Edward R. Urban Jr.
Venugopalan Ittekkot *Editors*

Blue Economy

An Ocean Science Perspective

Springer

Blue Economy

Edward R. Urban Jr. · Venugopalan Ittekkot
Editors

Blue Economy

An Ocean Science Perspective

Springer

Editors
Edward R. Urban Jr.
Scientific Committee on Oceanic Research
Newark, DE, USA

Venugopalan Ittekkot
University of Bremen
Bremen, Germany

ISBN 978-981-19-5064-3 ISBN 978-981-19-5065-0 (eBook)
https://doi.org/10.1007/978-981-19-5065-0

This Springer imprint is published by the registered company Springer Nature Singapore Pte Ltd.
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

Foreword

Of the 17 Sustainable Development Goals (SDGs) of the United Nations' 2030 Agenda, SDG 14 specifically focuses on "life under water", a major portion of which is related to the ocean. But the ocean's importance in sustainable development is not limited to the SDG 14 and the ocean's contribution to other SDGs should not be overlooked. The ocean is also an important component in achieving the SDGs that are related to economic activities and community development, including, SDGs 1, 2, 3, 5, 7, 8, 9, 10, and 11.

Obviously, ocean-related economy plays a vital role for global sustainable development. It is particularly important for developing coastal states and small islands. In these countries, tourism and other important ocean-based sectors can account for much higher portion of national GDP, compared to those of Organisation for Economic Co-operation and Development (OECD) countries. Because of this greater reliance on ocean-based sectors, developing countries are prone to greater risks from climate and anthropogenic change. In this respect, the blue economy has gained a lot of attention recently. However, the term "blue economy" has been used without a clear definition, sometimes interchangeable with similar terms such as "ocean economy" or "marine economy". A practical, succinct definition of the blue economy would be a sustainable kind of ocean or marine economy. Examples are sustainable fisheries, sustainable tourism, renewable ocean energy, green shipping, ocean conservation, and reduction of ocean pollution, just to name a few. However, the sustainability of ecosystem management is a complicated issue as we try to establish optimal use across many sectors. Multiple stakeholders have different interests and, consequentially, conflicts or problems may be incurred. To make matters more complicated, solutions would be specific to each level of geopolitical organization and governance. Every nation may have different solutions. Even within each nation, provinces may have different agendas. To achieve a balance between risks and benefits across all ocean sectors under various geopolitical settings, scientific guidance is vital. Despite its importance, the science for the blue economy is still largely an uncharted sea. To this end, this volume provides a very timely discussion on the science and technology for the blue economy. It discusses a comprehensive set of topics related to the blue economy: biodiversity, blue carbon, tourism, living and nonliving resources, various forms of threats, economics, observations, and capacity development. The science and technology for the blue economy has not been discussed in a rigorous, comprehensive manner and this book will open a new avenue for the forthcoming discussion.

Busan, Korea

Sinjae Yoo
President of SCOR

Preface

The ocean is now a major factor in the development of many coastal nations. For many developing countries resources and services from the ocean are a major source of income. To gain maximum benefits from the ocean, many of them have developed ocean-based national development plans. Very often economic gains remain at the core of these plans. Their implementation, however, occurs at a time when the ocean is already under threat from a variety of human activities, and now with the added stress from the impact of climate change. The combined effect of accelerating blue economic activities, and the impact of climate change threaten the sustainability of ocean use for human benefits. These challenges to blue economy are reflected in the World Bank definition of blue economy with its three pillars: environmental, economic, and social sustainability.

For blue economic development, the UN's Agenda 2030 and the SDGs provide a unique guiding platform, and its newly launched Decade of Ocean Science for Sustainable Development provides the necessary impetus to bring in the science for the sustainability of human interactions with the ocean. As a contribution to these efforts and with a view to creating awareness of the involved science and technology issues around blue economy among developing countries, the Science and Technology Centre of the Non-Aligned Movement and Other Developing Countries (NAM S&T Centre) initiated the preparation of this monograph and invited us to get involved as Editors.

The Monograph explores the challenges to blue economy from an environmental—ocean science—perspective. The premise is that scientific understanding of ocean processes and ecosystem functions is a prerequisite for functional and sustainable blue economy. The first set of chapters provide examples of ocean ecosystems and resources as well as the needed science to better understand and monitor their response to climate change and other human—blue economic—activities. Subsequent chapters describe the available ocean research and monitoring observation tools, the capacity development needs of developing countries for the practice of blue economy, and the opportunities available at national, regional, and global levels.

We are grateful to colleagues from around the world who were willing to share their time and efforts to contribute the chapters of the book. Their experience and knowledge gained in South-South and North-South cooperation in ocean studies and through their participation in SCOR's (Scientific Committee for Ocean Research) Visiting Scholars Program have enriched the chapters with a wide variety of regional examples. The discussion at a joint NAM S&T Centre—SCOR Exposure Workshop on the topic with the participation of the authors has been helpful in fine-tuning the chapter contents. Primarily organized as a capacity-development exercise for participants from NAM S&T Centre and SCOR member countries, the Workshop also helped to gather input from the global community on the topics of the book chapters, and to demonstrate the work of the NAM S&T Centre and SCOR to a global audience.

Chapter authors were selected based on their work in developing countries, either living and working there, or serving as visiting scientists through the SCOR Visiting Scholars program and other activities. A major strength of the book is the wealth of case studies provided. We appreciate the efforts of the many chapter authors, without which the book would have lacked the richness of local examples and expert knowledge. We thank the chapter reviewers, who helped improve the quality of this book: Janice Cumberbatch, Sean Fennessy, Ken Furuya,Tim Jennerjahn, Joanna Waniek, Robert Weller, and several anonymous reviewers.

We thank the NAM S&T Centre for initiating and inviting us to be part of this endeavor and Springer Nature for their commitment to producing such a book. We hope that this book can serve as a resource for training in developing countries. The editors will devote any royalties from sales of this book to training programs for developing country scientists through the Scientific Committee on Oceanic Research of the International Science Council.

Newark, DE, USA Edward R. Urban Jr.
Bremen, Germany Venugopalan Ittekkot

Introduction

The oceans provide a major source of income for many coastal nations, particularly in the developing world. Economic benefits from the oceans depend on wise management of resources based on scientific understanding and appropriate application of technologies available. The intersection of science, technology, and economy is most obvious in nations' coastal zones.

Recognition of the significance of economic benefits from the oceans for national economies led to the development of the term "Blue Economy" at the UN Conference on Sustainable Development held in Rio de Janeiro, Brazil, in 2012. A useful definition of Blue Economy that is used by the World Bank for a Sustainable Ocean Economy is given as: *"the sustainable* use *of ocean resources for economic growth, improved livelihoods and jobs while preserving the health of ocean ecosystems."*

Advancement in science and technology through research and observations is needed to maximize blue economic benefits in a sustainable manner. Ignoring science can lead to resource extraction that is not sustainable, damaging the resources, the natural environment, and human society in ways that may significantly reduce the benefits available. In many developing countries, however, the currently available capacity to conduct ocean research and observations is still inadequate. Governments need to put in measures to enhance this capacity at the national level, particularly to promote ocean education and research. Given the excellent oceanographic capacities achieved by some among the NAM Member Countries, there is also huge potential for South—South Cooperation, as well as Triangular Cooperation, to augment national efforts.

This Monograph—*Blue Economy: An Ocean Science Perspective*—in its sixteen chapters describes how science and technology can be applied to improve the management of coastal resources for the best economic outcomes. It brings together scientific communities from both the developing and the developed world with comprehensive foundational understanding of the ocean science and technology available and related gaps to maximizing the safe use of the resources, mitigating the threats, and building overall blue economic capacity in a sustainable manner.

The chapters of the book have been categorized into dedicated sections on: (i) Resources, (ii) Threats, (iii) Observations, and (iv) Developing Capacity for Ocean Science and Technology that provide significant insights focused on coral reefs, seagrasses and mangroves, coastal fisheries, freshwater extraction, tourism, oil and gas, minerals, coastal pollution, harmful algae, ocean acidification, climate change and coastal ecosystems, blue economic prospects of small islands, observing systems, and building capacity for ocean science and technology.

The book altogether summarizes that only through appropriate scientific understanding and experience in the latest technological developments related to conserving and managing ocean resources, blue economies can be developed and sustained worldwide.

In this connection, I am proud to mention that in anticipation of publication of this Monograph, the NAM S&T Centre in collaboration with the Scientific Committee on Oceanic Research (SCOR), Newark, Delaware, United States, organized an International Workshop on Application of Ocean Science and Technology for the Practice of Sustainable "Blue Economy" in Developing Countries during 8–9 November 2021, during which the contributed chapters of this book were presented by the lead authors/co-authors.

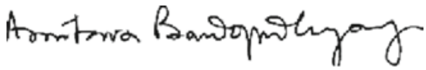
I am thankful to the editorial team of this book: Dr. Venugopalan Ittekkot, Former Director, Leibniz Center for Tropical Marine Research (ZMT), University of Bremen, Germany, and Dr. Edward R. Urban Jr., Former Executive Director, SCOR, for the scientific evaluation of the manuscripts and ensuring the best selection of the contents for wider dissemination of scientific knowledge on the chosen subject.

I express my sincere gratitude to Dr. Sinjae Yoo, President, Scientific Committee on Oceanic Research, USA, for kindly agreeing to write the "Foreword" of the Monograph.

I am thankful to Dr. Loyola D' Silva, Executive Editor, Springer Nature, Singapore, for considering this book for publication under the reputed banner of Springer Nature and Mr. Ramesh Kumaran, Project Coordinator, Springer Nature for monitoring and streamlining the publication process. I am confident that our association with "Springer" would lead to many more such valuable collaborative endeavors in future.

My sincere thanks are also due to the entire team of the NAM S&T Centre, especially to Mr. Madhusudan Bandyopadhyay (Senior Adviser) and Ms. Jasmeet Kaur Baweja (Programme Officer) for facilitating this book project. I am also thankful to Dr. Ranadhir Mukhopadhyay, Former Chief Scientist, CSIR-National Institute of Oceanography (NIO), Goa, for his inputs in bringing out this publication. I also record my appreciation for the invaluable assistance rendered by my colleagues Mr. Rahul Kumra and Mr. Pankaj Buttan towards bringing out this publication.

I am sure that this book would be a valuable reference material for scientists, researchers, government officials, policy makers, marine-sector professionals, managers, and representatives working in the areas of ocean sciences and sustainable coastal resource management.



Amitava Bandopadhyay, Ph.D.
Director General
NAM S&T Centre
New Delhi, India

Contents

Acronyms

ADCIRC	Advanced Circulation Model
AGB	Above-Ground Biomass
AIS	Automatic Identification System
AMO	Atlantic Multidecadal Oscillation
ANIBOS	Animal Borne Ocean Sensors
ASAP	Automated Shipboard Aerological Program (GOOS)
ASIRI-OMM	Air-Sea Interaction Research Initiative–Ocean Mixing Monsoon
ASP	Amnesic Shellfish Poisoning
ASV	Autonomous Surface Vehicle
AUV	Autonomous Underwater Vehicle
AWI	Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research
AZP	Azaspiracid Shellfish Poisoning
BBMP	Blue Bay Marine Park (Mauritius)
BC	Blue Carbon
BCC	Benguela Current Commission
BCE	Blue Carbon Ecosystems
BCLME	Benguela Current Large Marine Ecosystem
BMP	Balaclava Marine Park (Mauritius)
BRD	Bycatch Reducing Device
Bsi	Biogenic Silica
Bq	Becquerel
C	Carbon
CAL-VAL	calibration and validation
CARICOM	Caribbean Community
CBD	Convention on Biological Diversity
CBEMR	Community Based Ecological Mangrove Restoration
CCCCC	Caribbean Community Climate Change Centre
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utlilization, And Storage

CD	Capacity Development
CEOS	Committee on Earth Observation Satellites
CFP	Common Fisheries Policy (EC)
CGTMT	Criteria and Guidelines on the Transfer of Marine Technology (IOC)
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
COESSING	Coastal Ocean Environment Summer School in Ghana
COP	Conference of Parties
C_{org}	Organic Carbon
COSPPac	Climate and Oceans Support Program in the Pacific
CP	Ciguatera Poisoning
CPR	Continuous Plankton Recorder
CPUE	Catch Per Unit Effort
CREWS	Climate Risk and Early Warning System
DAC	Data Assembly Center
DBCP	Data Buoy Cooperation Panel
DDT	Dichlorodiphenyltrichloroethane
DIN	Dissolved Inorganic Nitrogen
DIP	Dissolved Inorganic Phosphorus
DO	Dissolved Oxygen
DOOS	Deep Ocean Observing Strategy
Dsi	Dissolved Silicon
DSP	Diarrhetic Shellfish Poisoning
DSS	Decision Support System
EAMNET	Europe Africa Marine Network program
EBM	Ecosystem-Based Management
EBSA	Ecologically and Biologically Significant Area (CBD)
EBV	Essential Biodiversity Variable
EC	European Commission
ECAL	Environment and Climate Adaptation Levy
ECMWF	European Centre for Medium-Range Weather Forecast
ECOP	Early Career Ocean Professional
ECOWAS	Economic Community of West African States
ECV	Essential Climate Variable
EEZ	Exclusive Economic Zone
EIA	Environmental Impact Assessment
EJ	Exajoules
ENSO	El Niño-Southern Oscillation
EOR	Enhanced Oil Recovery
EOV	Essential Ocean Variable
EPL	Exclusive Prospecting License (Namibia)
ESP	Environmental Sample Processor
ESSO	Earth System Science Organization (India)
EU	European Union

EU ETS	European Union Emissions Trading Scheme
EWS	Early Warning System
FAD	Fish Aggregator Device
FAIR	Findable, Accessible, Interoperable, and Reusable Data
FAO	Food and Agriculture Organisation
FDI	Foreign Direct Investment
FOO	Framework for Ocean Observations
FPSO	Floating Production Storage and Offloading
FPV	Floating Solar Photovoltaic Energy
FSDG	Freshwater Component of SDG
FSM	Federated States of Micronesia
GDAC	Global Data Assembly Center
GDP	Gross Domestic Product
GEF	Global Environment Facility
GEO BON	Group on Earth Observations Biodiversity Observation Network
GHG	Greenhouse Gas
GIS	Geographic Information System
GLOSS	Global Sea Level Observing System
GMES and Africa	Global Monitoring for Environment and Security and Africa
GMSL	Global Mean Sea Level
GMSLR	Global Mean Sea Level Rise
GOA-ON	Global Ocean Acidification—Observation Network
GOOS	Global Ocean Observing System
GO-SHIP	Global Ocean Ship-based Hydrographic Investigations Program
GOSR	Global Ocean Science Report (IOC)
GRACE	Satellite
GRAs	GOOS Regional Alliances
Gt	Gigaton
GTS	Global Telecommunication System
GW	Gigawatt
HAB	Harmful Algal Bloom
HAEDAT	Harmful Algal Event Database
HBCU	Historically Black College and University (USA)
HCH	Hexachlorocyclohexane
HRE	Huanghe River Estuary
HSE	Health, Safety and Environmental
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IFCB	Imaging Flow Cytobot
IGY	International Geophysical Year
IMBeR	Integrated Marine Biosphere Research program
INCOIS	Indian National Centre for Ocean Information Services
IndOOS	Indian Ocean Observing System

IN-MHEWS	International Network for Multi-Hazard Early Warning System
IOC	Intergovernmental Oceanographic Commission
IOD	Indian Ocean Dipole
IODE	International Oceanographic Data and Information Exchange
IOGOOS	Indian Ocean Observing System
IORA	Indian Ocean Rim Association
IPCC	Intergovernmental Panel on Climate Change
IRF	IndOOS Resources Forum
IRS	Indoor Residual Spraying
ISC	International Science Council
IUU	Illegal, Unreported, and Unregulated (Fishing)
LC-MS/MS	Liquid Chromatography with Tandem Mass Spectrometry
LDC	Least-Developed Country
LECZ	Low Elevation Coastal Zone
LiDAR	Light Detection and Ranging
LIFDC	Low-Income Food-Deficit Country
LM	Light Microscopy
LME	Large Marine Ecosystem
LMS	Learning Management System
LNG	Liquified Natural Gas
LOCO	Long-Term Ocean Climate Observation project
MACBIO	Marine and Coastal Biodiversity Management in Pacific Island Countries
MBON	Marine Biodiversity Observation Network
MCA	Marine Conservation Agreement
MEFT	Ministry of Environment, Forestry and Tourism (Namibia)
MESA	Monitoring for Environment and Security in Africa
MFMR	Ministry of Fisheries and Marine Resources (Namibia)
MJO	Madden-Julian Oscillation
ML2030	Marine Life 2030
MME	Ministry of Mines and Energy (Namibia)
MOOC	Massive Open Online Course
MPA	Marine Protected Area
MPS	Massively Parallel Sequencing
MSME	Micro Small Medium-Sized Enterprise
MSY	Maximum Sustainable Yield
Mt	Megatons
MTPA	Million Ton Per Annum
MW	Megawatt
N	Nitrogen
NAM	Non-Aligned Movement
NANO	NF-POGO Alumni Network for Oceans
NAO	North Atlantic Oscillation
NCP	Nature's Contributions to People

NCS	Norway Continental Shelf
NERR	North Equatorial Recirculation Region
ng	Nanogram
NG	Natural Gas
NGO	Non-Governmental Organization
NIOT	National Institute of Ocean Technology (India)
NODC	National Oceanographic Data Center
NOK	Norwegian kroner
NOx	Compounds Containing Nitrogen and Oxygen
NPD	Norwegian Petroleum Directorate
NPP	Net Primary Production
NWP	Numerical Weather Prediction
O&G	Oil and Gas
OA	Ocean Acidification
OACPS	Organisation for Africa Caribbean and Pacific States
OA-ICC	Ocean Acidification International Coordination Centre (IAEA)
OASIS	Observing Air-Sea Interactions Strategy
OBIS	Ocean Biodiversity Information System
OBON	Ocean Biomolecular Observing Network
OBPS	Ocean Best Practices System
OCG	Observations Coordination Group (GOOS)
OCIMS	Oceans and Coastal Information Management System (South Africa)
OCP	Organochlorine Pesticide
OOFS	Operational Ocean Forecasting System (GOOS)
OPD	Optical Phytoplankton Discriminator
OpenMODs	Open Access Marine Observation Devices
OSSE	Observing System Simulation Experiment
OTEC	Ocean Thermal Energy Conversion
OTGA	OceanTeacher Global Academy (IODE)
P	Phosphorus
PAH	Polycyclic Aromatic Hydrocarbon
Pb	Lead
PCCOS	Pacific Community Centre for Ocean Sciences
PCD	Pollution Control Department (Thailand)
PDO	Pacific Decadal Oscillation
PETM	Paleocene–Eocene Thermal Maximum
PFZ	Potential Fishing Zone
PI	Principal Investigator
PICTs	Pacific Island Countries and Territories
PM	Participant Modeling
PNG	Papua-New Guinea
POGO	Partnership for Observation of the Global Ocean
POP	Platform of Opportunity

PPEF	Pristine Paradise Environmental Fee (Palau)
Ppmv	Parts Per Million Volume
PRD	Pearl River Delta
PSMA	Port State Measures Agreement
PSP	paralytic shellfish poisoning
PUI	Peaceful Uses Initiative (IAEA)
qPCR	Quantitative Polymerase Chain Reaction
R&D	Research and Development
Ra	Radium
RAMA	Research Moored Array for African–Asian–Australian Monsoon Analysis and Prediction
RCP	Representative Concentration Pathway (IPCC)
REE	Rare Earth Element
REM	Remote Electronic Monitoring
RFMO	Regional Fisheries Management Organization
RGGI	Regional Greenhouse Gas Initiative (U.S.)
RIMES	Regional Integrated Multi-Hazard Early-warning Systems
RMICS	Regional Marine Instrument Centres
ROV	Remotely Operated Vehicle
RSCAPs	Regional Seas Conventions and Action Plans (UNEP)
RSP	Regional Seas Program (UNEP)
S&T	Science and Technology
SAGITTA	Social AGITation for Temperature Analysis
SAM	Southern Annular Mode
SAMOA	SIDS Accelerated Modalities of Action
SAMREF	South African Marine and Exploration Forum
SCOR	Scientific Committee on Oceanic Research
SDG	Sustainable Development Goal
SEM	Scanning Electron Microscopy
SGD	Submarine Groundwater Discharge
SIDS	Small Island Developing States
SL	Sea Level
SMART	Strategic Marine Alliance for Research and Training
SMART cables	Science Monitoring And Reliable Telecommunications cables
SMSP	Seychelles Marine Spatial Plan
SOI	Sustainable Ocean Initiative (CBD)
SOLAS	Surface Ocean—Lower Atmosphere Study
SOOP	Ships of Opportunity Programme (SOOP)
SOT	Ship Observations Team (GOOS)
SOx	Compounds Containing Sulfur and Oxygen
SPC	South Pacific Community
SPREP	Secretariat of the Pacific Regional Environment Programme
SPTO	South Pacific Tourism Organisation
SROCC	Special Report on the Ocean and Cryosphere in a Changing Climate (IPCC)

SRP	Soluble Reactive Phosphorus
SSP	Shared Socio-Economic Pathways (IPCC)
SST	Sea Surface Temperature
ST	Sea Temperature
TCP	Technical Cooperation Programme (IAEA)
TEM	Transmission Electron Microscopy
Tg	Teragram
TGR	Three Gorges Reservoir
Th	Thorium
TOGA	Tropical Ocean Global Atmosphere program
TSG	Thermosalinograph
TWh	Terawatt Hour
UN	United Nations
UNCLOS	United Nations Convention on the Law of the Sea
UNDP	United Nations Development Programme
UNEP	United Nations Environmental Programme
UNESCO	United Nations Educational Scientific and Cultural Organization
UNFC	United Nations Framework Classification for Resources
UNISDR	United Nations Office for Disaster Risk Reduction
USD	U.S. dollars
UV	Ultraviolet
VMCA	Voluntary Marine Conservation Area
VMS	Vessel Monitoring System
VOS	Voluntary Observing Ship Scheme (GOOS)
WESTPAC	IOC Sub-Commission for the West Pacific
WIMS	Women in Marine Science Network (WIOMSA)
WIO-ECSN	Early Career Scientists Network (WIOMSA)
WIOMSA	Western Indian Ocean Marine Science Association
WMO	World Meteorological Organization
WOCE	World Ocean Circulation Experiment
WOI	World Ocean Initiative (*Economist* Group)
WSRS	Water Sediment Regulation Scheme (China)
μatm	Microatmosphere

Chapter 1
Blue Economy and Ocean Science: Introduction

Edward R. Urban Jr., Venugopalan Ittekkot, and V. N. Attri

Abstract The book was developed to emphasize the importance of ocean science and technology in discussions of blue economy. The "blue economy" concept was developed in 1992 at the UN Conference on Sustainable Development, which also developed Agenda 21. The idea of the blue economy was used more commonly following the publication of a book by Gunter Pauli in 2010. For the purposes of this book, we adopt a World Bank definition of blue economy that balances economic, environmental, and social sustainability considerations. This chapter will introduce the blue economy concept and provide an introduction to the following chapters. The book begins with an in-depth look at a few of the most important blue economy resources (Chaps. 2–8) and threats to these resources (Chaps. 9–12). Chapter 13 focuses on the special situations of small island developing states. The need for enhanced observations (Chap. 14) and capacity development (Chap. 15) are highlighted. Finally, Chap. 16 summarizes the preceding chapters and makes recommendations for progress to better apply science and technology to developing and maintaining blue economies.

Keywords Blue economy · Ocean science and technology · Sustainability

1.1 Context

The ocean, with its huge water volume and covering 71% of Earth's surface, plays a major role in the life of humans, even those who live far from the coast. Both

E. R. Urban Jr. (✉)
Scientific Committee On Oceanic Research (SCOR) (retired), Newark, DE, USA
e-mail: ed.urban@scor-int.org

V. Ittekkot
Leibniz Centre for Tropical Marine Research, University of Bremen (retired), Bremen, Germany

V. N. Attri
Indian Ocean Studies (CIOS), Indian Ocean Rim Association (IORA), Ebene, Republic of Mauritius

E. R. Urban Jr. and V. Ittekkot (eds.), *Blue Economy*,
https://doi.org/10.1007/978-981-19-5065-0_1

products extracted from the ocean and services provided by the ocean yield benefits to humans that can be quantified in economic terms. Products from the ocean can be valued in a variety of ways, from their value as just-acquired raw materials to the sales price of value-added products. It is also possible, although more difficult, to quantify economic benefits from services provided by the ocean (Costanza et al. 1997), but not all experts agree with such valuations.

Recognition of the significance of economic benefits from the ocean for national economies led to the development of the terms "blue growth" and "blue economy" at the UN Conference on Sustainable Development (the "Earth Summit") held in Rio de Janeiro, Brazil from 3 to 14 June 1992 (e.g., IOC/UNESCO et al. 2011; Anon. 2012). The Earth Summit developed Agenda 21, focusing on sustainable development and its social, economic, conservation, and management aspects; and strengthening the role of major organizations as a means to implement Agenda 21. The concept of blue economy came into common use with the publication of the book *The Blue Economy: 10 Years, 100 Innovations, 100 Million Jobs* in April 2010 by Gunter Pauli (2010). The definition of blue economy has evolved since 2010, with different stakeholders using the term in different ways. The blue economy concept was made possible by the extension of "ownership" of coastal waters that resulted from the establishment of 200-nautical-mile Exclusive Economic Zones (EEZs) by the UN Convention on the Law of the Sea, which entered into force in 1994.

The UN continued to promote global sustainable development through the 2000 UN Millennium Declaration, which contained eight Millennium Development Goals to be achieved by 2015. Eradicating poverty and hunger; combating disease, illiteracy and environmental degradation; and achieving gender equality were among the goals. These goals were replaced by the UN's Agenda 2030 and its 17 Sustainable Development Goals (SDGs) (https://sdgs.un.org/goals) in 2015. Achievement of several of the SDGs will be made more possible by establishing blue economies. The achievement of SGD 14 (Life Below Water) and other SDGs depend on advancing and applying knowledge (Lee et al. 2020). Reaping benefits from the ocean while sustaining its health is at the core of SDG 14: "Conserve and sustainably use the oceans, seas and marine resources for sustainable development" (https://sdgs.un.org/goals/goal14). A variety of other terms including the word "blue" have been developed ("blue growth", "blue development", "blue carbon", "blue biotechnology", etc.) to indicate the importance of the ocean in environmental, economic, and social terms, as compared to the adjective "green" used for terrestrial counterparts (e.g., Eikeset et al. 2018).

