
Mesozooplankton	Plankton that graze on microplankton. (1)
Microplankton	Plankton cells larger than 20 micrometres; principally diatoms and large dinoflagellates. (1)
Microzooplankton	Plankton cells larger than 20 micrometres that feed on bacteria. (1)
Mitigation	The lessening or limitation of the adverse impacts, for example of pollution or of hazards and related disasters. (UNISDR 2007) In the context of climate change, a human intervention to reduce the sources or enhance the sinks of greenhouse gases. Examples include using fossil fuels more efficiently for industrial processes or electricity generation, switching to solar energy or wind power, improving the insulation of buildings, and expanding forests and other 'sinks' to remove greater amounts of carbon dioxide from the atmosphere. (UNFCCC 2014)

Multilateral environmental agreements (MEAs)	Treaties, conventions, protocols, and contracts between several states regarding specified environmental problems. (2)
Nano-picoplankton	Combined nanoplankton and picoplankton production. (1)
Nanoplankton	Plankton cells 2 to 20 micrometres. (1)
Nutrients	The approximately 20 chemical elements known to be essential for the growth of living organisms, including nitrogen, sulphur, phosphorus and carbon. (2)
Ocean acidification	An ongoing rise in acidity of ocean and sea waters. This is due to higher levels of dissolved carbon dioxide, which are a direct result of increased levels of carbon dioxide in the atmosphere. (SPREP 2012)
PCBs (polychlorinated biphenyls)	Synthetic organochlorine chemicals used for a variety of industrial applications from the 1950s to the early 1970s. One of the persistent organic pollutants listed for control under the Stockholm Convention on Persistent Organic Pollutants. (1)
Pelagic (fish and fisheries)	Pelagic fish spend most of their lives swimming in the water column with little contact with or dependency on the bottom. Usually refers to the adult stage of a species. (FAO 2015)
Persistent organic pollutants (POPs)	Chemical substances that persist in the environment, bioaccumulate through the food web, and pose a risk of causing adverse effects to human health and the environment. (2)
Phytoplankton	Microscopically small plants that float or swim weakly in fresh or saltwater bodies. (2)
Picoplankton	Plankton cells 0.2 to greater than 2 micrometres. (1)
Piscivores	Marine organisms that feed on fish. (1)
Planktivores	Marine organisms that feed on plankton. (1)
Policy	Any form of intervention or societal response. This includes not only statements of intent, but also other forms of intervention, such as the use of economic instruments, market creation, subsidies, institutional reform, legal reform, decentralization and institutional development. Policy can be seen as a tool for the exercise of governance. (2)
Policy cycle	The iterative process of decision making. A generalized cycle includes the provision of relevant data and information that are then provided in the form of analysis and advice to those making decisions. These decisions are then implemented, monitored, and evaluated to determine the level of success in addressing the problem for which the cycle was initiated. (1)
Pollutant	Any substance that causes harm to the environment when it mixes with soil, water or air. (2)
Pollution	The presence of minerals, chemicals or physical properties at levels that exceed the values deemed to define a boundary between good or acceptable and poor or unacceptable quality, which is a function of the specific pollutant. (2)
Poverty	The state of one who lacks a defined amount of material possessions or money. Absolute poverty refers to a state of lacking basic human needs, which commonly include clean and fresh water, nutrition, health care, education, clothing, and shelter. (2)
Primary productivity	Primary production, the photosynthesis of organic matter, supports and governs all ecosystem production. It drives the flow of energy through food webs in LMEs and is related to the carrying capacity of LMEs for supporting biological diversity, including fisheries resources. (1)
Principal Components Analysis (PCA) (statistics)	A classification and ordination statistical technique that develops new sets of variables (principal components) based on the variance of the values of the original variables. The first PC accounts for as much of the overall variance as possible, the second PC accounts for as much of the remaining variance as possible, and so on. (1)
Projection	The act of attempting to produce a description of the future subject to assumptions about certain preconditions, or the description itself. (2)
Protected area	A clearly defined geographical space, recognized, dedicated, and managed, through legal or other effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values. (2)
Purchasing power parity (PPP)	The number of currency units required to purchase an amount of goods and services equivalent to what can be bought with one unit of the currency of the base country, for example, the US$. (2)
Regression (statistical)	A statistical method which tries to predict the value of a characteristic by studying its relationship with one or more other characteristics. (Statcan 2013)
Resilience	The capacity of a system, community, or society potentially exposed to hazards to adapt by resisting or changing in order to reach and maintain an acceptable level of functioning and structure. (2)
Risk	The chance of danger, loss, income reduction, or diminished or lost opportunity for an improved life for an individual, a household, or a community. (2)
Run-off	A portion of rainfall, melted snow, or irrigation water that flows across the ground's surface and is eventually returned to streams. Run-off can pick up pollutants from air or land and carry them to receiving waters. (2)