The UN tracks progress toward achievement of each SDG and issues a progress report annually (e.g., United Nations 2021). The Sustainable Development Goals Report 2020 (United Nations 2021) documents that the protected percentage of waters under national jurisdiction increased from 2015 to 2019, having reached 17%. Likewise, the percentage of key biodiversity areas protected worldwide increased from 30.5% in 2000 to 46.0% in 2019. Unfortunately, Least Developed Countries (LDCs) and Small Island Developing States (SIDS) lag the global percentages in both measures. UN (2021) reported that countries have increased implementation of actions to curtail illegal, unreported, and unregulated fishing, while the proportion of fish stocks within biologically sustainable levels decreased to 65.8% in 2017. The COVID-19 pandemic has delayed implementation of several SDGs (e.g., Naidoo and Fisher 2020).

Identifying the necessity of ocean science and technology for blue economies is particularly timely, given the need to progress the SDGs to completion by 2030. SDG 14 recognizes the importance of scientific knowledge for attaining this goal. SDG Target 14A states: “Increase scientific knowledge, develop research capacity and transfer marine technology, taking into account the Intergovernmental Oceanographic Commission Criteria and Guidelines on the Transfer of Marine Technology (IOC-CGTMT), in order to improve ocean health and to enhance the contribution of marine biodiversity to the development of developing countries, in particular small island developing states and least developed countries” (https://sdgs.un.org/goals/goal14).

The UN recently launched its Decade of Ocean Science for Sustainable Development (https://oceandecade.org; hereafter referred to as the “Ocean Decade”), lasting from 2021 to 2030. The Ocean Decade was developed to generate the global ocean science needed to achieve the SDGs, particularly SDG 14. The Ocean Decade will provide an opportunity to strengthen international cooperation to develop scientific research and technologies to connect ocean science with the needs of society. It will contribute to an overall improvement in the scientific knowledge base though capacity development in regions and among groups where most needed. Successful implementation of the Ocean Decade will require cooperation across a range of stakeholders: scientists, governments, academics, policy makers, business and industry and civil society.

1.2 Blue Economy

Many different definitions of blue economy exist, depending on the goals of the organizations promoting their versions of blue economy (e.g., see Attri 2018 and Eikeset et al. 2018 for general discussions, Attri and Bohler-Muller 2018 for the Indian Ocean region, Clegg et al. 2020 for the Caribbean Sea region, Keen et al. 2017 for the Pacific Ocean region, and European Commission 2021 for the European Union). Voyer et al. (2018) present a helpful analysis of the different definitions of blue economy by different sectors, and the benefits and costs of the ambiguity of the term. Their analysis identified four primary perspectives of blue economy from the policy documents they examined: (1) “oceans as natural capital”, (2) “oceans as livelihood’, (3) “oceans as a driver of innovation”, and (4) “oceans as good business” (e.g., OECD 2016). Not all definitions of blue economy, as stated in many national and regional policy documents, include environmental and social sustainability (Garland et al. 2019), being focused more on the ocean as a source of funds to support national economies. There is a movement among some experts to promote the idea of “blue degrowth” (Ertör and Hadjimichael 2020), which rejects the idea that economic growth must be unending.

1.2.1 Definition

A useful definition of blue economy is that proposed by the World Bank for a "sustainable ocean economy": "the sustainable use of ocean resources for economic growth, improved livelihoods and jobs while preserving the health of ocean ecosystems" to achieve "triple bottom line objectives" that balance economic, environmental, and social outcomes (World Bank and United Nations Department of Economic and Social Affairs 2017). This is the definition that makes the most sense when discussing the role of science and technology in blue economies. **We will use this definition in the book without exploring other definitions in depth**. The definition does not explicitly include the idea of intergenerational equity in protecting national economies, environments, and culture, but sustainability implies continued availability of such resources into the future. WWF (2015) also presents principles for a sustainable blue economy.

The blue economy concept has become particularly attractive in recent years. Ocean resources have been recognized as important national assets, particularly in developing countries, as a key element of national ocean strategies to harvest ocean resources to support national economies (Okafor-Yarwood et al. 2020) (Table 1.1). Blue economy is particularly important to island nations, in which the areas of their exclusive economic zones far surpass their land areas, and land-based resources are scarce (see Chap. 13). However, some nations with large land areas (e.g., Australia and the United States) also have developed blue economy plans (CSIRO 2008; NOAA 2021), even though the ocean is a less substantial part of their overall economic development plans than for small island nations, and is likely to remain so. Natural resources are not distributed equally among nations' EEZs and not many nations are able to develop multiple resources simultaneously (Cisneros-Montemayor et al. 2021), which can impact a nation's blue economy goals. Developing multiple blue economy resources at the same time requires that a nation be able to balance among the environmental and social effects of each one, which may affect different stakeholders.

The term "sustainable ocean economy" has been gaining ground recently (Sumaila et al. 2021) and may supplant the term blue economy in the near future.

1.2.2 Blue Economy Components and Industries

The major components of blue economy are given in Table 1.1. Several of the industries based on these components already exist. Table 1.2 gives an idea of the existing and emerging blue economy industries. For this book, we selected a few of the most prominent resources found in blue economy plans worldwide and which most need inputs from ocean science.

Table 1.1 Components of blue economy (from World Bank and United Nations Department of Economic and Social Affairs 2017)

Type of activity	Activity subcategories	Related industries/sectors	Drivers of growth
Harvesting and trade of marine living resources	Seafood harvesting	Fisheries (primary fish production)	Demand for food and nutrition, especially protein
		Secondary fisheries and related activities (e.g., processing, net and gear making, ice production and supply, boat construction and maintenance, manufacturing of fish-processing equipment, packaging, marketing and distribution)	Demand for food and nutrition, especially protein
		Trade of seafood products	Demand for food and nutrition, especially protein
		Trade of non-edible seafood products	Demand for cosmetic, pet, and pharmaceutical products
		Aquaculture	Demand for food and nutrition, especially protein
Commerce and trade in and around the oceans	Transport and trade	Shipping and shipbuilding Maritime transport	Growth in seaborne trade; transport demand; international regulations; maritime transport industries (shipbuilding, scrapping, registration,
		Ports and related services	Seafaring, port operations, etc.)
	Coastal development	National planning ministries and departments	Coastal urbanization, national regulations
	Tourism and recreation	National tourism authorities private sector other relevant sectors	Global growth of tourism

(continued)

Table 1.1 (continued)

Type of activity	Activity subcategories	Related industries/sectors	Drivers of growth
Indirect contribution to economic activities and environments	Carbon sequestration	Blue carbon	Climate mitigation
	Coastal Protection	Habitat protection, Restoration	Resilient growth
	Waste Disposal for land-based nutrients, industry	Assimilation of solid waste	Wastewater management
	Existence of biodiversity	Protection of species, habitats	Conservation

Table 1.2 Blue economy industries (those discussed in this book are shown in boldface type)

Established	Emerging
Capture fisheries	Marine aquaculture
Seafood processing	**Deep-and-ultra-deep water oil and gas**
Shipping	Offshore wind energy
Ports	Ocean renewable energy
Shipbuilding and repair	**Marine and seabed mining**
Offshore oil and gas (shallow water)	Maritime safety and surveillance
Marine manufacturing and construction	Marine biotechnology
Maritime and coastal tourism	High-tech marine products and services
Marine business services	Other
Marine R&D and education	
Dredging	

Source OECD (2016)
Note Marine aquaculture may be misplaced as an "emerging" sector, as it has been practiced in some form for hundreds of years, but some aspects of this sector, such as open-ocean aquaculture and use of deep-ocean water sources, are relatively new.

1.2.3 Blue Economy and General Limitations

Discussions of blue economy in some countries put most of the emphasis on maximizing economic benefits without balancing the three blue economy factors. Countries sometimes approach blue economy resources as if they are inexhaustible, waiting to be extracted from the ocean, as though money is floating in the sea waiting to be netted, to fuel national economies. The reality is much more complicated because some resources are not renewable and there are environmental consequences to all resource extraction. Exploitation of one resource may diminish a nation's ability to exploit other resources or may damage local communities while primarily enriching large corporations located outside the country whose resources are being extracted. In addition, resource extraction can have negative impacts beyond a nation's waters to impact neighboring countries. Use of non-extractive ocean services can also diminish their availability, if care is not taken in their use. Costs and benefits can occur at different scales, both within a nation and regionally. Marine spatial planning (MSP) can help link different scales and different SDGs (Ntona and Morgera 2018). MSP is being used throughout the world to balance different user activities in different areas of a nation's EEZ and can be used in conjunction with ecosystem-based management (see Box 16.1).

The Rio + 20 concept paper on blue economy (Anon. 2012) identified equity for developing countries as a fundamental aspect of blue economies:

- "Optimize the benefits received from the development of their marine environments e.g. fishery agreements, bioprospecting, oil and mineral extraction.
- Promote national equity, including gender equality, and in particular the generation of inclusive growth and decent jobs for all.
- Have their concerns and interests properly reflected in the development of seas beyond national jurisdiction; including the refinement of international governance mechanisms and their concerns as States proximate to seabed development" (Anon. 2012).

Another key requirement for developing successful blue economies lies in the idea of "circular economies", in which resources are recycled, rather than being used once and discarded (e.g., Dantas et al. 2021). Circular economies require planning to design material flows and technologies for recycling that may require technology transfer from developed nations. Blue economies inevitably must be tied with land-based economic activities ("green economy"). These concepts, though important, are beyond the scope of this book.

Cisneros-Montemayor et al. (2021) point out that natural resources are a necessary, but insufficient, factor making blue economies possible. Also needed are stable political systems with limited corruption, equitable social systems, regulations to manage resources and balance among use sectors, and infrastructure necessary for harvesting resources and monitoring the effects of harvesting. Many countries have insufficient environmental impact assessment processes and favor development over protection. Enabling conditions are correlated with the human development index of nations and enabling conditions differ among regions (Cisneros-Montemayor et al. 2021).

1.2.4 Measuring Performance of Blue Economy

It is important to evaluate the performance of blue economic sectors and their effectiveness in terms of economic, social and environmental (ecological) sustainability (see also Sect. 1.2.5). This requires the development of methods to effectively measure the performance of ocean-based industries and economic sectors, and their contribution to the overall economy. The System of Environmental-Economic Accounting—Ecosystem Accounting (United Nations et al. 2021), and the Experimental Ecosystem Account (European Environment Agency 2011) are discussed in Sect. 1.2.5 (see Colgan 2016). Blue economy plans should explicitly identify appropriate metrics of success, including metrics for social and cultural objectives, which are often missing from tools for implementation of blue economies such as marine spatial plans (Zuercher et al. 2022).

From an ocean science perspective, sustainability indicators need to be developed for the various products and services derived from the ocean, as well as adequate methodologies to effectively measure and monitor the indicators. While making more effective decision making possible, appropriate indicators also could demonstrate the relevance of ocean research and observation in the practice of sustainable blue economy. Technology transfer and capacity development will be necessary to make the application of science and technology indicators of blue economies commonplace worldwide. As mentioned in Sect. 1.1, SDG Target 14A specifically mentions the use of IOC-CGTMT. Chapters 14 and 15 highlight the importance of the transfer and implementation of observational technologies and the means available for capacity development in developing economies, including least developed countries and small island developing states. A variety of constraining factors need to be overcome to accomplish technology transfer and maintenance of technology and expertise once developed.

1.2.5 Science and Technology for Sustainable Blue Economy

Among steps needed for improving the use of science and technology for establishing national blue economies are the following:

1. Commitment of national policymakers and administrators to the threefold goals of sustainable blue economies. This commitment should be demonstrated by the establishment of new laws and regulations needed to create and maintain a national blue economy.
2. Adoption of methods to properly quantify the costs and benefits of the extraction of renewable and non-renewable marine resources. This step should include periodic measurement and assessment of the performance of blue economy sectors, and the overall contribution of blue economy to national GDPs, as well as environmental and social objectives.

3. Investment in ocean science (natural and social science) in areas needed to fill information gaps related to understanding marine and human systems well enough to quantify costs and benefits.
4. Investment in technologies needed to observe ocean systems and the effects of resource extraction, and to mitigate the negative impacts of resource extraction.
5. Commitment to developing capacity for ocean science and technology to carry out the previous steps.

The first two steps above are beyond detailed discussion in this book, but are fundamental to implementing steps 3–5. We introduce some thoughts about steps 1 and 2 in the following paragraphs, but these do not capture the wealth of information available in the literature on these topics (see Chap. 16 for further discussion of steps 3–5).

1. *Commitment to Balancing Economics, Environmental Protection, and Social Equity*

This first step is probably the most difficult, but also the most important, because acceptance of the need to balance the three goals of blue economy underlies all the other steps and requires a commitment to the various investments described in the following steps. National policymakers can be tempted to focus on the economic benefits of harvesting tangible ocean resources and stop there, with no balancing of goals or investments to understand the impacts of the resource extraction activities. This inevitably leads to unsustainable resource-based economies, degraded environments, and/or social instability. National policymakers and government agencies have especially important roles to play in establishing and maintaining blue economies, by creating the necessary legislative and administrative frameworks, and prioritizing funding for ocean science and technology activities to underpin sustainable development coupled with environmental and social protections. Sumaila et al. (2021) identify means of financing sustainable ocean economies, and noted that an "enabling environment" is a necessary pre-condition for attracting finances for sustainable ocean economies. As pointed out by Cisneros-Montemayor et al. (2021), enabling factors within a nation are more important in predicting success in the establishment of blue economies than are the availability of natural resources. Tools related to Marine Spatial Planning, Integrated Coastal Zone Management, and Ecosystem-Based Management can be used to help balance among blue economy sectors.

An important part of national discussions in establishing blue economies relates to ensuring social equity among sectors that may be helped or harmed by government actions and policies. For example, if offshore mining reduces fish catches, how can fishers be compensated as they sacrifice income to benefit the national economy? If the creation of marine protected areas removes fishing areas from access by traditional fishers, how will they be compensated? Every policy created by governments creates winners and losers, resulting in conflict among competing sectors, and resistance to the new policies (e.g. Österblom et al. 2020).

Individual nations can increasingly rely on international organizations and projects to gain support and information for developing national blue economies.

For example, the High-Level Panel for a Sustainable Ocean Economy (https://oceanpanel.org/) was established in 2018 to advocate for sustainable use of the ocean, complementary to UN activities on SDG 14. The panel's report Ocean Solutions That Benefit People, Nature and the Economy (Stuchtey et al. 2020) proposed five "building blocks": (1) Using data to drive decision-making, (2) engaging in goal-oriented ocean planning, (3) de-risking finance and using innovation to mobilise investment, (4) stopping land-based pollution, and (5) changing ocean accounting so that it reflects the true value of the ocean". Their first building block indirectly emphasizes the role of ocean research and observations.

2. *Quantification of Costs and Benefits: Adopting Necessary Measurement and Data-Collection Methods*

After national governments commit to establishing a balanced and sustainable blue economy, the next tangible step is to determine how products and services related to the ocean will be valued and tracked. Placing values on resources and ocean processes is necessary to evaluate the costs and benefits of various policies and decisions properly. Methods of accounting for resources and environmental values have evolved over recent decades. Colgan (2016) shows how tracking of economic activity related to the ocean can use national income accounts. He extensively discusses the System of Environmental and Economic Accounting (SEEA: United Nations Statistics Division 2014). The Experimental Ecosystem Account (EEA: European Commission et al. 2013) provides methods for bringing ecosystem services (provision, regulating, and cultural) into the evaluation of costs and benefits. Successful accounting for ecosystem services requires the use of models that couple ecosystems and human actions, requiring investments in ocean science (see Step 3 in Chap. 16). EEA also brings in the concept that ecosystems and the services they provide vary by location (Colgan 2016). Designing systems to value natural products and services is a difficult step, but there is room for pilot activities related to resources for which there are abundant data, such as fisheries, mineral extraction, and tourism. Fenichel et al. (2020a) expand on the need for national accounts to include ocean economic activities and show an example of how ocean accounts can be presented in the form of "dashboards". A "Blue Paper" from the High-Level Panel for a Sustainable Ocean Economy (Fenichel et al. 2020b) further notes that national accounts can be used to provide information related to three areas of blue economy decision making: "output or national means—a measure of production; outcomes or policy ends—a measure of real income and its distribution; and sustainability—indicated by changes in the national balance sheet." They cautioned that, although some countries already estimate their "ocean Gross Domestic Product", this can be the wrong metric because it ignores sustainability issues. Also important are tracking of ocean assets (natural and human-produced) and ocean income. Some changes in international standards for national accounts will be necessary to achieve this step. Ocean national accounts can be a useful tool for marine spatial planning. Box 1.1 provides the High-Level Panel's advice on principles for national accounts that would help track blue economy activities.

Box 1.1. Principles of Accounting for a Sustainable Ocean Economy (from Fenichel et al. 2020b)

1. Ask multiple questions and expect multiple answers, especially questions about income and sustainability (balance sheets) in addition to production. This means that the impacts of policies and decisions about the ocean economy should be evaluated based on at least three indicators: income, production and ocean wealth.
2. Build on the existing structure of the System of National Accounts and System for Environmental-Economic Accounting so that ocean accounts are compatible with existing national accounts, and with international statistical standards.
3. Avoid an overreliance on GDP, which is not an indicator of either sustainability or the societal ends of economic activity. Do not use a hammer when you need a wrench.
4. Lead or contribute to collaboration efforts to improve national ocean accounting systems, including global partnerships to share best practices and build capacity. Such efforts will likely involve creating new integrated data management systems for ocean accounting and other purposes.

Blue economies must be adaptive and management approaches may need to be adjusted as more experience is gained. Adopting appropriate methods for valuing resources and for cost–benefit analyses should make it easier to attract external investments to help establish blue economies.

A major barrier to instituting blue economies is that it is relatively easy to quantify benefits from resources harvested from the ocean, but difficult to quantify the value of services derived from healthy ocean environments that would be lost from improper use of resources or damage to environmental and social values. In such a situation, it is easy for governments at all levels to treat the potential losses equal to zero, or at least of lesser cost than the tangible benefits received. In any resulting cost–benefit analyzes, the benefits of using resources outweigh the costs of using those resources. To approach such situations, some social scientists have attempted to assign monetary values to environmental and social benefits by asking consumers about their willingness to pay for various products and services. For example, as noted in Chap. 6, scientists in Palau compared the income of ecotourism related to diving with sharks to the income related to harvesting those sharks, and found that the ecosystem value of shark ecotourism vastly outweighed the value of harvested sharks (Vianna et al. 2010). Another effective means of assigning values to intangible benefits is to get someone to pay for the benefit, in terms of "debt-for-nature" swaps, "blue bonds" (Christ et al. 2020), or similar mechanisms. A key to establishing blue economies is to quantify and share benefits derived.

1.3 Ocean Services and Products, Threats from Human Activities

1.3.1 Services Provided by the Ocean

The ocean helps regulate many functions important to humans, from local to global scales. The ocean affects global temperature by absorbing heat and redistributing it, moderating temperatures on land. Evaporation of water from the ocean is the major source of moisture in the atmosphere, leading to rain on land and fueling the global hydrologic cycle. Phytoplankton and other plants in the ocean help control the levels of atmospheric gases such as oxygen and carbon dioxide. Coastal areas provide opportunities for commercial activities that can bolster local to national economies. Some other services that will be discussed in later chapters include the following:

Coral Reefs: Coral reefs provide a multitude of services to coastal populations in tropical areas, including food resources, protection from storm waves, cultural values in many island nations, ecotourism activities, and others. Coral reefs and the resources they provide are threatened by increasing ocean temperatures, ocean acidification, pollution, and direct human impacts from unsustainable fishing and tourism activities. See Chap. 2.

Blue Carbon: Atmospheric carbon dioxide is removed and stored by ocean plants (phytoplankton, seaweeds, mangroves, seagrasses), as so-called "blue carbon" (Nellemann et al. 2009; UNESCO 2020). Blue carbon intersects with blue economy (UNESCO 2020) because creation of certain types of blue carbon creates environments necessary for productive fisheries, tourism, and the health of ocean environments and removes carbon dioxide from the atmosphere, which slows atmospheric warming and ocean acidification. Like coral reefs, blue carbon ecosystems also help protect coastlines and may someday provide economic benefits from carbon sequestration credits. Negative effects of human activities on seagrass beds and mangrove forests can offset economic and environmental gains from the activities, releasing stored carbon dioxide back to the atmosphere, and disrupting the nursery grounds of important fish species. See Chap. 3.

Marine Tourism: The beauty of coastal and ocean areas provides tourism opportunities that enrich human lives and provide jobs in the service sector. Marine tourism is a major source of income for many developing countries, particularly coastal and island nations, and can help promote the protection of natural habitats and expansion of blue carbon, if conducted in a responsible way. Preservation of coral reefs, mangrove forests, and seagrass beds—and the populations of organisms they host—can be extremely important for developing and maintaining ecotourism, in additional to their importance for fisheries and coastline protection and carbon sequestration. However, negative effects of tourism can include increased production of wastewater and garbage, increased damage to environments and organisms by tourists who are not informed of or do not follow rules for sustainable tourism, and destruction of natural areas to build tourist facilities. See Chap. 6.

1.3.2 Products from the Ocean

A major use of the ocean by humans since ancient times has been to harvest food and other resources for personal use, and to barter with or sell to others. Centuries ago, primitive human technologies for ocean use made it difficult to exhaust ocean resources, except in small areas near human settlements. As technologies developed, humans became more efficient at removing renewable resources such as fish, whales, shellfish, and seaweed faster than the organisms could replenish their populations. A variety of management approaches have been developed to make the removal of products from the ocean more sustainable and less environmentally destructive.

A multitude of products are available from ocean areas to help support blue economies:

Coastal Fisheries: National EEZs are the most productive areas for fish and shellfish on a global level, and harvest of fish and shellfish is one of the most traditional blue economy activities practiced at local artisanal to national scales. Thus, fisheries are at the forefront of most blue economy plans. However, fisheries not conducted in an environmentally and socially sustainable manner might not be considered as contributors to a nation's blue economy. Aquaculture can also be an attractive and responsible industry, but has led in many locations to destruction of local habitats, over-enrichment of local environments with nutrients, and potential for genetic alterations of natural populations by organisms that escape from culture. See Chap. 4.

Oil and Gas: Petroleum products were first found on land, but production moved offshore and to progressively deeper waters as the new exploration and production technologies were developed. Ocean petroleum resources are important components of blue economy plans for nations with these resources in their EEZs, but extraction of oil and gas presents a host of local environmental issues and implications for continued global temperature increases, ocean acidification, and sea-level rise, as highlighted in the recent reports of the Intergovernmental Panel on Climate Change (IPCC 2021). Despite the carbon emissions from carbon-based fuels, these will need to be used for some time as transitional energy sources until non-carbon energy sources are adequately developed. See Chap. 7.

Mineral Resources: Minerals found offshore and in coastal dunes can provide a variety of resources in terms of metals, diamonds for jewelry and industrial use, and the nutrient mineral phosphorite. Deep-sea mining is being implemented by more developed blue economies, but are of limited interest for most developing countries because of the expensive technology required for mineral extraction in deep waters far from shore. Most deep-sea mining is being explored in Areas Beyond National Jurisdiction, under the purview of the International Seabed Authority (ISA) established under UNCLOS, which granted 18 exploration contracts in 2019, held by countries including China, India, Japan, Russia and the UK for poly-metallic nodules.[1] Coastal minerals are an important blue economy resource for many developing nations, but their extraction can pose significant environmental challenges. See Chap. 8.

[1] https://ocean.economist.com/innovation/articles/is-deep-sea-mining-part-of-the-blue-economy.

Renewable Energy: In recent decades, energy has been extracted from the atmosphere above the ocean, from the emplacement of "wind farms", but has mostly been done in the coastal areas of developed countries, so will not be considered in more detail here. Likewise, other means of renewable energy production (e.g., wave and tidal energy, thermal energy conversion) are not common contributors to blue economies of developing countries (see Chap. 8).

Freshwater Resources: Freshwater is an enabling resource that makes coastal areas habitable by humans and may be necessary to maintain the sources of goods and services from nations' coastal zones and EEZs. In many coastal regions, freshwater extraction from coastal areas has been done at unsustainable rates, causing coastal subsidence and salinization. See Chap. 5.

Marine Natural Products: The enormous biodiversity of oceanic organisms has provided genetic and biologic information that is just beginning to be deciphered. We do not discuss natural products in greater detail in this book, but note that the Convention on Biological Diversity (https://www.cbd.int/) has provisions for the sustainable use of biodiversity (Article 10). Natural products from pharmaceuticals has been proposed as a major future blue economy resource in many countries (see Chaps. 2 and 3).

1.3.3 Human Impacts on the Ocean

Stuchtey et al. (2020) provide a well-documented summary of human effects on the ocean and the economic benefits that the ocean can provide. Although the moderating functions of the ocean benefits humans, the increased heat and carbon dioxide absorbed by the ocean from the atmosphere damage ocean products and services, including important ecosystems, such as coral reefs, and the ability of the ocean to continue to absorb carbon dioxide. Non-renewable resources may be extracted in ways that damage renewable resources. As concepts of ecology and ecosystems developed, the interconnection of all species, and of species with the non-living environment, have become more obvious. At the same time, the concept of "ecological economics" has made it possible to estimate economic values of services provided by ocean environments. For example, fisheries, aquaculture, transport shipping, oil and gas extraction, and tourism are estimated to support an ocean economy worth trillions of dollars per year (e.g., Hoegh-Guldberg et al. 2015), and ocean-related industry and commerce sustain the livelihoods of large populations by providing opportunities for about half a billion jobs. Losses to the economy from the degradation of the natural ocean environment from changes in the climate and other global systems—resulting from human activities such as overfishing, pollution and hypoxia, ocean acidification, habitat loss, extreme oceanic events—are estimated to be almost a trillion dollars (Hudson 2012).

Coastal Pollution: Pollution is a major problem affecting blue economic resources, especially in developing countries. Pollution from conventional nutrients (nitrogen and phosphorous) causes eutrophication in coastal areas and creates oxygen-poor conditions, both of which are detrimental to marine biota (e.g., fish, corals) and their potential as blue economic resources. On the other hand, heavy metals, organic pollutants, and radionuclides interfere with physiological functions of marine organisms and in some cases are harmful to human health. Overall, pollution affects sectors such as human health, fisheries, and tourism. See Chap. 9.

Harmful Algal Blooms: Harmful algal blooms (HABs, both high-biomass and toxic) have been a feature of coastal ecosystems throughout history, but there is some evidence that bloom organisms are expanding their ranges, due to climate change and/or transport of causative organisms by human activities. HABs cause significant impacts on blue economies, by reducing fisheries and mariculture production, negatively affecting tourism due to the stigma of toxic fish and shellfish, and respiratory effects from some phytoplankton, and additional costs for monitoring and human health interventions. See Chap. 10.

Ocean Acidification and hypoxia (deoxygenation): Ocean acidification poses a widespread danger to blue economies, both acting alone and combined with other factors, such as seawater temperature increases and decreases in seawater oxygen levels. The most obvious impact of decreasing ocean pH will be the gradual decrease in the health of tropical coral reefs and all the negative consequences that will ensue. However, ocean acidification will also affect cold water corals that provide shelter for many fish and shellfish species in temperate and polar regions. Finally, ocean acidification may have pervasive negative impacts on the foundation of marine food webs as it becomes more difficult for single-celled algae and other small plankton and pteropod molluscs to calcify. Such effects would ripple up to fish, marine mammals, seabirds and turtles, and humans. In addition to ocean acidification, the extent of low-oxygen regions in the ocean is increasing, with adverse effects on many of the blue economy-relevant ecological functions (Zhang et al. 2010; Breitburg et al. 2018). See Chap. 11.

In summary, changes to the global ocean (increasing temperature, decreasing pH, decreasing oxygen, harmful algal blooms, pollution and others) complicate efforts to achieve blue economies. Sustainable blue economies must acknowledge that Earth and its ocean are changing in ways that complicate sustainable resource extraction and that environmental consequences of global change may require more conservative practices of resource extraction and other human uses of the ocean (see Chap. 12). Blue economies must be adaptable to changes ranging from local to global. Each of these changes can reduce the availability of living coastal resources, such as fish, coral reefs, mangroves, and seagrasses. National management must develop and use scientific knowledge to respond to such changes using proactive approaches.

1.4 The Role of Science in Blue Economies

Blue economy has recently begun to attract the attention of ocean scientists (see e.g., Rayner et al. 2019; Wenhai et al. 2019; Okafor-Yarwood et al. 2020). The importance of sustainable use of ocean resources has also been highlighted by The High-Level

Panel for a Sustainable Ocean Economy (Stuchtey et al. 2020), which noted that "using science and data to drive decision-making" is an important building block for sustainable use of the ocean. Advances in science and technology has allowed humans to better understand and locate ocean resources and then exploit these resources, often excessively. Ocean observations are key to monitoring and understanding ocean conditions and changes (see Chap. 15). Scientific understanding is important for sustaining blue economies in an unchanging world, but even more so as the ocean and coastal areas are constantly changing due to human forces (Stenseth et al. 2020).

Although the value and need for development of scientific information about the ocean and its resources has become more apparent, science often does not receive enough national funding to support wise management, particularly in developing countries, which experience pressing economic pressures to meet basic human needs of their populations. However, inadequate knowledge about natural and human systems or ignoring the available scientific knowledge (e.g., making fisheries management decisions based more on political considerations than science) can lead to resource extraction that is not sustainable, damaging the resource, the natural environment, and human societies in ways that reduce the benefits available. To sustain blue economies, adequate observing systems must be deployed and capacity for science and observations must be built in countries that rely on blue economies (Rayner et al. 2019).

This book limits its attention generally to the land–ocean interface and activities other than shipping and transport within nations' Exclusive Economic Zones, while recognizing that what happens on land and the area beyond national jurisdictions also affects nations' blue economy activities. We focus mostly on regions where there is inadequate scientific information to serve as a foundation for developing blue economies, which are often developing regions of the world. The book recognizes the transboundary nature of ecosystems supporting blue economic development and the related impacts, which will require novel approaches of ocean management. Voyer et al. (2021) document the potency of voluntary commitments from the stakeholders involved in blue economic development. As shown by Cisneros-Montemayor et al. (2021), most blue economy potential exists within EEZs, although these authors admit that a lack of data for both resource availability and enabling conditions for the high seas influence their conclusions. This book also focuses on natural science aspects of the applications of science to blue economy, while acknowledging that social science aspects are equally important, but would merit an entire book on the topic. Specifically, the bridges between knowledge and application of knowledge (from funding to generate knowledge to political will to implement science-based approaches to management of resources) must be built and maintained to simultaneously achieve the three blue economy objectives. This book provides insights into why sufficient knowledge in natural sciences and technology needs to be developed through research and observations, and applied in well-designed management, to serve as a foundation for blue economies. The chapters of the book highlight the role of science and technology in using ocean resources and mitigating environmental problems that plague the ocean and detail examples of how science has stimulated blue economies and how ignoring science can damage blue economies.

For the purposes of this book, we do not categorize human activities in the ocean as "good" or "bad", since such valuations depend on the care with which resources are used. Different countries have different resources available and may not have the "luxury" to leave the resources in place while their population is impoverished. Countries must use their available resources sustainably to ensure current and future health of their economies, environments, and societies. Our main concern is how the development and application of scientific knowledge affects the triple-objective of blue economy. We discuss these issues in greater detail in the final chapter of the book. We view blue economy as a potential means for developing countries to create sustainable income streams, if developed wisely.

1.5 Goals of the Book

We assembled a team of lead authors about equally comprised of developing and developed country individuals and with roughly equal gender balance among lead authors. The aim of this book is to highlight the potential of ocean science and technology to enable implementation of sustainable blue economies and to provide practical information for developing country scientists, managers, and policymakers about how ocean science can and should be used to create sustainable blue economies, and to respond to environmental threats to economies based on coastal ocean resources. The ideas in this book were presented to the broader community on 8–9 November 2021 in a virtual workshop jointly convened by the Centre for Science and Technology of the Non-Aligned & Other Developing Countries (NAM S&T Centre), New Delhi and the Scientific Committee on Oceanic Research (SCOR), Newark, Delaware (USA). More than 200 scientists, researchers, government officials, policy makers, marine-sector professionals, managers and representatives from 37 countries participated in the workshop. Presentations at the workshop raised questions that helped authors refine their chapters for final publication.[2]

The following chapters describe how science has been used (or not used) to ensure the sustainability of all forms of coastal resources and to mitigate the threats to such use.

The goals of the book are to provide the following:

1. Definitions of "blue economy" in science and technology contexts.
2. Information about selected blue economy-relevant coastal ecosystems, their services and products, as well as the current threats to their sustainability.
3. Information about applying science and technology to promote economically and environmentally sustainable use of coastal resources.
4. Examples of how scientific information has been used in relation to sustainable management of various coastal resource types in specific locations.

[2] See http://namstct.org/DOCU/Brief_Report/Workshop_Report_on_Blue%20Economy_November_8-9_2021.pdf for workshop report.

5. Examples of environmental/economic problems that have arisen from inadequate/improper interaction of science and economics in management of coastal resources.
6. Recommendations for enabling ocean science and technology actions for the practice of blue economy.

We hope that the information provided in this book will advance the use of science and technology as a basis for blue economies worldwide.

References

Anonymous (2012) Blue economy concept paper. https://sustainabledevelopment.un.org/content/documents/2978BEconcept.pdf#:~:text=The%20Blue%20Economy%20espouses%20the%20same%20desired%20outcome,and%20social%20inclusion%2C%20but%20it%20is%20grounded%20in

Attri VN (2018) IORA, blue economy and ocean governance. In: Jivanta Schöttli (ed.) Maritime Governance and South Asia, pp 141–143. https://doi.org/10.1142/9789813238237_0011

Attri VN, Bohler-Muller N (2018) The blue economy handbook of the Indian Ocean Region. Human Sciences Resources Council. AISA, Oxford

Breitburg D, Levin LA, Oschlies A et al (2018) Declining oxygen in the global ocean and coastal waters. Science 359(6371)

Christ HJ, White R, Hood L et al (2020) A baseline for the blue economy: catch and effort history in the Republic of Seychelles' domestic fisheries. Front Mar Sci 7:269. https://doi.org/10.3389/fmars.2020.00269

Cisneros-Montemayor AM, Moreno-Báez M, Reygondeau G et al (2021) Enabling conditions for an equitable and sustainable blue economy. Nature 591:396–401. https://doi.org/10.1038/s41586-021-03327-3

Clegg P, Mahon R, McConney P et al (2020) The Caribbean blue economy. Routledge, 262p

Colgan CS (2016) Measurement of the ocean economy from national income accounts to the sustainable blue economy. J Ocean Coastal Econ 2(2): Article 12. https://doi.org/10.15351/2373-8456

CSIRO (Commonwealth Scientific and Industrial Research Organisa (2008) Blue GDP: ocean-based industrial development and growth. Commonwealth Scientific and Industrial Research Organisation, Canberra

Costanza R, d'Arge R, de Groot R et al (1997) The value of world's ecosystem services and natural capital. Nature 387:253–260

Dantas TET, de-Souza ED, Destro IR et al (2021) How the combination of circular economy and industry 4.0 can contribute towards achieving the Sustainable Development Goals. Sustainable Prod Consumption 26:213–227

Eikeset AM, Mazzarella AB, Davíðsdóttir B et al (2018) What is blue growth? The semantics of "sustainable development" of marine environments. Mar Policy 87:177–179

Ertör I, Hadjimichael M (2020) Editorial: blue degrowth and the politics of the sea: rethinking the blue economy. Sustain Sci 15(1):1–10. https://doi.org/10.1007/s11625-019-00772-y

European Commission, European Climate, Infrastructure and Environment Executive Agency (2021) Sustainability criteria for the blue economy: main report. Publications Office, 64p. https://data.europa.eu/doi/10.2826/399476

European Environment Agency (2011). An experimental framework for ecosystem capital accounting in Europe. EEA Technical report No 13/2011. https://www.eea.europa.eu/publications/an-experimental-framework-for-ecosystem

Fenichel EP, Addicott ET, Grimsrud KM et al (2020a) Modifying national accounts for sustainable ocean development. Nat Sustainability 3:889–895. https://www.nature.com/articles/s41893-020-0592-8
Fenichel EP, Milligan B, Porras I et al (2020b) National accounting for the ocean and ocean economy. World Resources Institute, Washington, DC. Available online at https://www.oceanpanel.org/blue-papers/national-accounting-ocean-ocean-economy
Garland M, Axon S, Graziano M et al (2019) The blue economy: identifying geographic concepts and sensitivities. Geogr Compass 13(7):e12445. https://doi.org/10.1111/gec3.12445
Hoegh-Guldberg O et al (2015) Reviving the ocean economy: the case for action—2015. WWF International, Gland, Switzerland, Geneva, 60p
Hudson A (ed.), UNDP-GEF (2012) Catalyzing ocean finance. Volume 1. Transforming markets to restore and protect the global ocean. 54p. New York
IOC/UNESCO, IMO, FAO, UNDP (2011) A blueprint for ocean and coastal sustainability. IOC/UNESCO, Paris. http://www.unesco.org/new/fileadmin/MULTIMEDIA/HQ/SC/pdf/interagency_blue_paper_ocean_rioPlus20.pdf
IPCC (2021) Summary for policymakers. In: Masson-Delmotte V, Zhai P, Pirani A et al (eds.) Climate change 2021: the physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. In Press
Keen MR, Schwarz AM, Wini-Simeon L (2017) Towards defining the blue economy: practical lessons from Pacific Ocean governance. Mar Policy 88:333–341. https://doi.org/10.1016/j.marpol.2017.03.002
Lee KH, Noh J, Khim JS (2020) The blue economy and the United Nations' sustainable development goals: challenges and opportunities. Environ Int 137(January):105528. https://doi.org/10.1016/j.envint.2020.105528
Naidoo R, Fisher B (2020) Reset sustainable development goals for a pandemic world. Nature 583:198–201
Nellemann C, Corcoran E, Duarte CM et al (2009) Blue carbon: the role of healthy oceans in binding carbon. UN Environment, GRID-Arendal
NOAA (2021) NOAA blue economy: strategic plan 2021–2025. U.S. National Oceanic and Atmospheric Administration. https://aambpublicoceanservice.blob.core.windows.net/oceanserviceprod/economy/Blue-Economy%20Strategic-Plan.pdf
Ntona M, Morgera E (2018) Connecting SDG 14 with other Sustainable Development Goals through marine spatial planning. Mar Policy 93:214–222. https://doi.org/10.1016/j.marpol.2017.06.020
OECD (2016) Development co-operation report 2016: the Sustainable Development Goals as business opportunities. OECD Publishing, Paris. http://dx.doi.org/10.1787/dcr-2016-en
Okafor-Yarwood I, Kadagi NI, Miranda NA et al (2020) The blue economy-cultural livelihood—ecosystem conservation triangle: the African experience. Front Mar Sci 7:586.https://doi.org/10.3389/fmars.2020.00586
Österblom H, Wabnitz CCC, Tladi D et al (2020) Towards ocean equity. World Resources Institute, Washington, DC. Available online at www.oceanpanel.org/how-distribute-benefits-ocean-equitably
Pauli GA (2010) The blue economy: 10 years, 100 innovations, 100 million jobs. Paradigm Publications
Rayner R, Jolly C, Gouldman C (2019) Ocean observing and the blue economy. Front Mar Sci 6:330. https://doi.org/10.3389/fmars.2019.00330
Stenseth NC, Payne MR, Bonsdorff E et al (2020) Attuning to a changing ocean. Proc Natl Acad Sci USA 117(34):20363–20371
Stuchtey M, Vincent A, Merkl M et al (2020) Ocean solutions that benefit people, nature and the economy. World Resources Institute, Washington, DC. www.oceanpanel.org/ocean-solutions
Sumaila UR, Walsh M, Hoareau K et al (2021) Financing a sustainable ocean economy. Nat Commun 12:3259. https://doi.org/10.1038/s41467-021-23168-y

United Nations (2021) The Sustainable Development Goals report 2020. United Nations, New York. https://unstats.un.org/sdgs/report/2020/The-Sustainable-Development-Goals-Report-2020.pdf
United Nations et al (2021) System of Environmental-Economic Accounting—Ecosystem Accounting (SEEA EA). White cover publication, pre-edited text subject to official editing. Available at: https://seea.un.org/ecosystem-accounting
UNESCO (2020) UNESCO marine world heritage: custodians of the globe's blue carbon assets. France, Paris
Vianna GMS, Meekan MG, Pannell D, Marsh S, Meeuwig J (2010) Wanted dead or alive? The relative value of reef sharks as a fishery and an ecotourism asset in Palau. Australian Institute of Marine Science and University of Western Australia, Perth. https://www.pewtrusts.org/-/media/assets/2011/05/02/palau_shark_tourism.pdf
Voyer M, Quirk G, McIlgorm A et al (2018) Shades of blue: what do competing interpretations of the blue economy mean for oceans governance? J Environ Plann Policy Manage 20(5):595–616. https://doi.org/10.1080/1523908X.2018.1473153
Voyer M, Allison EH, Farmery A et al (2021) The role of voluntary commitments in realizing the promise of the blue economy. Glob Environ Chang 71:102372. https://doi.org/10.1016/j.gloenvcha.2021.102372
Wenhai L, Cusack C, Baker M et al (2019) Successful blue economy examples with an emphasis on international perspectives. Front Mar Sci 6:261. https://doi.org/10.3389/fmars.2019.00261
World Bank and United Nations Department of Economic and Social Affairs (2017) The potential of the blue economy: increasing long-term benefits of the sustainable use of marine resources for Small Island Developing States and coastal Least Developed Countries. World Bank, Washington, DC
World Wildlife Fund (WWF) (2015) Principles for a sustainable blue economy. https://wwf.panda.org/wwf_news/?247477/Principles%2Dfor%2Da%2DSustainable%2DBlue%2DEconomy
Zhang J, Gilbert D, Gooday AJ et al (2010) Natural and human-induced hypoxia and consequences for coastal areas: synthesis and future development. Biogeosciences 7:1443–1467
Zuercher R, Motzer N, Magris RA et al (2022) Narrowing the gap between marine spatial planning aspirations and realities. ICES J Mar Sci 2022:1–9. https://doi.org/10.1093/icesjms/fsac00

Chapter 2
Coral Reefs and Blue Economy

M. F. M. Fairoz

Abstract Coral reef ecosystems are rich in biodiversity, providing a variety of services and products relevant to blue economy that include sectors such as tourism, fisheries, biotechnology/bioprospecting, and coastal protection. Almost half a billion people, 8% of the total global population, live within 100 km of a coral reef and about 100 developing countries are highly dependent on coral reefs for their livelihoods. However, the health of coral reefs is at risk. Reefs are severely affected by ocean warming and acidification as well as land- and sea-based human activities that lead to coral disease and destruction of reef habitat. This chapter addresses aspects of coral reef ecosystems that are critical for their contribution to sustainable blue economies. The chapter discusses the structure and function of coral reefs, their current distributions, the threats they experience and their potential impact as a blue economy resource. The chapter then discusses necessary measures to detect, monitor, and reduce the adverse impacts, as well as the available science and technologies to monitor reefs. Finally, the chapter provides information about ongoing international efforts on reef research and monitoring, and the application of state-of-the-art tools that might be of interest to countries developing blue economies.

Keywords Coral reefs · Structure · Symbiosis · Bleaching · Threats · Research and monitoring · Ocean acidification

2.1 Introduction

Coral reefs cover about 1 million square kilometers (km^2) of Earth's surface. They are built by coral organisms producing their own mineral substrates, with thousands of different species living in coral ecosystems. Coral reefs are comparable with tropical rain forests in terms of their high levels of biodiversity and complexity of their ecosystems. They are also among the most productive ecosystems, in terms of

M. F. M. Fairoz (✉)
Faculty of Fisheries and Ocean Sciences, Ocean
University of Sri Lanka, Colombo 15 Crow Island,, Sri Lanka
e-mail: fairoz@ocu.ac.lk

E. R. Urban Jr. and V. Ittekkot (eds.), *Blue Economy*,
https://doi.org/10.1007/978-981-19-5065-0_2

gross organic production (Odum and Odum 1955; Lewis 1977; Birkeland 1983) and are often an oasis of life in otherwise rather barren tropical marine environments (Gove et al. 2016). Beside their ecological value, coral reefs are of major economic, social and cultural importance to the countries they border (Cesar 2000). Almost half a billion people, 8% of the total global population, live within 100 km of a coral reef and about 100 developing countries are highly dependent on coral reefs for their livelihoods.

A large number of studies have estimated the economic value of healthy coral reefs (e.g., Brander et al. 2012), which come from a variety of renewable resources that can be harvested (subsistence, commercial and recreational fishing) from reef areas, and services provided by reefs, including recreational opportunities (e.g., skin diving and SCUBA, enjoying aesthetic values), tourist development (hotels, vacation rentals), coastal protection provided by intact reef structures (Sheppard et al. 2005), and cultural value of reefs to local populations. Brander et al. (2012) compiled 160 separate reef valuation studies and used 45 of these to conduct a meta-analysis of reef value. The studies included in the analysis used a variety of common valuation methods. Brander et al. (2012) predicted (through modeling) a loss of 16–27% of global coral reef area under different IPCC scenarios available at that time. They estimated an annual loss of $870 billion in 2100 under the IPCC scenario A1 ("a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and rapid introduction of new and more efficient technologies"). However, these figures could be an over-estimate, as they do not consider the capacity of human populations to adapt, particularly if the ecosystem changes happen gradually (Hoegh-Guldberg et al. 2019).

This chapter gives a brief overview of reef ecosystems in relation to their role in blue economies and outlines the latest developments in coral reef monitoring and research technologies against the background of current scientific research, which is integral to the successful conservation and management of reef areas.

2.2 Structure, Taxonomy

Coral reefs are calcium carbonate features, precipitated by individual animals (polyps) (Fig. 2.1), that form large colonies that make up the three-dimensional structure of a reef. It is this structure that protects fragile fauna from being preyed on and also forms a fortress that defends reef biota against the destructive action of hydraulic stress created by waves and currents. The form and the shape of the reef construction largely result from the specific interactions of the coral colonies with the hydrodynamic stress to which they are exposed (Veron 2004).

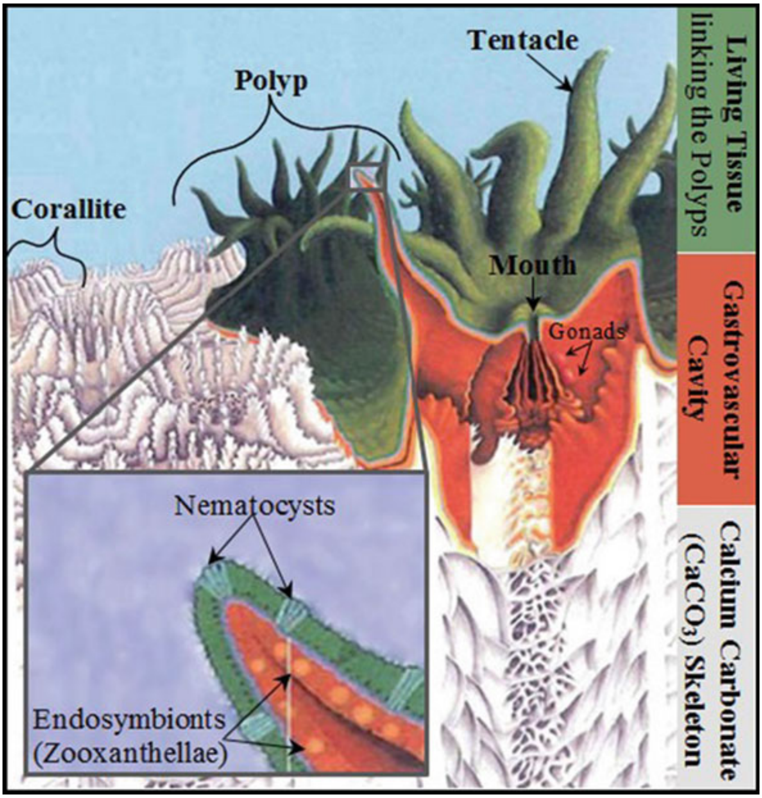


Fig. 2.1 General structure of the polyp and the underlying skeleton of reef building organism (*Source* Lentz 2012)

2.2.1 Classification of Coral Reefs

There have been many attempts to classify different types of reefs. They can be classified according to their geological history, shape, position relative to land masses, and by the nature of the material of which they are made. In spite of a great morphological variety of reef forms, common elements pertaining to the geomorphology such as buttress system, reef flat, lagoon, patch reef zone, etc. indicate a certain regularity in their origin and growth on different structural foundations of shelf and island coasts, across different parts of the coastal zone. This regularity, first recognized by Darwin (1842), can be distinguished into three basic types of coral reef: (1) fringing reefs, (2) barrier reefs, and (3) atolls (Fig. 2.2). Fringing reefs are directly attached to volcanic islands, barrier reefs are separated from volcanic islands or land masses by lagoons, and atolls are formed by ring reefs which enclose only a lagoon.

Fringing reefs grow in shallow waters and border the coast closely or are separated from it by a narrow stretch of water (Fig. 2.2a). They consist of several zones

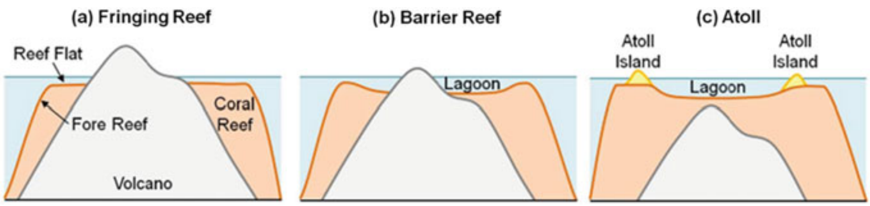


Fig. 2.2 Classification of coral reefs. **a** Fringing reef. **b** Barrier Reef. **c** Atoll (*Source* Pearson 2016)

that are characterized by their depth, structure of the reef and by plant and animal communities associated with them. These zones include the reef crest (part of the reef over which waves break), fore reef (the region of medium energy) and buttress zone or spur and groove (region of coral growth, which includes rows of corals with sandy canyons or passages between each row).

Barrier reefs are separated from land by a lagoon; examples are the Great Barrier Reef off Australia and the Belize Barrier Reef System. These reefs grow parallel to the coast and are large and continuous. Barrier reefs also include regions of coral formation that include the zones found in fringing reefs along with patch reefs (small reefs), back reefs (the shoreward side of the reef), as well as bank reefs (reefs that occur on deep bottom irregularities) (Fig. 2.2b). Barrier reefs also include reef flats (the reef not exposed); the reef crest runs parallel to the coast and is protected from waves and coral terrace (slope of sand with isolated coral peaks). Another coral terrace and a vertical drop follow these features into deeper waters (Veron 2000).

Atolls are annular reefs that develop at or near the surface of the sea when islands (usually volcanic) that are surrounded by reefs subside (Fig. 2.2c), and as sea level changes through glacial cycles (Droxler and Jorry 2021). Darwin (1842) proposed that atolls as corals continue to colonize sinking volcanic islands that eventually sink below the sea surface. More recently, Droxler and Jorry (2021) demonstrated that most modern atolls from the Maldives Archipelago and from the tropical Pacific and southwest Indian oceans occur on top of late Pliocene flat-topped banks. The volcanic basement, therefore, has had no influence on the late Quaternary period development of these flat-topped banks into modern atolls. During the multiple glacial sea-level low stands that intensified throughout the Quaternary, the tops of these banks were eroded by dissolution; then, during each of the five mid-to-late Brunhes deglaciations, coral reoccupied their raised margins and grew vertically, keeping up with sea-level rise and creating the modern atolls.