Scale	The spatial, temporal (quantitative or analytical) dimension used to measure and study any phenomena. Specific points on a scale can thus be considered levels (such as local, regional, national, and international). (2)
Scenario (or pathway)	A description of how the future may unfold based on if–then propositions, typically consisting of a representation of an initial situation, a description of the key drivers, and changes that lead to a particular future state. (2)
Sea-level rise	A phenomenon that has been increasing in recent decades due to global warming. There are two causes: thermal expansion as the ocean waters get warmer and the melting of ice from warming glaciers. (SPREP 2012)
Sediment	Solid material that originates mostly from disintegrated rocks and is transported by, suspended in, or deposited from water, wind, ice, and other organic agents. (2)
Species (biology)	An interbreeding group of organisms that is reproductively isolated from all other organisms, although there are many partial exceptions to this rule. A generally agreed fundamental taxonomic unit that, once described and accepted, is associated with a unique scientific name. (2)
Stock (fishing)	A taxon (at either species, genus, or family level of taxonomic assignment) that occurs in the catch records for at least five consecutive years, over a minimum of a ten-year time span, and that has a total catch in an area of at least 1 000 tonnes over the time span analyzed. (1)
Sustainability	A characteristic or state whereby the needs of the present population can be met without compromising the ability of future generations or populations in other locations to meet their needs. (2)
Sustainable development	Development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs. (2)
Threshold	The level of magnitude of a system process at which sudden or rapid change occurs. (2)
Toxic (pollutants)	Pollutants that cause death, disease, or birth defects in organisms that ingest or absorb them. (2)
Transboundary issue	An area of concern that has been identified and documented as affecting more than one country within a given LME. (1)
Transboundary LME	An LME bordered by two or more coastal countries. (1)
Trillion	10^{12} (1 000 000 000 000)
Trophic level	Successive stages of nourishment as represented by the links of the food chain. Put simply, the primary producers (phytoplankton) constitute the first trophic level, herbivorous zooplankton the second, and carnivorous organisms the third trophic level. (2)
Urbanization	An increase in the proportion of the population living in urban areas. (2)
Variance (statistical)	A measure of spread, calculated as the average squared deviation of each number from the mean of a data set. (Statcan 2013)
Vulnerability	The level of susceptibility of an individual, a community, an organization, or a system to adverse conditions, emergencies, or disasters; a measure of its ability, or inability, to cope. (SPREP 2012)
Warm-water coral reef	A wave-resistant carbonate structure which is gradually built by stony corals, calcareous algae, and other reef-building organisms. Warm-water coral reefs occur in the coastal areas of tropical and subtropical regions. (UNEP WCMC 2015)
Water quality	The chemical, physical, and biological characteristics of water, usually in respect to its suitability for a particular purpose. (2)
Western Pacific Warm Pool (WPWP)	An area of open-ocean warm water in the western Pacific Ocean, north of Papua New Guinea. (1)