2.2.2 *Taxonomy of Reef Building Corals*

Corals belong to the Phylum Cnidaria (Fig. 2.3) and are characterized by the presence of tentacles, a central digestive cavity and radial symmetry. Although coral reefs are commonly found in nutrient-poor waters of the tropics, paradoxically, they are among

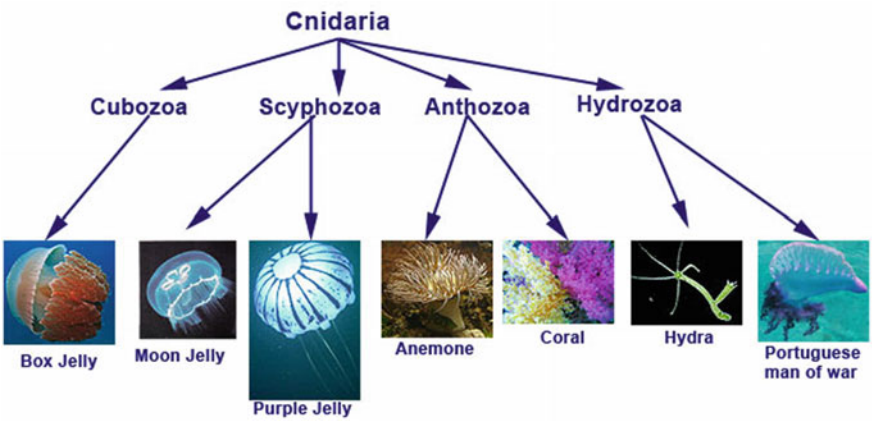


Fig. 2.3 Corals in the Phylum Cnidaria (*Source* http://www.mesa.edu.au/Cnidaria/default.asp)

the most productive of marine environments (Barnes 1987). Coral reef formation and maintenance are driven by the symbiosis between the coral animal and single-celled photosynthetic algae (dinoflagellates) belonging to the genus *Symbiodinium* that live within the tissues of stony coral polyps (Levinton 1995). The endosymbiotic dinoflagellates supply carbon from photosynthesis to the coral host, which in return provides the algae with nitrogen (Szmant et al. 1990). In addition, coral-associated bacteria play a key role in the health of the coral (Fairoz et al. 2008; Ziegler et al. 2016). Together this association is referred to as a holobiont (Rohwer et al. 2002) and the complex interactions among animal, algae and the microbiome intricately shape coral health and resilience (Bourne et al. 2016; Epstein et al. 2019).

Since the success of this symbiotic relationship relies largely on the photosynthetic output of the *Symbiodinium* algae, the distribution and growth of corals is strongly light-dependent (Levinton 1995), and limits reef growth to the top 100 m of the ocean. Therefore, coral reefs commonly thrive in clear, nutrient-poor water characteristic for tropical areas.

2.3 Global Distribution and Status

It has been estimated that shallow coral reefs occupy less than 0.1% of the world's ocean area (Costanza et al. 1997), an area about half the size of Madagascar (Fig. 2.4). This is less than 1.2% of the world's continental shelf area (Spalding et al. 2001). A mass coral bleaching event in 1998 (caused by a major El Niño), resulted in a decrease of hard coral cover by 8%, but reefs mostly recovered by 2009 (GCRMN 2021). From 2009 to 2018, however, there was a 14% decline in the coral coverage of shallow-water reef areas globally (Fig. 2.5a), accompanied by an increase in algal cover of reefs (Fig. 2.5b), due to various natural and anthropogenic processes

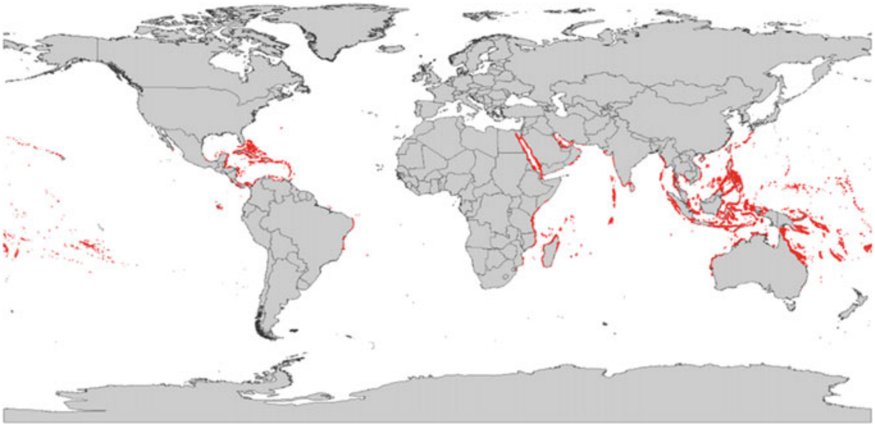


Fig. 2.4 Distribution of the coral reefs of the world (*Source* Teh et al. [2013]. Reef areas are indicated by shading. Attribution 4.0 International [CC BY 4.0])

(GCRMN 2021). The worldwide decline in coral cover is believed to be primarily the result of recurring coral bleaching events due to increasing sea surface temperatures (Fig. 2.6), augmented by local outbreaks of coral diseases and crown-of-thorn starfish (*Acanthaster planci*), as well as local effects of pollution and destructive fishing practices. Projected increases in sea surface temperatures with global warming will undoubtedly lead to continued coral bleaching events and further losses of coral cover (Schoepf et al. 2015).

The shift in reef areas from coral cover to algal cover (Figs. 2.5a and b), referred to as a regime shift (Bozec and Mumby 2015), was already noticed more than a decade ago (Hughes et al. 2007). These will be discussed in Sect. 2.6. Algal overgrowth appears to be most severe in South Asia and the Middle East, where regional-scale impacts of human activities have prevented coral recovery, even during short periods of favorable temperatures, particularly when reefs face greater challenges when exposed to multiple stresses simultaneously.

2.4 Ecosystem Services

Coral reef ecosystems provide services such as food, livelihood opportunities, carbon sequestration, and buffering against extreme climate events, which are critical resources for blue economy sectors. A large body of literature has quantified the values of coral reef ecosystem services from a global perspective (Table 2.1).

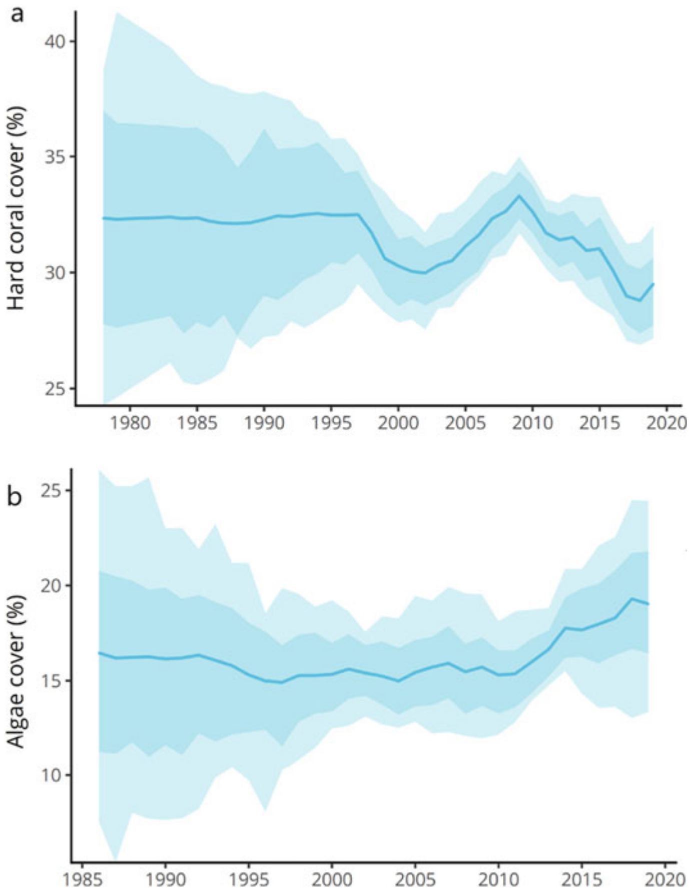


Fig. 2.5 **a** Estimated global average cover of hard coral (solid line) and associated 80% (darker shade) and 95% (lighter shade) uncertainty intervals. **b** Estimated global average cover of algae (solid line) and associated 80% (darker shade) and 95% (lighter shade) uncertainty intervals (*Source* GCRMN [2021])

2.4.1 Biodiversity

Millions of people living in countries with coral reef ecosystems gain benefits due to reef's unique capacity to host diverse groups of marine organisms (Fig. 2.7). Globally, it is estimated that there are between 600,000 and more than 9 million reef species (Knowlton 2001). There is evidence that ecosystems with higher biodiversity are more stable. Marine biodiversity can yield both ecosystem services and products that benefit blue economies. For example, biodiversity is an important attraction for marine ecotourism (see Chap. 6 on Tourism) and makes it possible for fishers to catch a variety of species (see Chap. 4 on Fisheries). The multitude of different species

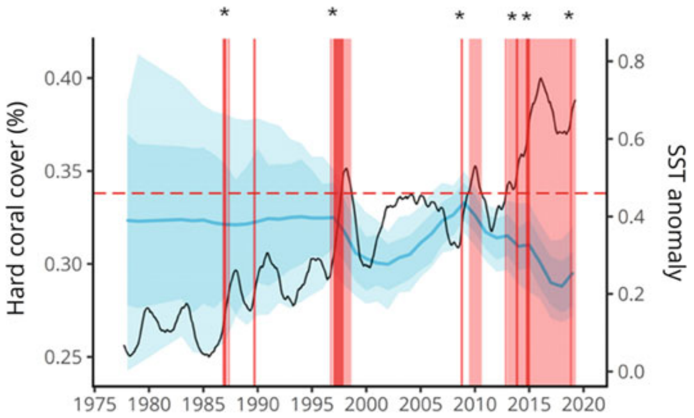


Fig. 2.6 The estimated global average hard coral cover (lighter sold line starting around 33% in 1977) is overlaid with the sea surface temperature (SST) anomaly from 1977 to 2020 (darker line starting at about 0.25 in 1977). The 80% (darker area) and 95% (lighter area) confidence intervals of coral cover estimates are shown. Periods of rapid increase in SST anomaly are indicated by asterisk [*] marks (*Source* GCRMN [2021])

Table 2.1 Values of coral reef ecosystem services quantified in the literature, from a global perspective

Statement	References
More than 275 million people worldwide live within 30 km of reefs (and <10 km from the coast), and ~850 million people live within 100 km of coral reefs	Burke et al. (2011a, b)
At least 500 million people rely on coral reefs for food, coastal protection, and livelihoods	Wilkinson (2004)
In developing countries, coral reefs contribute about one-quarter of the total fish catch, providing food to an estimated one billion people in Asia alone	Moore and Best (2001)
More than 150,000 km of shoreline in 100 countries and territories receive some protection from reefs	Burke et al. (2011a, b)
Globally, coral reefs provide 130 billion USD of flood protection from 100-year storm events	Beck et al. (2018)
Some 30% of the world's reefs are of value in the tourism sector, with a total value estimated at nearly US$ 36 billion, or over 9% of all coastal tourism value in the world's coral reef countries	Spalding et al. (2017)
There are at least 6 million reef fishers in 99 countries worldwide, accounting for about 25% of small-scale fishers	Teh et al. (2013)

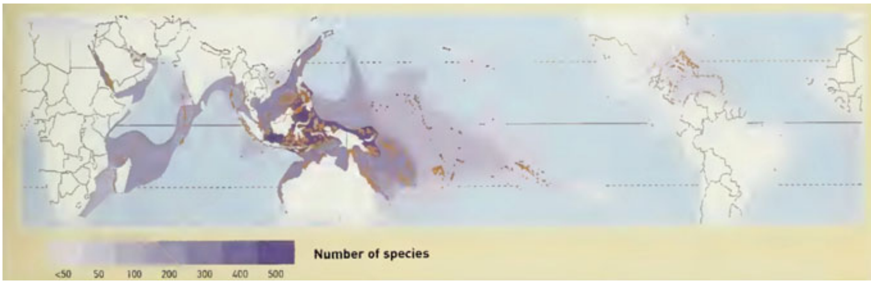


Fig. 2.7 Patterns of biodiversity of the coral reefs (*Source* Spalding et al. [2001])

produce many different classes of marine natural products that could serve as models for compounds useful for medicine, agriculture, and other purposes (see Sect. 2.5.3).

2.4.2 Coastal Protection

Coastal protection is an economically important ecosystem service provided by coral reefs, especially to island nations. Reefs shelter coastal settlements, and mangrove and seagrass areas, from waves, winds, and other ocean-related hazards though dissipation of wave energy by friction on reef structures (Goulay et al. 1996; Lugo-Fernandez et al. 1998; Sheppard et al. 2005). Protection of coastal settlements from storm damage reduces economic losses and loss of life. Mangroves and seagrasses offer additional protection from storms, serve as nursery areas for important fish species, and help process nutrients and other wastes from land to the ocean (see next section). Coastal protection value (CPV) has been defined to recognize the economic value of coastal protection and inform coastal management policies (Cesar et al. 2003; Burke and Maidens 2004). The annual global coral reef CPV was estimated as 9 billion USD by Cesar et al. (2003).

2.4.3 Blue Carbon

Blue carbon ecosystems play an important role in CO_2 sequestration and storage in the form of organic matter, and coral reefs can help protect these systems. Chapter 3 on Mangroves and Seagrasses provides a more detailed description of the benefits provided by these ecosystems. Blue carbon has gained much attention in efforts related to reducing atmospheric CO_2. For example, recent studies have shown that intact reefs can increase the capacity of seagrass meadows to store carbon by promoting carbon accumulation and avoiding erosion and export of carbon (Guerra-Vargas et al. 2020). These economic valuations are considered as “indirect use value”

(De Groot et al. 2010) or “hidden value” (Van Beukering et al. 2007; Sarkis et al. 2010) because these services are not visible in daily life.

2.5 Blue Economic Sectors

2.5.1 Tourism

Coral reef-associated tourism is one of the most prominent eco-tourism activities in tropical coastal countries. Coral reefs are very attractive destinations for tourists from all over the world, leading to the significant generation of foreign income for many developing country economies. Components of reef-related tourism include attractive beach sites and sheltered waterfronts with panoramic views, and underwater activities such as SCUBA diving and snorkeling (Hasler and Ott 2008). Approximately 30% of the world’s coral reefs are sites of tourism-related income generation, contributing nearly US$36 billion annually, or more than 9% of all coastal tourism value in the world’s coral reef countries (Spalding et al. 2017). See Chaps. 6 and 13 for more details on the relation of tourism and blue economies.

2.5.2 Fisheries

Coral reefs provide habitats for enormous biomass, including finfish and shellfish resources that are the basis for reef fisheries. A well-managed reef can provide 0.2–40 tons of seafood per km^2 annually (UNEP 2004), with an average of about 5 tons of seafood per km^2 per year. This translates to an annual yield of 1.42 million tons of seafood from coral reefs worldwide. Coral reef-associated fisheries are a source of income for many coastal communities, mainly in the developing world (Burke et al. 2011a, b). In terms of nutritional value, reefs supply half of the protein requirement of the people in some areas, and reef fish are important sources of vitamins A, B, and D, calcium, iron, and iodine. Across reef nations and territories, people consume an average of 29 kg of fish and seafood each year (Newton et al. 2007), with consumption of reef fish being the highest in the Maldives (180 kg/person/year). Reef fish and shellfish are also harvested for aquaria and curio exports. The economic importance of coral reef products varies by region. Southeast Asian countries generate $2.4 billion per year in products, and in the Caribbean $395 million per year is derived from reef-related fisheries (Teh et al. 2013). Reef-associated exports are valued at more than 1% of total exports in 21 countries and territories, and more than 15% of total exports in six other countries (Burke et al. 2011a, b). See Chap. 4 for more information about fishery contributions to blue economies.

2.5.3 Marine Biotechnology

Marine biotechnology (or blue biotechnology) is a rapidly developing field and applied to the areas of public health, human disease, and seafood safety, with new discoveries of promising products being made continually from marine organisms such as algae, sponges and mollusks. Due to their unique bioactive and structural diversity, natural products from marine organisms are a potent source of therapeutics that exhibit structural and chemical features not present in terrestrial organisms (Horta et al. 2015). During the last 50 years, about 20,000 novel compounds have been isolated and identified from marine organisms (Simmons et al. 2005), and more than 300 patents related to marine natural products have been approved (Blunt et al. 2013). Coral reefs—including coral-associated microorganisms and marine invertebrates—are the source of about 245 potent bioactive compounds identified so far, including substances with anti-inflammatory, cytotoxic, antimicrobial, antiviral, and antifouling properties (Bruckner 2002). It is noteworthy to mention that the development of marine natural products does not necessarily lead to the widespread harvesting of the organism producing the products, as the products often can be synthesized in the laboratory after the structure and activity of bioactive compounds have been determined.

2.6 Threats and Their Impacts

Coral reefs are adapted to thrive in a stable environment and are therefore easily affected by sudden changes of abiotic factors, such as decreased salinity and pH, increased temperature, hurricanes and wave action, nutrient pollution, and siltation. Human threats include overfishing, destructive fishing practices, damage by tourists, and destruction as part of coastal development. Over the last four decades, catastrophic events have affected coral reef systems globally, resulting in their destruction over vast areas.

A combination of increased seawater temperatures and food availability promote devastating outbreaks of the predatory crown-of-thorn sea stars that feeds exclusively on scleractinian corals and has caused extensive damage on the Great Barrier Reef and in other areas of the tropics (Uthicke et al. 2015).

In addition to such natural threats, various human activates are responsible for reef degradation. Tourism and recreational activities, and use of explosives (dynamite fishing), poison and destructive gear for reef fisheries are examples for destructive human activities. Impact from these activities, coupled with land-based activities such as shore development, farming, mining, deforestation, reclamation, sewage disposal exert tremendous stress on the ecological balance of reefs. Segel and Ducklow (1982) found that most corals are weakened by stress, particularly due to diseases caused by bacteria as a result of anthropogenic activities (see next paragraph). Changes in the extent of biotic and abiotic stressors are likely to be further compounded by the slow decrease in seawater pH, commonly referred to as ocean acidification (Hoegh-Guldberg et al. 2017; Cornwall et al. 2021) (see Sect. 2.6.3 and Chapter 11).

2.6.1 Coral Bleaching

Coral reefs support numerous blue economy activities and global warming is a challenging and emerging threat to the survival of coral animals. Tropical coral species generally live close to their upper temperature limits (Berkelmans and van Oppen 2006) and an increase in sea surface temperature of 0.5 °C can exceed a species' heat tolerance, which causes corals to expel their endosymbionts, leading to a phenomenon known as "coral bleaching". Because corals depend on algae for the majority of their energy requirements, prolonged coral bleaching frequently results in disease, reduced growth and reproduction and often large-scale coral mortality (LaJeunesse et al. 2018; Hughes et al. 2019; Sully et al. 2019). The mechanisms related to bleaching and subsequent mortality of different taxa are still not well understood (Hughes et al. 2018) and thermal tolerance of the symbiotic relationship can vary greatly between and within species as well as across different geographical areas (e.g., Cunning et al. 2021).

In order to mitigate the effect of coral bleaching, it is important to understand the underlying physiological mechanisms responsible for the dissociation between both symbiotic partners. Although coral reefs may be largely eliminated worldwide by the end of this century as a result of coral bleaching (Hoegh-Guldberg 1999; Hoegh-Guldberg et al. 2007; Veron et al. 2009; Bay et al. 2017; Heron et al. 2017), recent studies also suggest that many species are able to adapt and increase their resilience to reoccurring heat exposure (Matsuda et al. 2020).

2.6.2 Coral Diseases

Over the past few decades, there has been a marked rise in coral diseases (Rohwer et al. 2002) and epizootics of coral disease have resulted in significant losses of coral cover (Aronson and Precht 2001; Walton et al. 2018), The most notable disease outbreak was reported from Florida reef tracts from 2014 and it is ongoing to date (Precht et al. 2016; Walton et al. 2018). Although there is still a lot of uncertainty surrounding specific pathogens and/or their vectors, disease prevalence has been linked to an array of environmental disturbances pertaining to water quality such as nutrient load and sewage (Redding et al. 2013), as well as increases in seawater temperature (Maynard et al. 2015). Determining the drivers of disease outbreaks is an ongoing area of vigorous research aiming to disentangle the relative effects of host resilience and destabilized homeostasis within the holobiont on disease outbreaks (Burge et al. 2014; Thompson et al. 2014; Peixoto et al. 2017).

2.6.3 *Ocean Acidification*

Ocean acidification threatens many ocean ecosystems including coral reefs (see Chap. 11 for details on ocean acidification and its economic impacts). Economic impacts of ocean acidification are difficult to predict because the biological effects of acidification are not yet fully known or predictable. Pelagic organisms that live in the open ocean and benthic animals that live in shallow habitats or in deep waters are threatened by ocean acidification, but corals and pteropods appear to be most at risk (Caldeira and Wickett 2003; Fabry et al. 2008).

In the late 1980s, it was inferred from the geologic record that the chemical condition of the ocean controls the rate of production of carbonate shells and skeletons in the marine environment over geologic time scales (Veron 2000). Experiments performed on tropical corals showed coral growth rates slowing dramatically as seawater CO_2 concentrations increase (Gattuso et al. 1998). Soon after, a groundbreaking study combined model predictions of future ocean chemistry with results from laboratory experiments on corals. This study concluded that coral growth would be severely impeded later this century and that tropical reefs are likely to be most vulnerable (Kleypas et al. 1999).

The scientific and policy needs for coordinated, worldwide information gathering on ocean acidification and its ecological impacts, recognized by the United Nations General Assembly (UNGA 2013), and by many governmental and non-governmental bodies, resulted in the creation of the Global Ocean Acidification Observing Network (GOA-ON) (Newton et al. 2015) and inclusion of ocean acidification monitoring as a goal of Sustainable Development Goal 14. The methods of monitoring and research for ocean acidification are interdisciplinary, including carbon chemistry, meteorology, oceanography, biogeochemistry, ecology, and biology. Basic data collection includes temperature, salinity, water depth, oxygen concentration and carbon-system parameters, plus fluorescence, and irradiance. Benthic status (e.g., coral and coralline algae cover) is also included in monitoring coral reef habitats to correlate with the physical and chemical variations in the water column that correspond to those specified for the Global Coral Reef Monitoring Network (GCRMN), a program of the International Coral Reef Initiative. These methods will detect ocean acidification as more acidic conditions erode dead carbonate structures in coral reefs (Campbell et al. 2014; Hoegh-Guldberg et al. 2017).

2.7 Importance of Global Observing Systems for Coral Reefs

Several international projects and activities contribute data on ocean and marine biodiversity parameters, including data related to coral reefs. The following are among the notable high-level activities:

- The Global Ocean Observing System (GOOS) is a platform of the United Nations Education, Scientific and Cultural Organization's Intergovernmental Oceanographic Commission, UNESCO-IOC, along with other co-sponsors (Miloslavich et al. 2018b). GOOS established a new panel in 2015 to extend Essential Ocean Variables (EOVs) to the biological and ecosystem components of the ocean. The Biology and Ecosystems Panel identified a set of biological EOVs and is working on strengthening and developing coordinated observing networks around each of these (Miloslavich et al. 2018b) in response to identified global needs. See also Chap. 14.
- The Marine Biodiversity Observation Network (MBON) of the Group on Earth Observations Biodiversity Observation Network (GEO BON) (Mueller-Karger et al. 2018) was established to develop a global community of practice for the collection, curation, analysis, and communication of marine biodiversity data. This requires coordination and collaboration among countries, organizations and individuals involved in the Group on Earth Observations (GEO) and many other organizations.

These groups provided leadership in developing EOVs and Essential Biodiversity Variables (EBVs) for biological and ecological parameters (Table 2.2) and to promote the integration of regional datasets shared among scientific communities through global systems such as the Ocean Biogeographic Information System (OBIS).

Hard coral cover and composition was identified as one of the leading biological EOVs (see specification sheet at www.goosocean.org/eov), partly due to the two decades of coordinated coral reef monitoring already undertaken by the GCRMN (e.g., Wilkinson 2000, 2008). The GCRMN has been the unofficial global observing system for coral reefs since 1997 with the publication of the first global status of reefs report (Wilkinson 2000) that was motivated by the first global coral bleaching event of 1997–1998. After that, several reports on coral reefs on global and regional levels, including research methods, were published. These reports were incorporated into the Convention on Biological Diversity (CBD) (e.g., https://www.cbd.int/; Tittensor et al. 2014) and global assessments (GRID-Arendal and UNEP 2016).

2.7.1 The Global Coral Reef Monitoring Network (GCRMN)

The GCRMN was established by the International Coral Reef Initiative (ICRI) in 1995, initially with the primary task of reporting on the condition of the world's coral reefs in the context of the development of the ICRI "Call to Action" (Dight and Scherl 1997). Since then, the GCRMN has produced a range of global, regional and thematic reports on coral reef status and trends, with the support of regional coordinators and managers of marine parks.

The GCRMN has recognized that coral reefs in more than 100 countries are under significant pressure from human activities, and are uniquely vulnerable to climate change, as well as ocean acidification. This makes coral reefs a sensitive indicator

Table 2.2 Essential Ocean Variables (EOVs) important for monitoring and reporting coral reef health, and levels proposed to assist in assessing data quality by the Global Coral Reef Monitoring Network (GCRMN)

EOV name	Description and notes	Levels 1, 2, and 3*
Hard coral cover and composition	Hard corals are the architects of coral reefs, justifying this as the most important indicator of coral reef presence and health. Three-dimensional reef structure is strongly determined by the growth form of coral colonies. For the GCRMN, the growth (functional) form and genus-level identification provide sufficient detail for monitoring	1-total hard coral cover (%) 2-cover by functional group/growth form 3-cover by genus or species
Fleshy algae cover	Different algal groups serve unique functional roles in reef communities. In general, fleshy, macro and turf algae are primary competitors to corals for occupying reef substrates; some also release dissolved organic carbon into the water which fuels microbial activity that inhibits corals. Crustose coralline algae (CCA) are key contributors to reef building. Fleshy algal cover is the aggregation of fleshy, macro and turf algal forms	1-total fleshy algal cover (%) 2-cover by functional group (turf, fleshy/macro, CCA, and calcareous) 3-cover by genus or functional group, with canopy height
Fish abundance and diversity	Fish are highly diverse, occupy a range of functional roles, are mobile, and their size matters. The selection of target fish for monitoring is challenging and highly variable. Monitoring programs are therefore encouraged to focus on a subset of fish families and to record all species within them, though in many cases target species/taxa are more manageable	Assigning levels for fish data is premature. The most basic is abundance of key taxa, the most complex is biomass of all species in key families' status

*Data levels rank from Level 1 (minimum requirements) to Level 3 (maximum requirements) See additional details below from 2000 to 2008

system for coastal ocean health, climate change and ocean acidification impacts, and their implications for society.

The GCRMN Implementation and Governance Plan (Obura et al. 2019) identifies four goals for the GCRMN, with subsidiary objectives:

- Goal 1: Improve understanding of coral reef status and trends, globally and regionally.
- Goal 2: Analyze and communicate coral reef biophysical, social and economic trends, providing science-based recommendations in support of raising awareness, management and policy development.
- Goal 3: Enable and facilitate greater utilization of coral reef data, including in research.
- Goal 4: Build human and technical capacity to collect, analyze and report biophysical and socio-economic data on coral reefs.

Tracking and reporting on coral reef status and trends is needed to understand the extent and rate of change, and to design appropriate responses. As coral degradation is taking place at the global level, driven by global as well as local processes, systematic coral reef observation is required. These observations directly support planning and tracking coral reef health in relation to sustainable development, climate change and biodiversity conservation, and have broad application in awareness raising and outreach. High-quality coral reef data will also support research, including in relation to ecology and ecosystem service provision, and observational data are needed for modelling to better predict future reef responses to climate stress.

The role of the GCRMN is to provide these coral reef data, aggregating from national to regional levels, and then to a global level. The EOVs proposed by the GCRMN are important for monitoring and reporting coral reef health (Table 2.2).

2.7.1.1 Revitalizing the GCRMN

Greater precision and consistency in how data are measured and reported is a priority focus for the GCRMN in the coming years. The GCRMN is adopting the Essential Variable approach (Obura et al. 2019) and a data quality model (Table 2.2) that enables (a) effective submission of minimum data required to monitor and assess reef health (hard coral cover and composition), and (b) procedures for strengthening and extending the data to additional key variables (e.g., algae and fish), and improving the resolution and "quality" of each variable.

The data quality model scores three levels of data, from minimum requirements (Level 1) to maximum (Level 3), providing specific guidance on how to improve data quality from Level 1 to 3, and incentivizing monitoring teams to improve quality. The key method for ensuring data quality is the preparation and submission of appropriate metadata (GCRMN 2018a, b) that include information on sites and sampling, variable precision and replication, and any data processing or transformations applied after data collection. This approach enables two objectives: first, to maximize submission of data that meet a minimum standard from all parts of the globe, and second, to provide a pathway for capacity building to improve data quality to the highest levels possible.

2.8 Science and Technology Measures

For developing countries, there are specific needs related to observational monitoring and ecosystem-based management approaches at local levels (Obura et al. 2019). Awareness and access to available new technologies and capacity building are among some of the priorities, including for personnel at the science-policy interface. These aspects are discussed in detail in Chaps. 14 (Ocean Observations) and 15 (Capacity Development). This section presents a description of the science and technology options to better manage reef ecosystems in order to avoid threats to sustainable blue economies and discusses some of the latest studies on improving our understanding of coral reefs.

A large body of literature shows that the major threat to coral reefs globally is the series of unprecedented coral bleaching incidents that have occurred in various parts of the world. The major cause of this coral bleaching is global warming, caused by increased sea surface temperature. Research on coral physiology and adaptive capacities may help in devising approaches to mitigate the impacts of global warming.

2.8.1 Research on Coral Symbiosis and Coral Bleaching

Stony corals owe their success as reef builders to their symbiosis with endosymbiotic dinoflagellate algae of the genus *Symbiodinium*. These algae live in coral tissues in extremely high densities (greater than 10^6 cm^{-2}) and provide up to 90% of a coral's nutritional requirements (Muscatine and Porter 1977). Researchers have studied the connections between loss of endosymbionts, the global incidence of coral bleaching, and the loss of coral cover in recent decades. The effects of thermal stress on corals over the last century (Lough 2000) yield clues to the future of coral reefs in the context of global warming in the future (IPCC 2021).

Coral-*Symbiodinium* symbiosis is temperature sensitive; increased sea surface temperature can disrupt coral symbiotic complexes to cause coral bleaching resulting from the expulsion of symbiotic algae from the coral tissues due to the thermal stress. It is sometimes possible for the algae to recolonize coral tissues after the temperature returns to normal. This situation is called temporary bleaching and corals can recover within a couple of days. However, if elevated temperatures last for a longer period, bleaching can become permanent and there is no chance for the coral to maintain the symbiotic system (Muscatine 1990).

Recent research to understand coral bleaching and to improve knowledge of the effects of temperature on the breakdown of coral symbiosis also includes microbial ecology, to integrate into a larger explanation of status of the reef coral health (Dove and Hoegh-Guldberg 2006), as explained in the following section.

2.8.2 Coral Reef Microbiology

Coral reef microbiology is an emerging field that integrates existing knowledge of the coral endosymbiosis, with new studies of other organisms within the holobiont, such as endolithic algae, bacteria, protists, fungi and viruses (Rosenberg et al. 2007; Peixoto et al. 2017; Tong et al. 2020) (Fig. 2.8).

Bacteria are assumed to contribute to coral holobiont biology primarily in terms of stress tolerance and adaptation to disparate environments (Voolstra et al. 2021). Recognition of the importance of bacteria as part of the coral holobiont led to the proposal of several hypotheses of coral reef processes. For example, the coral probiotic hypothesis states that microbes support coral biology through selection of the most advantageous holobiont configuration in a given environment. This was also referred to as the "microbiome flexibility" hypothesis to include the notion that the potential and likelihood for microbiome change differs among host species (Peixoto et al. 2017). These concepts might help in attempts to select and manipulate specific microbes to aid the heat stress tolerance and resilience of the coral

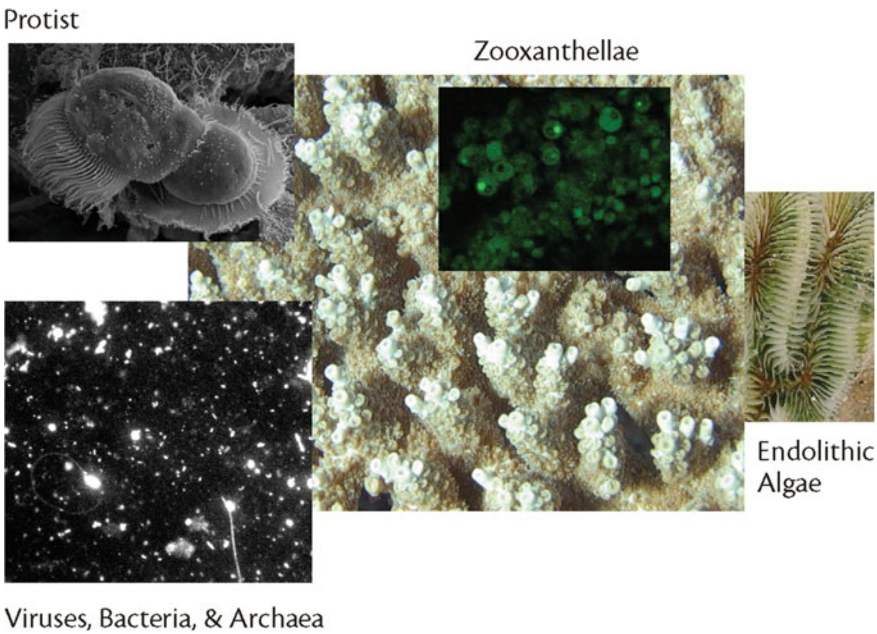


Fig. 2.8 The coral holobiont consists of symbiotic zooxanthellae, the coral animal and associated viruses, microbes (both bacteria and archaea), and endolithic organisms. Most of the viruses are bacteriophages, which attack the microbes. The endolithic organisms include algae, fungi, sponges, and microbes that bore into the coral skeleton. The holobiont likely occupies different coral reef niches by mixing and matching different components (i.e., the Probiotic Hypothesis). Zooxanthellae and protist micrographs by Linda Wegley and Ian Hewson, respectively (*Source* Rosenberg et al. 2007; Attribution 4.0 International [CC BY 4.0])

holobiont. Microbes included in the coral holobiont are also described as "beneficial microorganisms for corals" (BMCs) (Santoro et al. 2021). These coral-associated beneficial microbes generally fix atmospheric nitrogen, maintain sulfur cycling, scavenge reactive oxygen species (ROS) that otherwise harm coral tissues, and produce antibiotics to thwart pathogens (Robbins et al. 2019). The functional changes and host association of BMCs are largely unknown.

Knowledge gained from coral reef microbial ecology studies has been applied to explain the large-scale ecological status of coral reefs. Dinsdale et al. (2008) characterized microbial communities from pristine to human-populated atolls in the Pacific Ocean, including four coral atolls in the Northern Line Islands located in the central Pacific Ocean. The differences in microbial communities across atolls reflected the variation in the oceanographic conditions and direct and indirect human impacts, such as fishing and land use (Dinsdale et al. 2008; Sandin et al. 2008). Data from this study could serve as a baseline for future studies on reef microbes and the association of microbes on degradation of coral reef systems worldwide. Techniques used in this study represent a combination of methods from metagenomics, microscopy, microbial culture methods, and water chemistry.

2.8.2.1 Microbiome Studies

Another study was conducted of coral reefs at 11 Line Islands in the central Pacific Ocean that together span a wide range of biogeochemical and anthropogenic influences to examine coral microbiomes (Kelly et al. 2014). The percent cover of major benthic functional groups were significantly correlated with particular microbial taxa. Reefs with higher coral cover had a coral microbiome with higher abundances of Alphaproteobacteria (such as Rhodobacterales and Sphingomonadales), whereas microbiomes of algae-dominated reefs had higher abundances of Gammaproteobacteria (such as Alteromonadales, Pseudomonadales, and Vibrionales), Betaproteobacteria, and Bacteriodetes. In contrast to taxa, geography was the strongest predictor of microbial community metabolism. Microbial communities on reefs with higher nutrient availability (e.g., equatorial upwelling zones) were enriched in genes involved in nutrient-related metabolisms (e.g., nitrate and nitrite ammonification, total nitrogen transport). On reefs further from the equator with lower nutrient levels, microbes had more genes encoding chlorophyll biosynthesis and photosystems I/II.

2.8.2.2 Application of Environmental Genomics

Another approach to coral reef research has involved the application of metagenomics in coral reef studies to obtain a comprehensive view of microbial ecology of coral reefs. Metagenomics is the study of genetic material recovered directly from environmental samples, such as seawater. This is a broad field also referred to as environmental genomics, ecogenomics and community genomics. A detailed metagenomics study from Japanese reefs (Meirelles et al. 2018) suggest that synergistic effects among several regional stressors are driving coral decline. In a highly hydrodynamic reef environment, high algal/turf cover, stimulated by eutrophication and low fish abundance due to overfishing, promote water column microbial activity, together with crown-of-thorns sea star outbreaks and climate changes impacts; these coral reefs are likely to collapse.

2.8.2.3 Global Microbialization of Coral Reefs

Global coral reef status shows that coral-dominated reefs are becoming algal-dominant reefs worldwide, recognized as a "phase shift" (Hass et al. 2006). This shift in coral ecosystems was explained as "global microbialization" of coral reefs, an observed shift in ecosystem trophic structure towards higher microbial biomass and energy use. On coral reefs, the primary causes of microbialization are overfishing of herbivorous fish and eutrophication, both of which enhance the growth of fleshy algae, allowing it to out-compete calcifying corals and coralline algae. Haas et al. (2016) propose that the "DDAM (Dissolved organic carbon [DOC], Disease, Algae, Microorganism) positive feedback loop" gives fleshy algae a competitive advantage. The DDAM feedback loop involves ungrazed fleshy algae releasing DOC, supporting pathogenic bacteria that harm corals. Observations from three ocean basins were used to demonstrate the prevalence of DDAM processes. Besides promoting growth of fleshy algae, microbialization of reefs can also increase hypoxia and decrease pH from the microbial respiration of DOC. Following the explanation of microbialization in coral reefs, interest has increased regarding microbial metabolism and the microbiome over reefs and its connectivity to local environmental factors. Microbiome studies explain the maintenance and adaptation of microbiomes to local conditions, facilitated by the horizontal transfer of genes responsible for specific metabolic capabilities from one microbial species to another. The core microbiomes are determined by holobiont macroorganisms as explained above in this chapter.

2.8.3 Modelling and Monitoring for Threat Alert Systems

Global-scale coral bleaching risk alerts have been generated for the past 20 years based on satellite observations of sea surface temperature (SST), through detection and mapping of high positive SST anomalies relative to long-term averages. Bleaching alert products were developed by the U.S. National Oceanic and Atmospheric Administration (NOAA) Coral Reef Watch Program (http://coralreefwatch.noaa.gov/satellite/; Liu et al. 2014). Other regional forecast models of coral stress due to heat, extreme cold winter anomalies, and coral disease have been implemented, such as in Australia (Maynard et al. 2011). These models, combined with volunteer-based ground-truth monitoring networks (e.g., Gudka and Obura 2017), help generate awareness of the threat of coral bleaching, and build interest and capacity in management responses to mitigate the effects of these events and promote resilience and recovery from the events (Marshall and Schuttenberg 2006). A typical major bleaching event occurs over 2–4 months, and monitoring an event requires different approaches at its start, during the event, and afterward to track long-term impacts. Improved quantitative data helps to target management and policy responses more effectively.

Fixed buoys for monitoring aerial and subsurface biophysical properties of coral reef waters are used for monitoring in some locations, notably the NOAA Coral Reef Early Warning System (CREWS). Starting in 1997, this system combined software and sensor platform development to automatically detect conditions thought conducive to coral bleaching (Hendee et al. 2007). Buoys in this network of stations around the Caribbean and in Saipan (in the Pacific Ocean) relay data by satellite to the Atlantic Oceanographic and Meteorological Laboratory (AOML) in Miami, Florida, USA.

2.8.3.1 Remote Sensing and GIS

Satellite-based remote sensing enables the monitoring of shallow-water tropical coral reefs over a broad range of spatial and temporal scales (meters to global and from near-daily to decadal). Satellite images and other data, such as measures of the roughness of the sea surface and sea level can cover large areas, such as, hundreds to thousands of square kilometers, quickly and synoptically, frequently and repeatedly, over long periods of time (Eakin et al. 2010; McCarthy et al. 2017).

In recent decades, application of remote sensing and tools of image processing on coral reef ecological data have increased understanding of the status of reefs. Habitat mapping is a foundation for marine spatial planning and to detect changes of coral cover, reef heath, and ecosystem dynamics (Hamylton 2017; Purkis et al. 2019). Machine-learning algorithms are now embedded into image classification routines to map coral reef habitat at large geographic scales (see next section). For the global Allen Coral Atlas, "random forest" learning algorithms classify groups of image pixels (objects) into habitat maps from a collection of covariate data layers, including satellite image reflectance (e.g., from Landsat, Sentinel2, Planet Dove, and Worldview-2 satellites), bathymetry, slope, seabed texture and wave data (Lyons et al. 2020). Multiple decision trees were trained from known occurrences of bottom type ("ground truthing" data) to classify unknown objects from the mode of the individual tree classes. Working with covariate data and desired results, a machine learning classifier uses calibrated values to identify bottom type using the mode of individual tree classes. These data are applied at a global scale using Google Earth Engine to provide a repository of high-resolution Earth observation imagery using a remote supercomputer (Gorelick et al. 2017). Resulting habitat maps have clear potential management applications, for example, in evaluating reef connectivity for the dispersal of coral and crown-of-thorns sea star larvae, modeling water quality, and evaluating reef restoration sites (Roelfsema and Phinn 2010; Roelfsema et al. 2020). While machine-learning algorithms offer a reliable means of habitat classification,

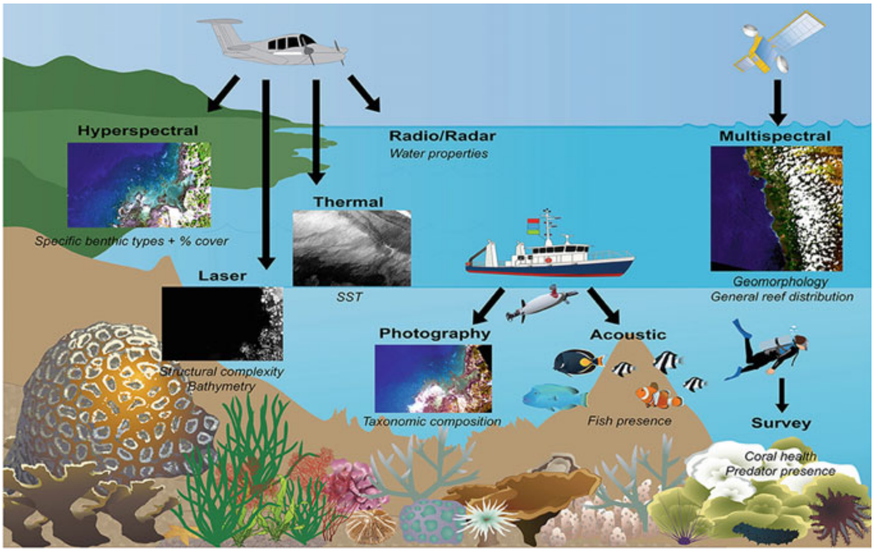


Fig. 2.9 Application of Remotly sensed measurements to coral reef restoration examples by the Carnegie Airborne Observatory [Asner et al. 2012]. Symbols are courtesy of the Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/symbols/) (*Source* Foo and Asner [2019] Attribution 4.0 International [CC BY 4.0])

their use for mapping relies on input of covariate biophysical data. Feature extraction provides an alternative application of machine-learning algorithms to coral reef imagery.

Remotely sensed measurements can be useful for coral reef restoration activities (Fig. 2.9). Key criteria considered by restoration practitioners are paired with the current platform and sensing technology that is most mature and developed, for the criterion at the required resolution to inform fragment collection, coral out-planting, and monitoring efforts.

2.8.3.2 Machine Learning for Detecting Features in Coral Reef Environments

Discrete features visible within images can be directly detected as recurring patterns across multiple pixels. This is commonly achieved through a family of multi-layered deep-learning algorithms known as convolutional neural networks (CNN) that were initially developed for facial and handwriting recognition. These algorithms define a series of mathematical convolutions to generate the output from the input, allowing all instances of a feature falling within an image to be located based on a predefined set of features (LeCun et al. 2015). On sand cay islands and reef flats, features that are amenable to detection include fallen trees, particularly on narrow beaches, which signify erosion of sand cay shorelines (Lowe et al. 2019) and individual mangrove

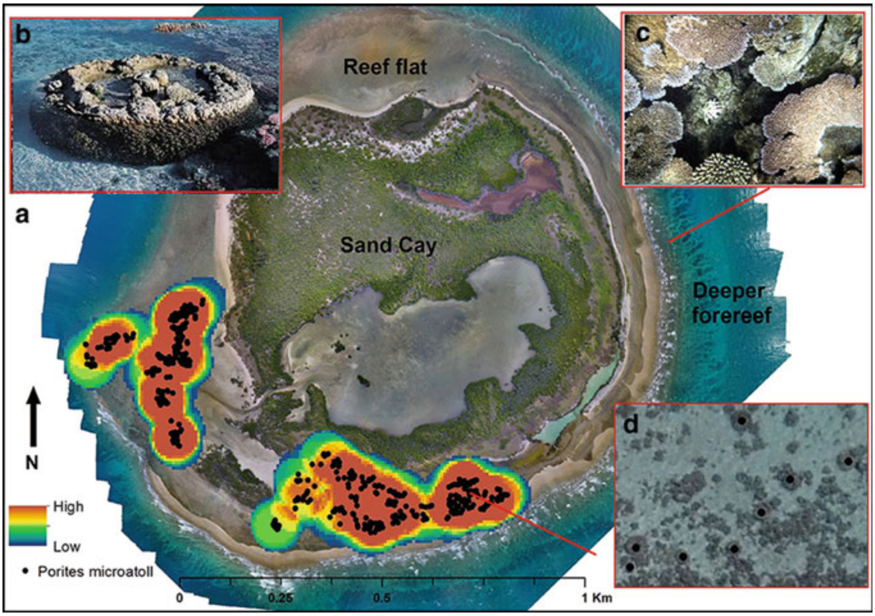


Fig. 2.10 Example of mapping possible by drone, showing a composite picture composed from 1400 UAV images of Nymph Island on Australia's Great Barrier Reef. Panel A shows the photo-mosaic, which Panel C that the detail available can show individual corals (*Source* Hamylton et al. [2020] Attribution 4.0 International [CC BY 4.0])

trees, from which forest expansion and contraction can be monitored over time (Hamylton et al. 2020). Individual corals are now clearly visible in drone images acquired above reefs (Fig. 2.10) and machine-learning algorithms hold good potential for detecting reef features, opening up a wealth of potential management applications for monitoring coral restoration and bleaching. For example, on degraded reefs, restoration activities include planting tens of thousands of juvenile corals (Lirman and Schopmeyer 2016), whose planting sites can be optimized by analysis of existing coral distributions.

2.8.3.3 Citizen Science and Coral Reef Monitoring (www.citizenscience.org/)

Community-based monitoring is important to gather information for reef management and involve local communities in protecting the reefs on which they depend. Many programs have arisen to monitor reef conditions in local areas involving local communities, with limited expert support, including Reef Life Survey (Stuart-Smith et al. 2017) and Reef Check (Hodgson 1999, 2001). The need of this type of program and training opportunities are described by Miloslavich et al. (2018a).

2.8.3.4 Data Collection and Analysis

Human observation in underwater environments is limited due to the harsh seawater environment and the large geographic scales involved, but it has been possible to begin new observations of coral reef environments in some areas, using new technologies for coral research and monitoring. Ideally, autonomous systems can be deployed to collect physical, chemical, and biological data to overcome in-person observation limitations. Environmental data such as oxygen concentrations, temperature, chlorophyll levels, and seawater turbidity and salinity help scientists interpret biological features and trends. Besides moored instruments, automated underwater vehicles (AUVs) and unmanned aerial vehicles (UAVs) (Gasmueck et al. 2006; Chirayath and Earle 2016; Koparan et al. 2018; Levy et al. 2018; Monk et al. 2018) can be used to survey reef areas.

Passive acoustic monitoring of the sounds of organisms on coral reefs is an emerging field (Servick 2014) that can complement visual methods and make continuous observations during day and night regardless of weather or storm conditions. It is becoming possible to calculate measures of acoustic diversity (Kaplan et al. 2015; Mooney et al. 2020) and efforts are underway to create an international library of underwater biological sounds to make automatic detection of animals possible (Parsons et al. 2022). Passive acoustic monitoring may make it possible to monitor reef health with less personnel required, and making it possible to observe rarely seen species and provide information about daily and monthly variation in reef ecosystems as well as to record isolated acoustic events (Staaterman et al. 2014; Parsons et al. 2016; Lillis and Mooney 2018).

Photographic reef surveys can be conducted using automated image capture and analysis tools. This type of monitoring can be conducted using images collected by platforms navigated underwater by a diver (e.g., the XL Catlin Seaview Survey http://catlinseaviewsurvey.com/) or using remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs) (Beijbom et al. 2015), with some caveats (Lesser and Slattery 2021). There are rapidly developing technologies to both acquire and process 3-dimensional photomosaic imagery using structure-from-motion (SfM) photogrammetry (Burns et al. 2015).

Studies of marine benthic and microbial biodiversity have been conducted using one square foot structures called Autonomous Reef Monitoring Structures (ARMS) (https://naturalhistory.si.edu/research/global-arms-program) by the Smithsonian Institution, U.S. National Oceanic Atmospheric Administration, and others (Pearman et al. 2019). Deployment of ARMS has demonstrated rates of colonization by reef-related species, including cryptic and invasive species (Ransome et al. 2017; Palomino-Alvarez et al. 2021), and the feasibility of using artificial structures to assist in rehabilitation of reef areas.

2.8.4 Coral Ecosystem Restoration and Conservation Tools

2.8.4.1 Coral Mitigation/Restoration Research

As pointed out in Chap. 11 on Ocean Acidification, managers of coral reef areas can do little to slow the global increase in ocean acidification due to increasing CO_2 in the atmosphere. However, there are some potential means of mitigating ocean acidification at local levels, or perhaps repair damage to coral reef ecosystems due to ocean acidification and other stresses. Albright and Cooley (2019) described a variety of passive and active approaches to help protect coral reefs or to help them recover if damaged. Passive measures are those that reduce controllable stresses on coral reefs and increase the resilience of reef areas. Examples of passive approaches include more conservative management of fisheries and coral reef areas to make them more resilient, implementation of marine spatial planning to separate conflicting uses from reef areas, protecting reef areas as part of marine protected areas, factoring reef health and sustainability into national blue economy plans (Andersson et al. 2019), and improving wastewater treatment to decrease eutrophication and other coastal pollution (Guan et al. 2020). Active measures to reef protection and mitigation mentioned by Albright and Cooley (2019) include using aquatic plants such as seagrasses to remove CO_2 from seawater, chemical balancing of pH in reef areas, reef restoration from coral nurseries, and "assisted evolution" for both corals and the dinoflagellates they host. Application of these passive and active approaches will require significant research, technology transfer, and capacity development.

2.8.4.2 Coral Reef Arks

Restoration efforts that target ecosystem-level processes, such as nutrient cycling, structural complexity and herbivory, are necessary to restore balance to these ecosystems and the services they provide. The success in colonization of ARMS deployed in various locations led to the development of Coral Reef Arks as a potential reef restoration technique. Coral Reef Arks were conceived to address a global need for new technologies that can help mitigate widespread coral reef degradation. The Arks concept has been tested by building miniature Ark models and deploying them in a coral mesocosm system. Arks are midwater structures that can be weighed in place to determine if the corals residing on them are growing (i.e., getting heavier). By moving corals up into the water column—distancing them from degraded substrates and providing improved access to light, flow, and nutrients—and by moving corals alongside the surrounding reef organisms that support coral health, Coral Reef Arks could create thriving "mini-reef" communities to support conservation and restoration goals. Arks could support the economic development of reef fisheries and tourism, and enhance coastal protection and carbon sequestration. They can also support research on marine natural products. This new tool can support restoration of reef-associated marine life as a potential option for preserving coral reefs of the world. Arks will create an entirely new way to study coral reefs and allow for the continued discovery of new marine natural products. Arks could serve as midwater nurseries and reservoirs for restoration projects, providing flora and fauna to restore reef communities following damage or degradation, and critically preserving coral reefs of the world.

2.9 Conclusions

Coral reef ecosystems provide critical services and products that are foundations of several conventional (tourism, fisheries) and emerging blue economic sectors. Intact reef ecosystems also provide protection against or reduce threats from natural hazards and extreme events. Climate change and other human activities have led to a decline in coral reefs globally, limiting their ability to provide products and services. This decline in live coral cover over the last two decades has been due to coral bleaching, coral diseases, and mechanical destruction from uncontrolled tourism and destructive fishing methods. In many regions, there have been regime shifts due to impacts of complex natural and anthropogenic factors still under investigation, where coral cover is being replaced by algal cover. There is strong evidence-based research on mechanisms explaining why corals die. However, research and monitoring are needed to continue to better understand and observe coral ecosystem dynamics and reef behavior in support of ecosystem-based management of resources. New scientific understanding could lead to new methods of conservation and launch coral restoration initiatives. Shallow-water corals are mostly bordered by developing countries in the tropics with specific local needs for observational monitoring and management approaches. Awareness and access to available new technologies and capacity building, including for personnel at the science-policy interface, are among some of the priorities.