References

FAO (2015). *FAO term portal.* Food and Agriculture Organization of the United Nations. http://www.fao.org/faoterm/en/?defaultCollId=21 (accessed 29 December 2015)

Froese, R. and D. Pauly. Editors. 2015. *FishBase*. World Wide Web electronic publication. http://www.fishbase.org version (10/2015) (accessed 29 December 2015)

SPREP (2012). *Glossary, Pacific Climate Change Portal.* Secretariat of the Pacific Regional Environment Programme. http://www.pacificclimatechange.net/index.php/glossary (accessed 29 December 2015)

Statcan (2013). *Statistics: power from data! Glossary*. Statistics Canada. http://www.statcan.gc.ca/edu/power-pouvoir/glossary-glossaire/5214842-eng.htm#v (accessed 29 December 2015)

UNEP (2012). *Global Environment Outlook GEO 5: Environment for the future we want*. United Nations Environment Program, Nairobi, Kenya

UNFCCC (2014). *Glossary of climate change acronyms*. United Nations Framework Convention on Climate Change. http://unfccc.int/essential_background/glossary/items/3666.php (accessed 29 December 2015)

UNISDR (2007). *Terminology*. The United Nations Office for Disaster Risk Reduction. https://www.unisdr.org/we/inform/terminology (accessed 29 December 2015)

UNITAR (2005). *A Glossary of terms for UN delegates*. United Nations Institute for Training and Research. http://www.unitar.org/mdp/sites/unitar.org.mdp/files/Glossary_E.pdf (accessed 29 December 2015)

WHO 2015. *Programmes: food security*. http://www.who.int/trade/glossary/story028/en/ (accessed 29 December 2015)

The water systems of the world – aquifers, lakes, rivers, Large Marine Ecosystems (LMEs), and the open ocean – sustain the biosphere and underpin the health and socioeconomic wellbeing of the world's population. Many of these systems are shared by two or more nations. The transboundary waters, which stretch over 71% of the planet's surface, in addition to the transboundary subsurface aquifers, and the water systems entirely within the boundaries of the individual countries, comprise humanity's water heritage.

Recognizing the value of transboundary water systems, and the reality that many of them continue to be overexploited and degraded, and managed in fragmented ways, the Global Environment Facility (GEF) initiated the Transboundary Waters Assessment Programme (TWAP) Full Size Project in 2012. The Programme aims to provide a baseline assessment to identify and evaluate changes in these water systems caused by human activities and natural processes, as well as the possible consequences of these changes for the human populations that depend on them. The institutional partnerships forged in this assessment are expected to seed future transboundary assessments.

The final results of the GEF TWAP are presented in six volumes:

Volume 1 – ***Transboundary Aquifers and Groundwater Systems of Small Island Developing States: Status and Trends***
Volume 2 – ***Transboundary Lakes and Reservoirs: Status and Trends***
Volume 3 – ***Transboundary River Basins: Status and Trends***
Volume 4 – ***Large Marine Ecosystems: Status and Trends***
Volume 5 – ***The Open Ocean: Status and Trends***
Volume 6 – ***Transboundary Water Systems: Crosscutting Status and Trends***

A ***Summary for Policy Makers*** accompanies each volume.

This document - Volume 4 - presents the first global indicator-based comparative baseline assessment of the world's 66 Large Marine Ecosystems. An assessment of the Western Pacific Warm Pool is also included. LMEs produce nearly 80 per cent of the world's annual marine fish catch, and their ecosystem services contribute an estimated US$28 trillion annually to the global economy. Yet, they are centers of land-based pollution, coastal habitat degradation, overfishing, biodiversity loss, and climate change effects.

www.unep.org

United Nations Environment Programme
P.O. Box 30552 - 00100 Nairobi, Kenya
Tel.: +254 20 762 1234
Fax: +254 20 762 3927
e-mail: publications@unep.org
www.unep.org

UNEP

ISBN: 978-92-807-3531-4
Job Number: DEW/1953/NA