References

Albright R, Cooley S (2019) A review of interventions proposed to abate impacts of ocean acidification on coral reefs. Reg Stud Mar Sci 29:100612. https://doi.org/10.1016/j.rsma.2019.100612

Andersson AJ, Venn AA, Pendleton L et al (2019) Ecological and socioeconomic strategies to sustain Caribbean coral reefs in a high-CO_2 world. Reg Stud Mar Sci 29:100677. https://doi.org/10.1016/j.rsma.2019.100677

Aronson RB, Precht WF (2001) White-band disease and the changing face of Caribbean coral reefs. Hydrobiologia 460:25–38

Asner GP, Knapp DE, Boardman J et al (2012) Carnegie Airborne Observatory-2: increasing science data dimensionality via high fidelity multi-sensor fusion. Remote Sens Environ 124:454–464

Barnes, R.D. 1987. Invertebrate zoology, 5th edition. Fort Worth, TX: Harcourt Brace Jovanovich College Publishers, pp 92–96, 127–134, 149–162

Bay RA, Rose NH, Logan CA et al (2017) Genomic models predict successful coral adaptation if future ocean warming rates are reduced. Sci Adv 3 (11). https://doi.org/10.1126/sciadv.1701413
Beck MW, Losada IJ, Meendez P (2018) The global flood protection savings provided by coral reefs. Nat Commun 9:2186. https://doi.org/10.1038/s41467-018-04568-z
Beijbom O, Edmunds P, Roelfsema C et al (2015) Towards automated annotation of benthic survey images: variability of human experts and operational modes of automation. PLoS One 10:e0130312. https://doi.org/10.1371/journal.pone.0130312
Berkelmans R, van Oppen MJH (2006) The role of zooxanthellae in the thermal tolerance of corals: a 'nugget of hope' for coral reefs in an era of climate change. Proc R Soc B 273:2305–2312
Birkeland C (1983) Review of nutrient flow in tropical coastal ecosystems with suggestions for management of coral reef resources and for increasing the production of sea grass beds. ESCAP/SACEP Symposium on Environmental Management of Mangrove, Coral and land Ecosystems in South Asia, 21–28 August 1983. ESCAP/UN, Bangkok
Blunt JW, Copp BR, Keyzers RA et al (2013) Marine natural products. Nat Prod Rep 30:237–323
Bourne DG, Morrow KM, Webster NS (2016) Insights into coral microbiome: underpinning the health and resilience of reef ecosystems. Ann Rev Microbiol 70:317–340
Bozec Y-M, Mumby P (2015) Synergistic impacts of global warming on the resilience of coral reefs. Philos Trans R Soc London, Ser B 370(1659):20130267
Brander LM, Rehdanz K, Tol RSJ et al (2012) The economic impact of ocean acidification on coral reefs. Climate Change Econ 3(1):1250002. https://doi.org/10.1142/S2010007812500029
Bruckner, AW (2002) Life-saving products from coral reefs. Issues Sci Technol 18(3):39–44. http://www.jstor.org/stable/43314163
Burge CA, Eakin CM, Friedman CS et al (2014) Climate change influences on marine infectious diseases: implications for management and society. Ann Rev Mar Sci 6:249–277. https://doi-org.udel.idm.oclc.org/10.1146/annurev-marine-010213-135029
Burke L, Maidens J (2004). Economic valuation methodology. World Resources Institute
Burke L, Reytar K, Spalding M et al (2011a) Enabling conditions for an equitable and sustainable blue economy. Nature 591:396–401
Burke L, Reytar K, Spalding M et al (2011b) Reefs at risk revisited. Washington, DC, World Resources Institute (WRI), The Nature Conservancy, WorldFish Center, International Coral Reef Action Network, UNEP World Conservation Monitoring Centre and Global Coral Reef Monitoring Network, 114p. https://files.wri.org/d8/s3fs-public/pdf/reefs_at_risk_revisited.pdf
Burns J, Delparte D, Gates R et al (2015) Integrating structure-from-motion photogrammetry with geospatial software as a novel technique for quantifying 3D ecological characteristics of coral reefs. PeerJ 3:e1077. https://doi.org/10.7717/peerj.1077
Caldeira K, Wickett ME (2003) Anthropogenic carbon and ocean pH. Nature 425(6956):365–365
Campbell LM, Corson C, Gray NJ et al (2014) Studying global environmental meetings to understand global environmental governance: collaborative event ethnography at the Tenth Conference of the Parties to the Convention on Biological Diversity. Global Environ Polit 14(3):1–20
Cesar H (2000) Collected essays on the economics of coral reefs. CORDIO Kalmar University, Sweden
Cesar HLP, Burke L, Pet-Soede L et al (2003) The economics of worldwide coral reef degradation. Cesar Environmental Consulting, Arnhem, The Netherlands
Chirayath V, Earle S (2016) Drones that see through waves—developing new tools in coastal marine conservation. Aquat Conserv Mar Freshw Ecosyst 26:237–250. https://doi.org/10.1002/aqc.2654
Cornwall CE, Comeau S, Kornder NA et al (2021) Global declines in coral reef calcium carbonate production under ocean acidification and warming. Proc Natl Acad Sci USA 118(21): e2015265118. https://doi.org/10.1073/pnas.2015265118
Costanza R, d'Arge R, de Groot R et al (1997) The values of the world's ecosystem services. Nature 387:253–260
Cunning R, Parker KE, Johnson-Sapp K et al (2021) Census of heat tolerance among Florida's threatened staghorn corals finds resilient individuals throughout existing nursery populations. Proc Roy Soc B 288:1961. https://doi.org/10.1098/rspb.2021.1613

Darwin CR (1842) The structure and distribution of coral reefs: being the first part of the geology of the voyage of the Beagle, Under the Command of Capt. Fitzroy, R. N. during the years 1832 to 1836, 2nd edn. Smith, Elder & Co

De Groot RS, Alkemade R, Braat L et al (2010) Challenges in integrating the concept of ecosystem services and values in landscape planning, management and decision making. Ecol Complex 7(3):260–272

Dight IJ, Scherl LM (1997) The International Coral Reef Initiative (ICRI): global priorities for the conservation and management of coral reefs and the need for partnerships. Coral Reefs 16:S139–S147. https://doi-org.udel.idm.oclc.org/10.1007/s003380050250

Dinsdale EA, Pantos O, Smriga S et al (2008) Microbial ecology of four coral atolls in the Northern Line Islands. PLoS One 3(2):e1584. https://doi.org/10.1371/journal.pone.000158

Dove SG, Hoegh-Guldberg O (2006) Coral bleaching can be caused by distress to the coral. The cell physiology of coral bleaching. In: Hoegh-Guldberg O, Phinney JT, Skirving W, et al (eds) Coral reefs and climate change: science and management. American Geophysical Union, Washington, DC. ISBN 978-0-87590-359-0

Droxler AW, Jorry SJ (2021) The origin of modern atolls: challenging Darwin's deeply ingrained theory. Ann Rev Marine Sci 13:537–573. https://doi.org/10.1146/annurev-marine-122414-034137

Eakin MC, Nim CJ, Brainard RE et al (2010) Monitoring coral reefs from space. Oceanography 23(4):118–133. https://doi.org/10.5670/oceanog.2010.10

Epstein HE, Smith HA, Torda G, van Oppen MJH (2019) Microbiome engineering: enhancing climate resilience in corals. Front Ecol Environ 17:100–108

Fabry VJ, Seibel BA, Feely RA et al (2008) Impact of ocean acidification on marine fauna and ecosystem processes. ICES J Mar Sci 65:414–432

Fairoz MFM, Suzuki Y, Casareto BE et al (2008) Role of organic matter in chemical symbiosis at coral reefs: release of organic nitrogen and amino acids under heat stress. Proc 11th Int Coral Reef Symp 2:922–926

Foo SA, Asner GP (2019) Scaling up coral reef restoration using remote sensing technology. Front Mar Sci 6:79. https://doi.org/10.3389/fmars.2019.00079

Gasmueck M, Eberli GP, Viggiano DA et al (2006) Autonomous underwater vehicle (AUV) mapping reveals coral mound distribution, morphology, and oceanography in deep water of the Straits of Florida. Geophys Res Lett 33:1–6. https://doi.org/10.1029/2006GL027734

Gattuso JP, Frankignoulle M, Bourge I et al (1998) Effect of calcium carbonate saturation of seawater on coral calcification. Glob Planet Change 18:37–47

GCRMN (2018a) GCRMN implementation and governance plan. International Coral Reef Initiative (ICRI)

GCRMN (2018b) GCRMN Technical Note. International Coral Reef Initiative (ICRI)

GCRMN (2021) Status of coral reefs of the world: 2020. https://gcrmn.net/2020-report/

Gorelick N, Hancher M, Dixon M et al (2017) Google earth engine: planetary-scale geospatial analysis for everyone. Remote Sens Environ 202:18–27. https://doi.org/10.1016/j.rse.2017.06.031

Goulay AM, Tsakiris J, de Lara ECD (1996) Molecular interactions in nanoporous adsorbents: adsorption of N_2 and O_2 in zeolites with cavities or channels: Na12A, Ca6A, NaX, and decationated mordenite. Langmuir 12(2):371–378

Gove JM, McManus MA, Neuheimer AB et al (2016) Near-island biological hotspots in barren ocean basins. Nat Commun 7:10581

GRID-Arendal and UNEP (2016) World ocean assessment overview. GRID-Arendal, Norway

Guan Y, Hohn S, Wild C et al (2020) Merico A: vulnerability of global coral reef habitat suitability to ocean warming, acidification and eutrophication. Glob Change Biol 26:5646–5660. https://doi.org/10.1111/gcb.15293

Gudka M, Obura DO (2017) The 2016 coral bleaching event in the Western Indian Ocean—overview. In: Obura DO, et al (eds) Coral reef status report for the Western Indian Ocean: Global Coral Reef Monitoring Network (GCRMN)/International Coral Reef Initiative (ICRI), pp 22–37

Guerra-Vargas LA., Gillis LG, Mancera-Pineda JE (2020) Stronger together: do coral reefs enhance seagrass meadows "blue carbon" potential? Front Mar Sci 7:628. https://doi.org/10.3389/fmars.2020.00628

Haas AF, Fairoz FM, Kelly LW et al (2016) Global microbialization of coral reefs. Nat Microbiol 1:16042. https://doi.org/10.1038/nmicrobiol.2016.42

Hamylton SM (2017) Mapping coral reef environments: A review of historical methods, recent advances and future opportunities. Prog Phys Geogr 41(6):803–833

Hamylton SM, Zhou Z, Wang L (2020) What can artificial intelligence offer coral reef managers? Front Mar Sci 7:603829. https://doi.org/10.3389/fmars.2020.603829

Hasler H, Ott JA (2008) Diving down the reefs? Intensive diving tourism threatens the reefs of the northern Red Sea. Mar Pollut Bull 56(10):1788–1794

Hendee JC, Gramer L, Kleypas J et al (2007) The integrated coral observing network: sensor solutions for sensitive sites. Proceedings of the 2007 International Conference on Intelligent Sensors, Sensor Networks and Information Processing. https://ieeexplore-ieee-org.udel.idm.oclc.org/stamp/stamp.jsp?tp=&arnumber=4496923

Heron SC, Eakin CM, Douvere F et al (2017) Impacts of climate change on world heritage coral reefs: a first global scientific assessment. UNESCO World Heritage Centre, Paris

Hodgson G (1999) A global assessment of human effects on coral reefs. Mar Pollut Bull 38(5):345–355

Hodgson G (2001) Reef check: the first step in community-based management. Bull Mar Sci 69(2):861–868

Hoegh-Guldberg O (1999) Climate change, coral bleaching and the future of the world's coral reefs. Mar Freshwater Res 50:839–866

Hoegh-Guldberg O, Mumby PJ, Hooten AJ et al (2007) Coral reefs under rapid climate change and ocean acidification. Science 318:1737–1742

Hoegh-Guldberg O, Pendleton L, Kaup A (2019) People and the changing nature of coral reefs. Reg Stud Mar Sci 30:100699. https://doi.org/10.1016/j.rsma.2019.100699

Hoegh-Guldberg O, Poloczanska ES, Skirving W et al (2017) Coral reef ecosystems under climate change and ocean acidification. Front Mar Sci 4:158. https://doi.org/10.3389/fmars.2017.001582017

Horta A, Alves C, Pinteus S et al (2015) The marine origin of drugs. In Phycotoxins, 2nd edn. Wiley, London, UK

Hughes TP, Anderson KD, Connolly SR et al (2018) Spatial and temporal patterns of mass bleaching of corals in the Anthropocene. Science 359:80–83

Hughes TP, Kerry JT, Baird AH et al (2019) Global warming impairs stock-recruitment dynamics of corals. Nature 568:387–390

Hughes TP, Rodrigues MJ, Bellwood DR et al (2007) Phase shifts, herbivory, and the resilience of coral reefs to climate change. Curr Biol 17(4):360–365

IPCC (2021) Summary for policymakers. In: Climate Change 2021: the physical science basis

Kaplan MB, Mooney TA, Partan J et al (2015) Coral reef species assemblages are associated with ambient soundscapes. Mar Ecol Prog Ser 533:93–107. https://doi.org/10.3354/meps11382

Kelly LW, Williams GJ, Barott KL et al (2014) Local genomic adaptation of coral reef-associated microbiomes to gradients of natural variability and anthropogenic stressors. Proc Natl Acad Sci USA 111(28):10227–10232

Kleypas JA, Buddemeier R, Archer D et al (1999) Geochemical consequences of increased atmospheric carbon dioxide on reefs. Science 284:118–120

Knowlton N (2001) Coral reef biodiversity—Habitat size matters. Science 292(5521):1493–1495. https://doi.org/10.1126/science.1061690

Koparan C, Koc AB, Privette VC et al (2018) In situ water quality measurements using an unmanned aerial vehicle (UAV) system. Water 10:264. https://doi.org/10.3390/w10030264

Lajeunesse TC, Smith R, Walther M (2018) Host-symbiont recombination versus natural selection in the response of coral-dinoflagellate symbioses to environmental disturbance. Proc Royal Soc B. https://doi.org/10.1098/rspb.2010.0385

LeCun Y, Bengio Y, Hinton G (2015) Deep learning. Nature 521(7553):436–444
Lentz JA (2012) Developing a geospatial protocol for coral epizootiology. Dissertation, Louisiana State University
Lesser MP, Slattery M (2021). Mesophotic coral reef community structure: the constraints of imagery collected by unmanned vehicles. Mar Ecol Prog Ser 663:229–236. https://doi-org.udel.idm.oclc.org/10.3354/meps13650
Levinton JS (1995) Marine biology: function, biodiversity, ecology. Oxford University Press, New York, pp 306–319
Levy J, Hunter C, Lukacazyk T et al (2018) Assessing the spatial distribution of coral bleaching using small unmanned aerial systems. Coral Reefs 37:373–387. https://doi.org/10.1007/s00338-018-1662-5
Lewis JB (1977) Processes of organic production on coral reefs. Biological Review 52:305–347
Lillis A, Mooney TA (2018) Snapping shrimp sound production patterns on Caribbean coral reefs: relationships with celestial cycles and environmental variables. Coral Reefs 37:597–607. https://doi.org/10.1007/s00338-018-1684-z
Lirman D, Schopmeyer S (2016) Ecological solutions to reef degradation: optimizing coral reef restoration in the Caribbean and Western Atlantic. PeerJ 4:e2597
Liu G, Heron SF, Eakin CM et al (2014) Reef-scale thermal stress monitoring of coral ecosystems: new 5-km global products from NOAA coral reef watch. Remote Sens 6:11579–11606. https://doi.org/10.3390/rs61111579
Lough JM (2000) 1997–98: Unprecedented thermal stress to coral reefs? Geophys Res Lett 27(23):3901–3904
Lowe JR, Williamson DH, Ceccarelli DM et al (2019) Responses of coral reef wrasse assemblages to disturbance and marine reserve protection the Great Barrier Reef. Mar Biol 166(9):1–21
Lugo-Fernandez A, Roberts HH, Wiseman WJ (1998) Tide effects on wave attenuation and wave set-up on a Caribbean coral reef. Estuar Coast Shelf Sci 47(4):385–393
Lyons BM, Roelfsema CM, Kennedy EV et al (2020) Mapping the world's coral reefs using a global multiscale earth observation framework. Remote Sens Ecol Conserv 6(4):557–568
Marshall PA, Schuttenberg HZ (2006) A reef manager's guide to coral bleaching. Great Barrier Reef Marine Part Authority, Australia (ISBN 1-876945-40-0)
Matsuda SB, Huffmyer AS, Lenz EA et al (2020) Coral bleaching susceptibility is predictive of mortality within but not between coral species. Front Ecol Evol 8:178. https://doi.org/10.3389/fevo.2020.00178
Maynard J, van Hooidonk R, Eakin CM et al (2015) Projections of climate conditions that increase coral disease susceptibility and pathogen abundance and virulence. Nat Clim Chan 5:688–694. https://doi.org/10.1038/nclimate2625
Maynard JA, Anthony KRN, Harvell CD et al (2011) Predicting outbreaks of a climate-driven coral disease in the Great Barrier Reef. Coral Reefs 30:485–495
McCarthy MJ, Colna E, El-Mezayen M et al (2017) Satellite remote sensing for coastal management: a review of successful applications. Environ Manage 60:323–339. https://doi.org/10.1007/s00267-017-0880
Meirelles PM, Soares AC, Oliveira L et al (2018) Metagenomics of coral reefs under phase shift and high hydrodynamics. Front Microbiol 9:2203. https://doi.org/10.3389/fmicb.2018.02203
Miloslavich P, Bax NJ, Simmons SE et al (2018a) Essential ocean variables for global sustained observations of biodiversity and ecosystem changes. Glob Change Biol 24:2416–2433. https://doi.org/10.1111/gcb.14108
Miloslavich P, Seeyave S, Muller-Karger F et al (2018b) Challenges for global ocean observation: the need for increased human capacity. J Oper Oceanogr Oceanography 12:S137–S156. https://doi.org/10.1080/1755876X.2018.1526463
Monk J, Barrett N, Bridge T et al (2018) Marine sampling field manual for autonomous underwater vehicles (AUVs). In field manuals for marine sampling to monitor Australian Waters. In: Przeslawski R, Foster S (eds) National Environmental Science Programme (NESP), pp 65–81

Mooney TA, Di Iorio L, Lammers M et al (2020) Listening forward: approaching marine biodiversity assessments using acoustic methods. R Soc Open Sci 7:201287. https://doi.org/10.1098/rsos.201287

Moore F., Best B (2001) Coral reef crisis: causes and consequences, In: Best BA, Bornbusch (eds) Global trade and consumer choices: coral reefs in crisis. Proceeding of 2001 Annual Meeting of the AAAS, San Francisco, California

Mueller-Karger FE, Miloslavich P, Bax NJ et al (2018) Advancing marine biological observations and data requirements of the complementary Essential Ocean Variables (EOVs) and Essential Biodiversity Variables (EBVs) frameworks. Front Mar Sci 5:211. https://doi.org/10.3389/fmars.2018.00211

Muscatine L (1990) In coral reefs: ecosystems of the world. In: Dubinsky Z (ed). Elsevier, pp 75–88

Muscatine L, Porter JW (1977) Reef corals: mutualistic symbioses adapted to nutrient-poor environments. Bioscience 27:454–460

Newton JA, Feely RA, Jewett EB et al (2015) Global ocean acidification observing network: requirements and governance plan, 2nd edn, GOA-ON. Available online at: http://www.goa-on.org/docs/GOA-ON_plan_print.pdf

Newton K, Côté IM, Pilling GM et al (2007) Current and future sustainability of island coral reef fisheries. Curr Biol 17:655–658

Obura D, Aeby G, Amornthammarong N (2019) Coral reef monitoring, reef assessment technologies and ecosystem-based management. Front Mar Sci 6:580. https://doi.org/10.3389/fmars.2019.00580

Odum HT, Odum EP (1955) Tropic structure and productivity of a windward coral reef community on Eniwetok Atoll. Ecol Monogr 25:295–230

Palomino-Alvarez LA, Vital XG, Castillo-Cupul RE et al (2021) Evaluation of the use of Autonomous Reef Monitoring Structures (ARMS) for describing the species diversity of two coral reefs in the Yucatan Peninsula, Mexico. Diversity 13(11):579. https://doi.org/10.3390/d13110579

Parsons MJ, Lin TH, Mooney TA et al (2022) Sounding the call for a global library of biological underwater sounds. Front Ecol Evol 10:810156. https://doi.org/10.3389/fevo.2022.810156

Parsons MJG, Salgado Kent CS, Recalde-Salas A et al (2016) Fish choruses off Port Hedland, Western Australia. Bioacoustics 26(2):135–152. https://doi.org/10.1080/09524622.2016.1227940

Pearman JK, Aylagas E, Voolstra CR (2019) Disentangling the complex microbial community of coral reefs using standardized Autonomous Reef Monitoring Structures (ARMS). Mol Ecol 28(15):3496–3507

Pearson SG (2016) Predicting wave-induced flooding on low-lying tropical islands: using a Bayesian network. Dissertation, Delft University of Technology

Peixoto RS, Rosado PM, Leite DCA et al (2017) Beneficial microorganisms for corals (BMC): proposed mechanisms for coral health and resilience. Front Microbiol 8:34

Precht WF, Gintert BE, Robbart ML et al (2016) Unprecedented disease-related coral mortality in Southeastern Florida. Sci Rep 6: Article number 31374

Purkis SJ, Gleason AC, Purkis CR et al (2019). High-resolution habitat and bathymetry maps for 65,000 sq. km of Earth's remotest coral reefs. Coral Reefs 38(3):467–488

Ransome E, Geller JB, Timmers M et al (2017) The importance of standardization for biodiversity comparisons: a case study using autonomous reef monitoring structures (ARMS) and metabarcoding to measure cryptic diversity on Mo'orea coral reefs French Polynesia. Plos One 12(4):e0175066. https://doi.org/10.1371/journal.pone.017506

Redding JE, Myers-Miller RL, Baker DM et al (2013) Link between sewage-derived nitrogen pollution and coral disease severity in Guam. Mar Pollut Bull 73(1):57–63

Robbins SJ, Singleton CM, Chan CX et al (2019) A genomic view of the reef-building coral *Porites lutea* and its microbial symbionts. Nat Microbiol 4(12):2090–2100

Roelfsema C, Phinn S (2010) Integrating field data with high spatial resolution multispectral satellite imagery for calibration and validation of coral reef benthic community maps. J Appl Remote Sens 4:1. https://doi.org/10.1117/1.3430107
Roelfsema CM, Kovacs EM, Ortiz JC et al (2020) Habitat maps to enhance monitoring and management of the Great Barrier Reef. Coral Reefs 39:1039–1054
Rohwer F, Seguritan V, Azam F et al (2002) Diversity and distribution of coral-associated bacteria. Mar Ecol Prog Ser 243:1–10
Rosenberg E, Kellogg CA, Rohwer F (2007) Coral microbiology. Oceanography 20:146–154
Sandin SA, Smith JE, DeMartini EE (2008) Baselines and degradation of coral reefs in the Northern Line islands. PLoS One 3(2):e1548. https://doi.org/10.1371/journal.pone.0001548
Santoro EP, Borges RM, Espinoza JL et al (2021) Coral microbiome manipulation elicits metabolic and genetic restructuring to mitigate heat stress and evade mortality. Sci Adv 7(33):eabg3088
Sarkis J, Helms MM, Hervani AA (2010) Reverse logistics and social sustainability. Corporate Social Responsibility Environ Manage 17:337–354. https://ww.doi.org/10.1002/csr.220
Schoepf V, Grottoli AG, Levas SJ et al (2015) Annual coral bleaching and the long-term recovery capacity of coral. Proc R Soc B: Biol Sci https://doi.org/10.1098/rspb.2015.1887
Segel AL, Ducklow WH (1982) A theoretical investigation into the influence of sublethal stresses on coral-bacterial ecosystem dynamics. Bull Mar Sci 32(4):919–935
Servick K (2014) Eavesdropping on ecosystems. Science 343:834–837. https://doi.org/10.1126/science.343.6173.834
Sheppard C, Dixon DJ, Gourlay M et al (2005) Coral mortality increases wave energy reaching shores protected by reef flats: examples from the Seychelles. Estuar Coast Shelf Sci 64:223–234. https://doi.org/10.1016/j.ecss.2005.02.016
Simmons TL, Andrianasolo E, McPhail K et al (2005) Marine natural products as anticancer drugs. Mol Cancer Ther 4:333–342
Spalding M, Burke L, Wood SA et al (2017) Mapping the global value and distribution of coral reef tourism. Mar Policy 82:104–113
Spalding MD, Ravilious C, Green EP (2001) World atlas of coral reefs. Prepared at the UNEP World Conservation Monitoring Centre. University of California Press, Berkeley, USA
Staaterman E, Paris CB, DeFerrari HA et al (2014) Celestial patterns in marine soundscapes. Mar Ecol Prog Ser 508:17–32. https://doi.org/10.3354/meps10911
Stuart-Smith RD, Edgar GJ, Barrett NS et al (2017) Assessing national biodiversity trends for rocky and coral reefs through the integration of citizen science and scientific monitoring programs. Bioscience 67:134–146. https://doi.org/10.1093/biosci/biw180
Sully S, Burkepile DE, Donovan MK et al (2019) A global analysis of coral bleaching over the past two decades. Nat Commun 10:1264. https://doi.org/10.1038/e41467-019-09238-2
Szmant A, Ferrer LM, FitzGerald LM (1990) Nitrogen excretion and O:N ratios in reef corals: evidence for conservation of N. Mar Biol 104:119–127
Teh LSL, Teh LCL, Sumaila U (2013) A global estimate of the number of coral reef fishers. PLoS One 8:e65397
Thompson A, Schroeder T, Brando VE et al (2014) Coral community responses to declining water quality: Whitsunday Islands, Great Barrier Reef, Australia. Coral Reefs 33:923–938
Tittensor DP, Walpole M, Hill SLL et al (2014) A mid-term analysis of progress toward international biodiversity targets. Science 346:241–244. https://doi.org/10.1126/science.1257484
Tong H, Cai L, Zhou G et al (2020) Correlations between prokaryotic microbes and stress-resistant algae in different corals subjected to environmental stress in Hong Kong. Front Microbiol 11:686. https://doi.org/10.3389/fmicb.2020.00686
UNEP (United Nations Environment Programme) (2004) People and reefs: successes and challenges in the management of coral reef Marine Protected Areas
UNGA (2013) Resolution 68/70, paragraph 153. United Nations General Assembly
Uthicke S, Logan M, Liddy M et al (2015) Climate change as an unexpected co-factor promoting coral eating seastar (*Acanthaster planci*) outbreaks. Sci Rep 5:8402. https://doi.org/10.1038/srep08402

Van Beukering PJH, Brander L, Tompkins E, McKenzie E (2007) Valuing the environment in small islands: an environmental economics toolkit joint nature conservation committee. Peterborough, GB 125pp
Veron JEN (2000) Corals of the World (No. C/593.6 V4)
Veron JEN (2004) A new estimate of global reefal carbonate production including the fore-reefs. Global Planet Change 43:1–18
Veron JEN, Hoegh-Guldberg O, Lenton TM et al (2009) The coral reef crisis: The critical importance of <350 ppm CO_2. Mar Pollut Bull 58(10):1428–1436
Voolstra CR, Suggett DJ, Peixoto RS et al (2021) Extending the natural adaptive capacity of coral holobionts. Nat Rev Earth Environ 2(11):747–762
Walton C, Hayes N, Gilliam D (2018) Impacts of a regional, multi-year, multi-species coral disease outbreak in Southeast Florida. Front Mar Sci 5:323. https://doi.org/10.3389/fmars.2018.00323
Wilkinson C (2004) Status of coral reefs of the world. Global Coral Reef Monitoring Network 21
Wilkinson C (2008) Status of coral reefs of the world: 2008 (2008) Global Coral Reef Monitoring Network and Reef and Rainforest Research Centre, Townsville, Australia
Wilkinson C (ed) (2000) Status of coral reefs of the world: 2000. Australian Institute of Marine Science, Townsville, QLD
Ziegler M, Rolk A, Porter A et al (2016) Coral microbial community dynamics in response to anthropogenic impacts near a major city in the central Red Sea. Mar Pollut Bull 105:629–640

Chapter 3
Mangroves and Seagrasses

Marília Cunha-Lignon, Jocemar Tomasino Mendonça, Luis Americo Conti, Kcrishna Vilanova de Souza Barros, and Karine Matos Magalhães

Abstract Mangroves and seagrass contribute to people's quality of life, taking an important place in the Blue Economy context. Activities such as fishing contribute to the national economies of many developing nations. Carbon sequestration in these systems is considered among the most effective among ecosystem types—even including terrestrial systems—and helps mitigate climate change impacts. Nature-based tourism activities, including in mangrove and seagrass systems, add to the conservation values of these systems, engaging both stakeholders and local communities and generating income through these activities. Biotechnology research and new studies continually reveal the potential of these blue systems for discovery of marine natural products that could be important for medicine, cosmetics, and other products. Despite their importance and potential, mangrove and seagrass systems are under-considered by decision-makers as vulnerable environments, faced by several threats, which has led to decreased areas of these systems. For our future and better exploration of their potential in the blue economy context, mapping Blue Carbon Ecosystems, implementation of restoration programs, and incorporating the

M. Cunha-Lignon (✉)
Universidade Estadual Paulista, Campus de Registro, Av. Nelson Brihi Badur 430, Registro, SP 11900-000, Brazil
e-mail: cunha.lignon@unesp.br

J. T. Mendonça
Instituto de Pesca, Núcleo de Pesquisa Do Litoral Sul, APTA/SAA, Av. Prof. Besnard, s/n., Cananéia, SP 11990-000, Brazil
e-mail: jocemar.mendonca@sp.gov.br

L. A. Conti
Universidade de São Paulo, São Paulo, SP, Brazil
e-mail: lconti@usp.br

K. V. de Souza Barros
Universidade Federal do Ceará, Fortaleza, CE, Brazil

K. M. Magalhães
Universidade Federal Rural de Pernambuco, Recife, PE, Brazil
e-mail: karine.mmagalhaes@ufrpe.br

E. R. Urban Jr. and V. Ittekkot (eds.), *Blue Economy*,
https://doi.org/10.1007/978-981-19-5065-0_3

ecosystem services they provide into financial valuation frameworks need to be urgent priorities all over the world, especially in developing countries.

Keywords Ecosystem services · Ecosystem management · Sustainable Development Goals · Remote sensing techniques

3.1 Introduction

Human communities depend on coastal ecosystems to sustain them, but the continued health of coastal ecosystems depend on their careful use. In these coastal environments, several conflicts are triggered by the multiple uses of natural resources, sometimes conflicting, such as fishing and tourism. Although these activities are often not the most impactful, they are sectors of the blue economy that must be managed appropriately to achieve their potential for sustainable use. Many developing coastal and island nations depend on tourism and fisheries for a significant part of their gross domestic product and public revenues. Coastal tourism is a key component of small island state economies (World Bank 2016) (see also Chap. 6 on Tourism). The impacts of overfishing, coastal development, pollution, and climate change are being felt by coastal communities around the world. However, countries are looking to the ocean as a new frontier for food security, poverty reduction, and economic growth (Patil et al. 2016). The need to balance the economic, social, and environmental dimensions of sustainable development in relation to the ocean is a key component of the blue economy (World Bank 2017).

Protection of coastal ecosystems relates to the United Nations Decade of Ocean Science for Sustainable Development and Agenda 2030 Sustainable Development Goals (SDGs), especially SDG 14 (Life below Water). As noted in Chap. 1, blue economies balance economic, social and environmental benefits, and may require development paradigms other than those historically considered. These triple pillars reflect the SDGs, which are now the primary instruments that frame the international policy context. The unique importance of the ocean, and the challenges it faces, are reflected in SDG 14: 'Conserve and sustainably use the oceans, seas and marine resources for sustainable development,' and the seven targets that underpin it. Other SDGs also have to be considered, such as SDG 1 (No Poverty), SDG 2 (Zero Hunger), SDG 3 (Good Health and Well-Being), SDG 6 (Clean Water and Sanitation) SDG 13 (Climate Action) and SDG 15 (Life on Land). As key ecosystems that promote a productive ocean, keeping blue carbon ecosystems healthy maintains the quality of life of human populations on the planet.

Although mangroves make up less than 1% of all tropical forests worldwide, they are highly valuable ecosystems, providing an array of essential goods and services which contribute significantly to the livelihoods, well-being, and security of coastal communities (Fig. 3.1). The complex network of mangrove roots can help reduce wave energy, limiting erosion and shielding coastal communities from the destructive forces of tropical storms. Mangrove ecosystems are often an essential source of

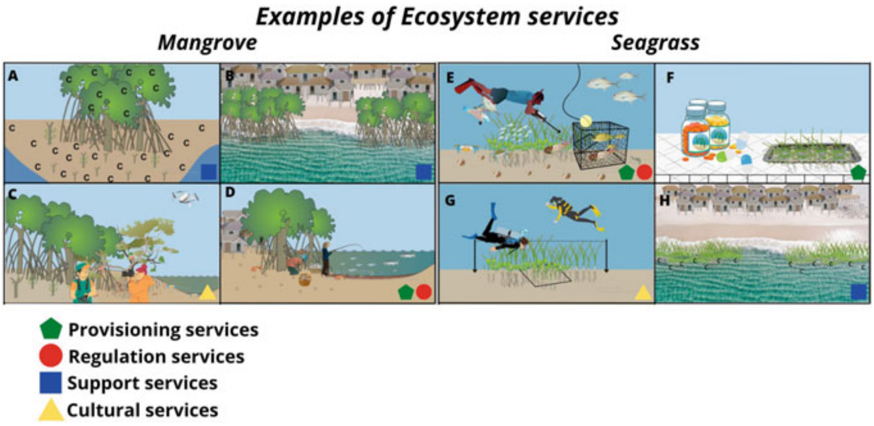


Fig. 3.1 Examples of ecosystem services of mangroves and seagrasses. **a** carbon sequestration and storage; **b** coastal protection; **c** recreation activities; **d** fishing and food provisioning; **e** fisheries; **f** medicine; **g** research and monitoring; **h** carbon sequestration and storage and shoreline protection. Art: Gabriel Henrique Silva @gabriielnk. Diagram symbols are from the Integration and Application Network, University of Maryland Center for Environmental Science (http://ian.umces.edu/imagelibrary/)

seafood for both subsistence consumption and the local and national seafood trade, in addition to providing other materials (e.g., firewood and timber) that support the livelihoods of thousands of coastal communities. Beyond their direct benefits, mangroves also play an important role in global climate regulation. On average, they store around 1000 tons of carbon per hectare in their biomass and underlying soil, making them some of the most carbon-rich ecosystems on the planet. Despite their value, mangrove ecosystems are one of the most threatened on the planet (UNEP 2014).

With the recently increased recognition of the seagrass contribution to people's quality of life (McKenzie et al. 2021), as well as the ecosystem services they provide (Nordlund et al. 2016), seagrasses are also considered, together with mangroves, as fundamental ecosystems in the Blue Economy context (Steven et al. 2019). Seagrasses are submersed marine flowering plants represented by approximately 72 species distributed on estuaries and coastal shores of at least 191 countries, up to a maximum depth of 60 m (Silva et al. 2021). Seagrass meadows are under-mapped, but recent estimates suggest that their cover may range from 160,387 km^2 to 266,562 km^2 worldwide (McKenzie et al. 2020). Although not well represented in management plans and under-considered by authorities, decision-makers and stakeholders, seagrass systems play a significant role in supporting food security as they provide nursery habitat for over 20% of the world's main fisheries (Unsworth et al. 2018). The wide range of ecosystem services they provide may vary among species and bioregions (Nordlund et al. 2016), but are enhanced by their connectivity to other coastal ecosystems like coral reefs and mangroves.

Mangroves and seagrasses are considered vulnerable environments, subject to several threats, such as the loss and fragmentation of vegetation cover and deterioration of the quality of aquatic habitats. Such deterioration is mainly due to development for human use and pollution and changes in hydrodynamics, which has decreased the supply of resources on which many traditional communities and sectors depend directly to survive, such as the communities of artisanal fishers (MMA 2018).

3.2 Role in the Blue Economy

Mangroves and seagrasses contribute to the blue economy in several aspects, in line with SDG 14 (Life Below Water): carbon sequestration and storage, nursery for commercially and socially important fish species, sediment retention and stabilization, port activities viability, among others. Understanding the importance of these systems for small-scale fishers is relevant to several SDGs, especially SDG 14, which includes the aim of promoting small-scale fishers' access to "marine resources and markets (SDG 14.b)". Therefore, effective management of mangrove areas with high fishing intensity should be prioritized (Zu Ermgassen et al. 2020), as well as for seagrass, as degradation of these ecosystems severely affects fisheries (Nordlund et al. 2018).

3.2.1 Blue Carbon

The carbon market is an instrument to monetize reductions of greenhouse gas (GHG) emissions by providing compensation for each unit of carbon sequestered and/or stored (Perdan and Azapagic 2011). It is based on the concept that the carbon stored in ecosystems can be quantified and traded as credits by buyers (public and private) who need to offset their emissions. Such carbon credits are verified through standards that determine their verification and certification, and establish registration and enforcement systems. The credits are then sold either on the compliance market, in which parties such as national governments or members of industry are obliged to reduce their emissions under a treaty, or on the voluntary market, in which buyers buy credits voluntarily in an effort to be more sustainable (Wylie et al. 2016).

The creation of an international regulatory framework to counter global warming is the core of a market for carbon offsets. The United Nations Framework Convention on Climate Change in 1992 aimed for the "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic human-induced interference with the climate system" (Kyoto Protocol 1998). From 1997 onwards, the carbon market expanded considerably with the establishment of the Kyoto Protocol and regional initiatives such as the European Union Emissions Trading Scheme (EU ETS) and the U.S. Regional Greenhouse Gas Initiative (RGGI).

In this context, the term "blue carbon" (BC) refers to the organic carbon that is accumulated by specific coastal wetlands ecosystems (Blue Carbon Ecosystems—BCEs) which, despite their relatively small global extent, are disproportionately important in sequestering carbon dioxide when compared with terrestrial habitats (referred as "green carbon") (McLeod et al. 2011). These BCEs include vegetated environments such as mangroves, tidal marshes, and seagrass meadows, which not only incorporate atmospheric carbon in their living biomass, but also in the substrate enhanced by anoxic and saturated conditions, which prevents the action of bacteria on the organic matter they produce. This carbon originates mainly from plant roots, although woody tissue and leaf litter can also contribute to the carbon deposited in these environments (Lovelock and Reef 2020).The carbon stored in these ecosystems may originate within the BCE ecosystems, when it is gathered from plant biomass debris; or may enter the BCE system from external sources when it is brought through the currents, being deposited in the soil for centuries or millennia (Mateo et al. 2006). Carbon storage is affected not only by vegetation characteristics, but also by biochemical and sedimentary substrate factors such as sedimentation rate and organic matter decomposition.

Numerous studies and research have been conducted in order to quantify the amount of BC sequestered in coastal systems. The most recent estimates (Macreadie et al. 2021) reveal that global distribution of BC is stored in ~36–185 million ha of coastal ecosystems, potentially storing ~8970–32,650 teragrams (Tg). Protecting existing BCE could avoid emissions of 304 (95% confidence interval bounds of 141–466) Tg carbon dioxide equivalent (CO_2e) per year and large-scale restoration could remove an extra 841 (621–1064) Tg CO_2e per year by 2030, equivalent to ~3% (0.5–0.8% from protection and 2.3–2.5% from restoration) of annual global greenhouse gas emissions.

3.2.1.1 Mangroves

Mangrove habitat is among the coastal blue carbon components that provides economically and ecologically significant ecosystem services, including carbon and nutrient sequestration, due to the high primary productivity and efficiency in carbon storage and nutrients in soils. Numerous studies and research have been conducted to quantify the amount of carbon sequestered in mangroves, given the high values involved in the BC market associated with these ecosystems.

However, there are some considerations regarding the concepts and definitions of blue carbon in the form of mangroves. First, the term "carbon sequestration" refers to the process of carbon absorption by these ecosystems, mainly the Net Primary Production (NPP), whose main factors are associated to the type of structure (species, density), nutrient availability and ecological and environmental settings that determine the aboveground biomass accumulation (Alongi 2014). On the other hand, the term "carbon stock" alludes to the total carbon stored in the plant and in the soils underneath the trees, and in the long-lived tissues (e.g., roots and wood) of the plants themselves (Vanderklift et al. 2019). Such carbon stock accumulation is generally associated with more complex long-term processes over tens of thousands of years, and involves not only vegetation characteristics, but also biochemical and sedimentary factors such as sedimentation rate and organic matter decomposition. Thus, the amount of carbon sequestered per unit of mangrove can be highly variable, according to the coastal geomorphological and geological settings that determine aspects of sedimentary processes, nutrient loads and limitations (e.g., the nitrogen-to-phosphorus [N:P] stoichiometric ratio), organic matter decomposition, and, ultimately, C storage in vegetation (Twilley et al. 2018). For example, C sequestration is enhanced in deltaic environments because rivers continuously deposit sediment in mangrove soils, leading to higher C sinking rates (Breithaupt et al. 2012; Cragg et al. 2020). However, fluvial sediments tend to have less organic matter associated, so deltaic mangrove substrates have a relatively low C content by volume. In contrast, in carbonate settings such as in Florida Everglades, Australia, and Caribbean islands, most of the BC volume is associated with the mangrove tree mass, leading to higher C stocks (Breithaupt et al. 2020). But, soils form in deltas more quickly than mangrove trees grow, since rivers are always depositing new sediment (Kusumaningtyasa et al. 2019).

Even taking these uncertainties into account, new estimates show that the global storage of C in mangrove biomass is estimated at 6.4 petagrams (Pg), which equates to only 0.4–7% of terrestrial ecosystem C_{org} stocks, but 17% of total tropical marine C_{org} stocks (Alongi 2020); 70% of this C occurs in equatorial and tropical coastal margins from 0° to 10° N and S latitudes. The average rate of wood production is 12.08 megagrams (Mg) ha^{-1} yr^{-1}, which is equivalent to a global estimate of cumulative sequestration potential of 24.0 ± 3.2 MtC yr^{-1} (million tons—or megatons—of carbon per year) for mangroves (Bertram et al. 2021).

Mangrove BC projects around the world are currently being implemented through a wide range of methodologies and funding mechanisms but, in general, there are two ways to promote the market for BC focused on mangroves, both in voluntary and compliance markets: through incentives for conservation and restoration (Wylie et al. 2016). In the case of conservation, the aim is to prevent the loss of carbon from mangrove ecosystems by maintaining natural geochemical and biophysical processes in order to avoid the loss of this carbon to the atmosphere. Given the alarming loss of mangrove areas—specifically from changes in land use through logging and degradation of areas due to variations in climate regime and sea level—the enhancement of conservation programs can be very important for such environments to maintain existing carbon stores and increase the rate of carbon sequestration.

In restoration programs, on the other hand, there is an effort to replant mangrove forests in areas already deforested or in the process of degradation. These projects, in most cases, are based on local or regional actions and are often associated not only with the recovery of mangrove areas aiming for the BC market, but also focusing on the regeneration and rehabilitation of other ecosystem services such as artisanal fisheries and tourism (see Sect. 2.2).

Conservation programs for mangrove ecosystems using project-based approaches tend to be more effective than restoration programs, considering their implementation, legislation or control actions. In the case of restoration programs, there is a need for high investment for the recovery of areas; moreover, in many cases, the general condition of the region has already been so altered that the planting of new mangrove forests is extremely difficult and not cost-effective. However, both conservation and restoration contribute to climate change adaptation, and therefore restoration offers opportunities to develop market-based mechanisms that take advantage of existing frameworks for carbon offsets (Macreadie et al. 2021).

Mangrove carbon markets are currently constrained by gaps in knowledge on the potential climate mitigation benefits and financial return on investment of mangrove blue carbon projects at national, regional, and global scales (Zeng et al. 2021). There are many technical and methodological difficulties in quantifying the rate of carbon sequestered in soils in reforested areas, which makes it difficult to establish certifications and regulations for accessing the carbon compliance or volunteer markets.

Therefore, one of the most important issues regarding the implementation of large-scale funding programs for conservation and restoration of BC in mangroves is the generation of accurate information about not only the areas of mangrove cover around the world, but also their biophysical characteristics and environmental settings (Howard et al. 2014). Pham et al. (2019) provided a critical overview of the most common mapping and monitoring techniques used for Blue Carbon Ecosystems and found that, in local or regional scales, most of the studies that established quantitative measurements of BC from spectral remote sensing in mangroves were based on regression models from medium-resolution images (e.g., Landsat and Sentinel satellites) and had varying degrees of accuracy depending on the characteristics of the mapped areas, ground truthing and the image processing and classification methodologies (see Pham et al. 2019; Rovai and Twilley 2021; Stankovic et al. 2021, and references within). Thus, the estimated mangrove areas as well as the quantities of BC can vary significantly depending on the precision and accuracy of the techniques used (Fatoyinbo et al. 2018).

3.2.1.2 Seagrasses

Seagrass meadows alter the biogeochemical cycles of nutrients in the coastal zone, significantly contributing to some bacteria groups and reducing human impacts on the coastal ecosystems by absorbing nutrients and other pollutants. They are important systems for carbon cycling, mainly because of their broad distribution in the coastal zones, with high sediment organic content and productivity (Kennedy et al. 2010). Carbon sequestration is considered one of the most relevant ecosystem services provided by seagrass meadows, mitigating global warming (Duarte and Krause-Jansen 2017), but also increasing resilience of coastal environments (Barañano et al. 2018).

Seagrass meadows are one of the main carbon sinks in the ocean, as they store around 20% of the total carbon stored by marine ecosystems and can contain 2–15 times more carbon than terrestrial ecosystems per area, with an export of 30% (approximately 24 Tg year^{-1}) of carbon to the deep sea (Duarte et al. 2005; Kennedy et al. 2010; Fourqurean et al. 2012; Duarte and Krause-Jensen 2017). Several factors may influence the carbon capture and storage in seagrass meadows, including the species composition, growth rates and structural complexity of the plants, landscape (patched or continuous), trophic web imbalance (herbivory, presence of invasive species, extinction of the top predator), environmental interactions (high temperatures, high organic supply, low water motion, low turbidity, low sediment grain size, depth, nutrient availability and geographical location), and other circumstances such as material export, burial rates, anoxic conditions and a low decomposition rate of the sediment that affect the carbon accumulation (Mateo et al. 2006; Duarte and Krause-Jensen 2017).

The carbon accumulated in the seagrass soil is almost always derived from below-ground biomass; carbon originating from leaves has a short residence time in the detrital compartment, although this compartment comprises a short-term sink of organic carbon accumulated after the first year and subject to biological degradation (Mateo et al. 2006). Long-term carbon storage is derived from below-ground tissues, dead and buried in the soil, with material that can be only affected by geochemical processes (Mateo et al. 2006). The first layer of 1 m of the sediment of seagrass meadows can contain about 40 times more carbon than that found in the living biomass, being approximately 74% of the carbon stored below ground (Ganguly et al. 2017).

The importance of seagrass meadows—especially as carbon sinks and thus to climate change mitigation—has been emphasized in recent decades. However, seagrass meadows remain forgotten in global models of the carbon cycle and traditional programs for reduction of greenhouse gas effects (Duarte and Krause-Jensen 2017). Table 3.1 summarizes the values of global cover and C stock and C burial rate of mangroves, seagrasses, and saltmarshes.

Restoring and managing mangrove and seagrass ecosystems for climate change mitigation and adaptation is challenging, but feasible, with the potential to extract an extra 841 Tg CO_2 per year by the year 2030 (Macreadie et al. 2021). However, these systems can provide several additional benefits beyond the issue of the BC itself, including ecosystem services that can benefit the economy at local, regional and national levels.

Table 3.1 Values of global cover, carbon stock and carbon burial rate of coastal Blue Carbon Ecosystems

Ecosystem	Global cover (km^2)	Global C stock ($Mg\ C\ km^{-2}$)	Global C burial rate ($Tg\ C\ yr^{-1}$)
Mangroves	81,485[1]	3.86[2]	23.6[3]
Seagrasses	160,387–266,562[4]	1.08[5]	48–112[6]
Saltmarshes	54,951[7]	2.55[2]	60.4[3]

Legend 1-Hamilton and Casey (2016); 2-IPCC (2014); 3-Duarte et al. (2005); 4-McKenzie et al. (2020); 5-Fourqurean et al. (2012); 6-McLeod et al. (2011); 7-Mcowen et al. (2017)

3.2.2 *Fisheries (See Also Chap. 4)*

Human uses are diverse, in terms of raw material, food, and their relative importance in the blue economy. On a global scale, small-scale fisheries are important in many developing countries, not only by contributions to national economies, but also as a critical source of food and employment in many parts of the world where there are few alternative livelihoods and protein sources. The importance of food security and the association of many fisheries with healthy mangrove forests is obvious at national scales, particularly in Asia, West and Central Africa and in South America (Zu Ermgassen et al. 2020). Similar is the case regarding the importance of seagrass meadows to fishing activities, as they provide an environment for commercial and non-commercial species (but are also important in the food chain of other species in the ecosystem) as nursery areas for growth, feeding and protection (Gillanders 2006).

3.2.2.1 Mangroves

The importance of mangrove areas for fishing activity is well known, as highly productive environments of coastal food chains, hosting a huge range of organisms permanently or temporarily, and often providing especially productive activities for coastal populations, such as fishing communities (Sukardjo 2004; Sulochanan 2013). However, many estimated numbers of fish supported by mangrove systems around the world are unreliable, being generally based on catch delivered to ports, making it difficult to relate catches to specific mangrove areas (Hutchison et al. 2014a, b). Many studies have valued mangroves, but these values are relative, with a huge variation caused by local characteristics, which do not faithfully reflect the importance of these areas for fishing activity. In any case, values expressed in simple catch statistics, in monetary terms or other metrics, are site-specific and are useful in these places where management decisions, conservation actions and fishing activities take place (Hutchison et al. 2014a, b).

Many fisheries occur near mangrove areas, whether fishery products are attached to the roots of vegetation (e.g., mollusks), totally dependent products (e.g., crabs), or products that need the mangrove areas for food, growth or protection (e.g., various fish). The number of fishers associated with mangrove areas was recently estimated at 4.1 million individuals around the world, with the highest number of mangrove fishers found in Indonesia, India, Bangladesh, Myanmar, and Brazil (Zu Ermgassen et al. 2020).

It is observed in Brazil, for example, that a significant number of fishers depend on fishing in mangrove areas. In this coastline of almost 8000 km, there are 14 thousand km^2 of mangroves, which occupy almost the entire coast. Of the total number of fishers in the country, 99% are artisanal and 43% (more than 460,000 fishers) are in the coastal region (Table 3.2). This shows the importance of mangroves in maintaining fishing and fishing communities in this country.

Table 3.2 Total number of fishers by federation region in Brazil in 2015, including fishers of mangrove and other environments

Federation Region	Total	Artisanal fisheries	Industrial fisheries	Coast	Continent
North	405,718	404,887	831	106,754	298,964
Northeast	513,082	512,626	456	275,974	237,108
Midwest	21.89	21,888	2	0	21.89
Southeast	84,833	83,026	1,807	33,615	51,218
South	62,202	55,444	6,758	47,663	14,539
Total	1,087,725	1,077,871	9,854	464,006	623,719
Percentage		99	1	43	57

Source Ministry of Fisheries and Agriculture's General Fisheries Records of Brazil (RGP) database (Secretariat of Aquaculture and Fisheries/Ministry of Agriculture, Livestock and Supply, Brazil—SAP/MAPA), obtained in March 2016

The fishery products associated with Brazilian mangrove areas are numerous, depending on the geographic area. According to fishing production data from the federation units presented in Freire et al. (2015), in the North and Northeast regions of Brazil, products such as crabs, weakfish, catfish, crevalle jack, southern red snapper, yellowtail snapper, "sururu" mussels, caitipa mojarra, snook and white mullet are closely associated with mangrove areas. In the Southeastern and Southern regions, other species, such as snook, crab-uçá, oysters, white mullet, anchovy, crabs, estuarine shrimp, caitipa mojarra are strongly associated with mangrove areas (Cunha-Lignon and Mendonça 2021).

In mangroves, species of interest to the fishing sector are found at all levels of the food chain, with detritivores such as crabs, shrimp and small fish; filter feeders such as bivalves, planktivorous fish; as well as large consumers such as crabs and fish (Sulochanan 2013; Hutchison et al. 2014a, b). In summary, mangroves are an extremely important environment for the maintenance of fishery resources that are most important for both coastal fishing and fishing activities in deeper waters that exploit resources with a life cycle linked to shallow areas. The maintenance of mangrove areas is essential for the sustainability of fishing that involves both artisanal and industrial participants. Fishing productivity maintains both fishing communities and the entire commercial chain that depends on it, sustaining the cultural diversity of traditional communities, since a multiplicity of traditional fishing gears is used to capture different species of fish and shellfish that use mangrove ecosystems during part or all of their life cycles. Mangrove forest conservation strategies involving local communities are seen as more effective than simply involving top-down state or national government control (Erwiantono 2006). The empowerment of users who are dependent on these environments, and the division of responsibilities, multiply the chances of success in environmental preservation processes, bringing sustainability to the activities and conservation of the environments that maintain these activities.

3.2.2.2 Seagrasses

Seagrass meadows are habitats of commercially important species from small to large vertebrates. Fishes inhabiting seagrass meadows can be permanent (throughout their entire lifecycle), temporal (one phase of their life) or visitors to the meadows with greater or lesser frequency, contributing to energy circulation along the coast (Fig. 3.2). Thus, seagrasses provide food security as a crucial link in the food web for animals and people in both coastal (Duarte et al. 2008) and offshore industrial fisheries (Unsworth et al. 2018). According to Unsworth et al. (2018), this significant role in global fisheries is not formally recognized worldwide. However, it shows high economic importance of seagrasses as they are critical habitat for subsistence and commercial species in addition to recreational and endangered species. Seagrass areas cover between 160,000 and 266,000 km^2 worldwide, being associated with numerous fishing communities (McKenzie et al. 2020).

A variety of fishing gear are used to capture fish in seagrass meadows. Fishing gear used directly on the seagrass meadows varies from the traditional ones (e.g., nets, spears, traps, poisons and narcotics) to local adaptations involving gleaning methods. Even spoons are used in these processes, which usually damage the underground systems of the plants (Musembi et al. 2019; Furkon et al. 2020).

Gill nets are the most used in these areas to capture different fish but, depending on the region of the planet, several other devices can be found that have more significant impacts on the environment, such as explosives and trawling (Veitayaki et al. 1995; Tioti et al. 2021). For example, during trawling, there is displacement over the meadow at low tide, when fishers walk over the meadows at low tide, they leave an extensive trail of destruction behind. Such trawling devices are used in the

Fig. 3.2 Ecosystem connectivity between mangroves and seagrasses and human uses. Art: Gabriel Henrique Silva @gabriielnk. Diagram symbols are from the Integration and Application Network, University of Maryland Center for Environmental Science (http://ian.umces.edu/imagelibrary/)

Pacific region by women fishers (Tioti et al. 2021). Fishing fences or traps (i.e., artisanal structures of wood commonly used by fishing communities in tropical areas to capture fishes when tides recede) are also frequently placed on seagrass meadows, representing another threat by alterations in local hydrodynamics, causing clearings and sand deposition on the meadows (Barros et al. 2016).

Although several different types of fishing equipment and methods target various fishery products, whether fish, crustaceans or molluscs, the activity is carried out by small-scale fishing, developed by communities, which in general are more fragile socio-economically than industrial fisheries. Men, women, and children (usually dominated by women) of coastal and island people around the world have been observed to gather invertebrate species (e.g., clams, sea cucumbers, sea urchins, conch, lobster, shrimp, octopus) during low tides in shallow and intertidal meadows, in Asia, Oceania, Africa and the Americas. In Green Island (Australia), a marine protected area, recreational and commercial fishing is prohibited, but artisanal fishing is allowed for indigenous people (Cullen-Unsworth et al. 2014). This activity is almost always for subsistence, but it can be considered a "backup livelihood" for people when food or money is scarce (Cullen-Unsworth et al. 2014). However, it can be an essential economic activity for villages, with community organizations dedicated to this activity, as in northeastern Brazil (Wojciechowski et al. 2014). But, in general, the environmental impacts of artisanal activities are often low, with fishers (especially women) being concerned with the environment, through an intergenerational transmission of collection techniques taking into account habitat preservation (Cullen-Unsworth et al. 2014; Wojciechowski et al. 2014; Barros et al. 2016).

Other manual collections of fish and shellfish are also conducted in seagrass meadows, such as "flashlight fishing", where fishers use a flashlight during the night to immobilize and capture shrimp (Santos et al. 2016), mullet and crabs (Comissão Ilha Ativa, personal communication) on the meadows. During low tides, women and children manually collect bivalve species (e.g., *Anomalocardia flexuosa*, *Phacoides pectinatus* and *Tivela mactroides*), which can be both commercialized and serve as a protein source for these traditional people (Barros et al. 2016). To get an idea of how important seagrass can be in maintaining fishery resources, Furkon et al. (2020) related the density of seagrass meadows with abundance indices (catch per unit effort, CPUE) of artisanal fishers in Indonesia, showing a high positive relationship in CPUE increase with the higher density of meadows, with yields from 0.05 to 3 kg person^{-1} hour^{-1}.

It should be noted that the different genders of fishers can influence the impacts on fish resources within areas with seagrass, as men generally use larger equipment than women, causing greater impacts to the environment. For example, when fishers harvest bivalves, men use larger and heavier implements, including construction tools (e.g., shovels and garden rakes) and liquor crates to wash more of the seagrass substrate, with a net production greater than that of women per unit, but women fishers fear that these methods are not sustainable for the species (Wojciechowski et al. 2014). Artisanal fishing activities carried out by women are typically on the edge of the meadows and use larger meshes that minimize damage to the ecosystem, as they avoid clearings in the center of the meadows and capture of juvenile specimens.

However, despite the known rich commercial biodiversity exploited in seagrass meadows as a livelihood for many coastal communities around the world, little or no attention is given by governments to create awareness among stakeholders on ecosystem functioning and the need for correct management. Sector conflict resolution and trade-offs that are necessary for a sustainable blue economy should be considered as several of the practices reported above can damage the meadows and cause seagrass cover loss. The plants need some time to restore their tridimensional structure and substrate to support larval replacement and attract visiting fish species. This review already found some concern of fishers, especially with the correct use of fishing tools, in order to maintain fish stocks and, thus, sustainable use of the ecosystems.

3.2.3 Tourism (See Also Chap. 6)

Coastal tourism is one of the most important and obvious activities linked to the blue economy. It includes both direct recreational activities that take place in the ocean, such as snorkeling, sailing, and sports competitions, and the infrastructure involved in the tourism sector, such as accommodation, ports, restaurants, and shopping centers. Although economically important, these activities, if mismanaged, may damage natural systems and reduce their economic and ecologic viability in the long term as pressure on coastal systems causes the deterioration of the main attraction.

3.2.3.1 Mangroves

The use of mangroves as a travel and tourism destination is gaining attention because these areas provide a high-value, low-impact use of these important ecosystems. Ecotourism and recreation in mangrove areas include facilities such as boardwalks, viewing towers and information centers, as well as activities such as boating, fishing, hiking and wildlife watching (Spalding and Parret 2019). Spalding and Parret (2019) identified 93 countries and territories with mangrove attractions, with boating being the most widespread activity, recorded in 82% of English-language sites. Mangrove tourism attracts tens to hundreds of millions of visitors annually and is a multi-billion-dollar industry (Spalding and Parret 2019). These activities can be increased worldwide, especially in protected areas, reinforcing community-based tourism.

Caribbean mangrove ecosystems are displayed as mysterious natural and wild sites and as good places to practice leisure activities and to relax, enjoying the paradisiacal seascapes. Mangrove ecotourism is often accomplished as one-day trips, combining the discovery of natural sceneries and relaxing activities. In Jamaica, Martinique, and Guadeloupe, 62% of local stakeholders use the mangroves directly as the main message for their business (Avau et al. 2011).

Mangrove fauna and flora may enrich coastal tourism experiences. Mangrove nature tourism alternatives can be developed as additional tourism activities for

Indonesian tourist destinations (Kissinger et al. 2020). East Java (Indonesia) still lacks a mangrove tour program, important to deliver the objectives of ecotourism. For the sustainable use of mangrove biodiversity as a tourist attraction, it is essential to know the basic characteristics of mangroves and establish mangrove tourism programs which are able to support conservation of these ecosystems. The incorporation of local wisdom could increase the sustainability of mangrove ecosystems. In Gambia, a boardwalk construction inside an urban mangrove ecosystem received a positive response from local stakeholders. Tourism is one of the major income-generating activities in this area (Satyanarayana et al. 2012). According to Thompson and Rog (2019), charismatic megafauna (tigers, lemurs, trunk monkeys, manatees, dolphins, sea turtles and crocodiles) are underrepresented in research in mangroves, in relation to their benthic invertebrates (crabs, shrimp and bivalves). These flagship species have wide geographic ranges and should be used more to promote mangrove conservation in many regions of the world.

3.2.3.2 Seagrasses

Among the Nature's Contributions to People (NCP), despite the importance of seagrass meadows for a healthy and diverse environment, recreation and tourism are not always considered a direct contribution provided by seagrass ecosystems, but tourism indirectly benefits from services provided by seagrasses, such as biodiversity, water quality and coastal stabilization. Other services provided are fish and shellfish resources used in local cuisines sought by tourists (Ruiz-Frau et al. 2019), food ingredients, handcrafts, fish (Syukur et al. 2019), and seafood supply for hotels in important tourist destinations around the world, such as the Caribbean and the Maldives.

Sighting charismatic megafauna such as green sea turtle, dugongs, and manatees—in addition to ornamental and edible fishes—are also common in many seagrass locations, such as in Florida (USA), Brazil and Australia. In locations where local populations still threaten dugongs (*Dugong dugon*), the monetary gain from local tourism linked with seagrass ecosystems and the animal's conservation is under development, such as in Indonesia. The same efforts have been observed during recent decades in Brazil, where coordinated manatee-related tourism is encouraged, and it is linked with tourism in the nearby systems for diving, for example, near seagrass meadows and coral reefs. This activity could be an interesting starting point to include the appreciation of the habitats of charismatic megafauna, promoting environmental education. Snorkeling, recreational fishing, scuba diving, sea walks, kayaking and wildlife watching in seagrass meadows also offer additional interest to coastal tourist areas (Björk et al. 2008; Cullen-Unsworth et al. 2014). In Lombok Island, Indonesia, tourists reported that they were visiting seagrass meadows in order to fish or observe the plants and associated benthic fauna, such as sea stars, sea cucumbers and sea urchins (Syukur et al. 2019).

Networks such as Seagrass Watch, Seagrass Ecosystem Services Project, Project Seagrass, Save Posidonia Project, Bermuda Seagrass Project and other non-governmental organizations (NGOs) have provided information on seagrass ecosystems, societal engagement and environmental education for national citizens and tourists in some countries around the world. In addition to mapping and monitoring seagrass meadows, national tour operators also include sirenians (dugongs and manatees) and seagrasses as important elements of marine-based tourism, as in Timor-Leste and Fiji (United Nations Environmental Programme 2020). Marine Conservation Agreements (MCAs) among tourism operators, communities, and NGOs produce local economic incentives, which includes income opportunities for people and funds for development of projects of the community in addition to ecosystem improvements (United Nations Environmental Programme 2020). In the eastern Mediterranean Sea, the Save Posidonia Project proposed a sustainable tourism and an action plan to raise funds that will be used exclusively for seagrass conservation, with the main objective of sensitizing nationals, tourists, entrepreneurs and NGOs about seagrass sustainability, by promoting fairs, festivals, conferences and forums (Save Posidonia Project 2021). However, taking into account seagrass distribution around the world, actions as those mentioned above are still very restricted and need to be further expanded.

Also, most of the activities associated with tourism in areas of seagrass meadows have still been indicated as harmful for the meadows' preservation, as they cause physical damage to the plants (e.g., trampling, anchorage, sedimentation, etc.). The intentional removal of the plants by hotels and resorts in order to "clean" the substrate is also a common practice in several parts of the world, but entrepreneurs are starting to be made aware of the importance of preserving the meadows. Several recent studies from around the world have endeavored to highlight the important contributions of seagrasses as a useful tool for ecotourism. Replicating these studies in many other regions is important because of the uniqueness of each location in terms of seagrass diversity and landscape, associated megafauna, lifestyle and needs of the local people, local preservation policies, etc. Furthermore, seagrass ecotourism increases seagrass value and raises awareness among nationals, decision makers and tourists. According to Syukur et al. (2019), ecotourism has been identified as a potential alternative for seagrass conservation, in addition to contributing for livelihood of local communities and environmental preservation.

3.2.4 Blue Biotechnology

In the search for sustainable development for humankind, underexplored marine resources are gaining attention as alternative products. Blue biotechnology is developing fast, especially in the last decade, providing benefits as new protein sources, alternative wastewater treatments, new biofuels, and new forms of pharmaceuticals. Among the benefits of this technology are contributions for marine conservation itself, improving aquatic ecosystems to better cope with climate changes, for example, and enhancing blue carbon sequestration to promote stabilization of ecosystem services. Blue biotechnology follows the same principles as other biotechnologies, such as green ones, but its development still faces numerous challenges, especially to prevent over-harvesting of the systems that are already under stress; therefore, the precepts for bioproduct development should be based on isolating and testing potential products as a basis for further synthetization so as not to provoke pressures of harvesting wild organisms.

3.2.4.1 Mangroves

Beyond ecosystem services and carbon storage capacity, mangroves have been widely used as a source of basic resources for local communities and, increasingly, in the use of bioproducts and raw materials for the development of pharmaceuticals and substances with potential biological properties. Historically, the exploitation of mangroves has been more linked to destructive processes such as logging for domestic and commercial uses and land clearing for agriculture and urban expansion, as well as artisanal processes such as harvesting, fishing, and mariculture. In recent years, however, interest in products of pharmacological and industrial interest has been increasing, although research on bioproducts associated with wood and mangrove endophytic organisms is still in the beginning phases. Wu et al. (2008) and Patra et al. (2020) have reviewed the various studies on the utilization of mangrove bioproducts from around the world. There are more than 350 metabolites described in mangroves and more than 200 of them are unique to species of these environments including phenols, alkaloids and terpenoids that are produced by plants and endophytic organisms, which have medicinal benefits such as antidiabetic, antifungal, antimicrobial, anticancer and antioxidant capabilities, in addition to industrial products such as biofertilizers and pigments.

Although this high potential for the exploitation and use of bioproducts is well known to science and industry, little research has yet reached the advanced stages of clinical trials beyond in vitro analyses. As some examples, *Rhizophora racemosa* has clinical use in the treatment of type 2 diabetes (Tsabang et al. 2016), and extracts from *Excoecaria agallocha* plants have anticancer, anti-HIV, and antiviral potential. *Bruguiera sexangula* is used in the treatment of cancer, and extracts of *Avicennia marina* have been exploited for their anticoagulant activities (Gajula et al. 2020). The use of these bioproducts may be one of the greatest added values to the preservation of mangroves, since in most cases, they can be exploited in a sustainable way without destroying mangrove forests; however, more research and information is still needed about the real value of these bioproducts and how they can be used, either by local communities or industry.

3.2.4.2 Seagrasses

Blue biotechnology is a growing field for seagrass. Several metabolites with multiple bioactivities have been reported for these plants, varying from antioxidant, antibacterial, anti-larval, antiviral (including anti-HIV) and cytotoxicity against cancer cell lines (Kim et al. 2021). Antibacterial activity for potential disease control has been tested in *Halophila* and *Cymodocea* species (Kannan et al. 2010; Yuvaraj et al. 2012). The seagrass *Syringodium isoetifolium* was proved to have larvicidal potential against the mosquito *Aedes aegypti*, which transmits the tropical disease dengue fever (Ali et al. 2012); the associated microbiome on the roots of this species has potential use as an antibacterial agent (Ravikumar et al. 2012).

At least 10 of the 72 recognized seagrass species were reported as having ethnopharmacological properties by a local population in India (Newmaster et al. 2011); these authors pointed out a medical potential that is not yet well explored. For example, *Enhalus acoroides* rhizome, and sometimes roots, can be processed to produce juices that can be consumed raw to treat seasickness, ease indigestion, treat hangovers and even mental disorders and low blood pressure. Paste from leaves of different species is used to treat wounds and skin diseases. *Halophila* species can be toasted with oil and consumed to treat iron deficiency. For malaria and fever treatment, it can be used as vapors for inhalation therapy.

Seagrass nutritional composition may also have the potential for the development of functional food ingredients. The direct consumption of seeds is common by people in areas where *Enhalus acoroides* is distributed and fed to goats and sheep in India. Their caloric value is similar to plants of terrestrial origin and is reported to have aphrodisiac and contraceptive properties (Montaño et al. 1999). The efficacy of *E. acoroides* seeds to HIV-AIDS patients was tested, indicating potential in increasing the number of T-CD4 cells for patients who consumed seeds (Nindatu et al. 2018), showing the potential seagrass may have for this therapy.

Species such as *Halophila* are directly consumed in salads; *Enhalus* flour is used for baking cookies, and seagrass is also used as tea. However, human consumption took another step as a Spanish three-star Michelin chef brought *Zostera marina* seeds to the spotlight. The Aponiente Marine Project[1] cultivates seagrasses in a low-cost and environmentally friendly way. They present the marine grains as a "superfood" for the unique nutritional qualities the seeds have as gluten-free, high in omega 6 and 9 fatty acids, and containing 50% more protein than rice per grain. Since 2017, they have been cultivating seagrass as crops for their use, restoring the seagrass meadows of the area and improving social systems to generate jobs.

The energy potential of seagrass harvest as a biofuel is also an essential part of its blue economy interest. For seagrass, biofuel studies were initiated with seeds, but increasing the production capacity of seagrass seeds and developing culturing and harvesting skills are among the further activities needed to pursue this use. Studies to contribute to the marine fermentation industry to develop alcoholic beverage and food

[1] https://www.cerealmarino.com/wp-content/uploads/2021/01/APONIENTE_CEREAL-MARINO_DOSSIER-DE-PRENSA_ENG.pdf.

products may be possible from seagrass seeds (Uchida et al. 2014). Another potential of seagrass biofuel potential being tested is as a substrate for ethanol production; as a low-cost and eco-friendly bio-adsorbent material for effective synthetic dye removal from the aquatic environment; and phosphate removal from synthetic and natural wastewater in a circular economy concept. Green fertilizer for gardens is also frequently mentioned, as is the use as roof covering and filling, and building material for many species in different countries.

3.3 Threats

Natural and anthropogenic impacts have been observed in BC environments around the world. Coastal ecosystems have rapidly declined in recent decades, evidencing the losses of their recognized goods and services. In review, Lovelock and Reef (2020) pointed out the main threats of climate changes, which can vary according to factors such as sensitivity, exposure, adaptive capacity and global distribution of each ecosystem. Mangroves and saltmarshes are highly affected by droughts and storm events (and saltmarshes are also exposed to mangrove encroachment), in addition to hydrodynamic changes related to the ocean changes. Seagrasses are affected by marine heat waves at the lower limit of the latitudinal distribution of the species, resulting in degradation, loss and change of the ecosystems, among other consequences. It is worth mentioning that a very important threat factor is also urban and industrial development and, in recent decades, aquaculture expansion in these extremely fragile environments.

The effects of climate changes on blue carbon ecosystems can be even more intensified, together with harmful human actions, accelerating losses of these ecosystems. Hence, BC ecosystems can contribute to global climate regulation in the face of climate changes, while at the same time they have also been threatened by these environmental changes, human actions, or both. It has been estimated that 67% of total mangrove forests, 35% of tidal marshes and 29% of seagrass beds have been lost from their historical maximum levels. If the rates of decline continue, around 30–40% of tidal marshes and seagrasses will be lost and nearly all unprotected mangrove areas could be lost in the next 100 years (Pendleton et al. 2012). Losses of these vegetated environments in coastal areas have caused significant carbon dioxide emission by disturbing and releasing the carbon previously trapped in biomass and sediments. Conversely, the expansion of blue carbon ecosystems can contribute to carbon sequestration, reducing the consequences of the effects of climate change, but this balance still needs to be further understood.

3.3.1 Mangroves

Mangroves are being destroyed at rates 3–5 times greater than average rates of forest loss and over a quarter of the original global mangrove cover has already disappeared. These losses are driven by land conversion for aquaculture and agriculture, coastal development, pollution and over-exploitation of mangrove resources, as well as the impacts of climate change (Gilman et al. 2008; Mitra 2013). As mangrove forests become smaller and more fragmented, important ecosystem goods and services will be diminished or lost, with high ecological and economic importance, making them susceptible to additional pressures from human activities. The consequences of further mangrove degradation will be particularly severe for the well-being of coastal communities in developing countries, especially where people rely heavily on mangrove goods and services for their daily subsistence and livelihoods. However, the future of mangroves does not have to be bleak, with greater recognition of the importance of mangrove ecosystems for biodiversity and human well-being and global efforts aiming to conserve, manage and restore these ecosystems (UNEP 2014).

To date, relative sea-level rise has likely been a smaller threat to mangroves than non-climate related anthropogenic stressors, outlined above, which have likely accounted for most of the estimated global average annual rate of mangrove loss of 1–2%, with losses during the last quarter century ranging between 35 and 86% (Valiela et al. 2001; Duke et al. 2007; Gilman et al. 2008; FAO 2010). In Brazil, for example, actions such as sewage and solid waste dumping, real estate speculation, deforestation and shrimp farming have been identified as important threats to these ecosystems (Costa and Pegado 2016; Silva et al. 2017; Celeri et al. 2019; Lacerda et al. 2021). However, relative sea-level rise may constitute a substantial proportion of predicted future losses. Biotic factors related to the physiology, development and distribution of mangroves may be the most vulnerable to changes in sea level and may affect mangrove ecosystems in the short term (Richieri 2006). However, the patterns of mangrove responses to sea level rise depend on local geographic characteristics and conditions in adjacent areas, in addition to rates of sea-level rise (Bezerra 2014).

3.3.2 Seagrasses

Assessing current distribution and trends of seagrass meadows is critical. The loss of seagrass areas increased from 0.9% (Duarte et al. 2005) to 7% annually since 1990 (Waycott et al. 2009). However, many areas are still being mapped and registered. Large stocks of blue carbon may be lost as seagrass meadows are being destroyed (Lovelock and Reef 2020).

Rapid population growth, urbanization, destructive fishing practices and overexploitation using fishing gear and fish fences, in addition to physical damage with algae cultivation on seagrasses, are indicated as some threats to seagrass around the world. Seaweed cultivation commonly occurs on seagrass meadows of Indonesia and Tanzania, but this activity can generate severe damage to the plants by removal of leaves and roots, causing clearings (Cullen-Unsworth et al. 2014). Other potential impacts, like oil spills, can also be a threat to these systems, both in the contamination itself and the cleaning process (Magalhães et al. 2021).

Tourism can be either a positive or negative factor for seagrasses as a blue economy resource. The positive impacts of tourism relate to seagrass meadows as locations for ecotourism. Negative consequences occur with the removal of seagrass to make way for tourists to access the water (Zuidema et al. 2011). In addition, activities such as permanent boat moorings, extensive anchor use, and diving have been considered unfavorable for seagrass meadows, possibly contributing to the seagrass loss worldwide (Cullen-Unsworth et al. 2014). Damage from anchors linked to tourism also occurs in seagrass meadows in sheltered locations and in small commercial fishing harbors, where small to medium-sized vessels anchor. Other recreational activities, such as kayaking, swimming, diving and recreational collection of shrimps are tourism-related sources of damage to seagrass meadows.

Climate-related threats involve acidification, increasing frequency of extreme events, and sea levels and temperatures rising. As reviewed by Connolly et al. (2020), the accuracy of the global change effect predictions is still limited as the global models may not be appropriate for seagrass biology and long-term studies are still necessary to address variations due to seagrass species and different effects at different latitudes. Massive losses have been reported to be linked to marine heatwaves events in Australia, cyclones in Mozambique, run-off from degraded lands, among others. We recommend that management goals should focus on local threats as preservation locally may make these meadows less susceptible to extreme events.

The impacts on seagrasses have local consequences, such as the reduction of fauna, which is often the main means of survival for fishing communities, which depend on intact ecosystems. The value of seagrass ecological services has been estimated at $1.9 trillion per year in the form of nutrient cycling and increased productivity of coral reef fish, and as a habitat for thousands of fish, birds, and invertebrate species (Waycott et al. 2009).

3.4 Outlook and Potential Challenges

As the potentials of blue economy coastal systems are still being truly understood, they are under threat. Alternatives for mapping, restoring, valuing the services, and managing and engaging society, are essential in order to protect the future of the sustainable economy we expect to achieve. Only by raising the awareness of these systems' service values can they be recognized and properly included in the blue economy (Fig. 3.2). Science and technology have an important role to play in these blue economy activities.

3.4.1 Mapping

Locating and estimating areas of mangrove and seagrass meadows are very important to develop proper management of these ecosystems. Recent efforts have been made to create models of global mangrove and seagrass services and BC estimation, with standardized methodologies using climate proxies, multi-source remote sensing data and surface observations. For example, Hutchison et al. (2014a, b) developed a climate-based model for estimating potential mangrove above-ground biomass (AGB) linked to global data based on models from the literature. Hu et al. (2020) produced a global mangrove forest above-ground biomass map at 250-m resolution by combining ground inventory data, spaceborne LiDAR, optical imagery, climate surfaces, and topographic data with a machine-learning method. Simard et al. (2019) released a 30-m resolution dataset of global distribution, biomass, and canopy height of mangrove-forested wetlands based on remotely sensed and in situ field measurement (region-specific allometric models). Many of these products can serve as a basis for generic blue carbon estimates. They are publicly available in digital formats and ready to be used in GIS tools (see map in Fig. 3.3).

To map seagrass meadows, the use of several methods has been mentioned in the literature, such as aerial photographs, multi-beam sonar, acoustic telemetry, satellite images and remote sensing. A recent study suggested a hierarchical mapping approach that includes combining eco-geomorphological principles and hierarchical object-based analysis to create maps that should be validated with field observations (McKenzie et al. 2021). We note that the priority is to centralize all the data already available in a global GIS clearinghouse, such as the World Conservation and Monitoring Center. Such datasets are highly suitable for determining generic BC and ecosystem service strategies and market application policies, but they may

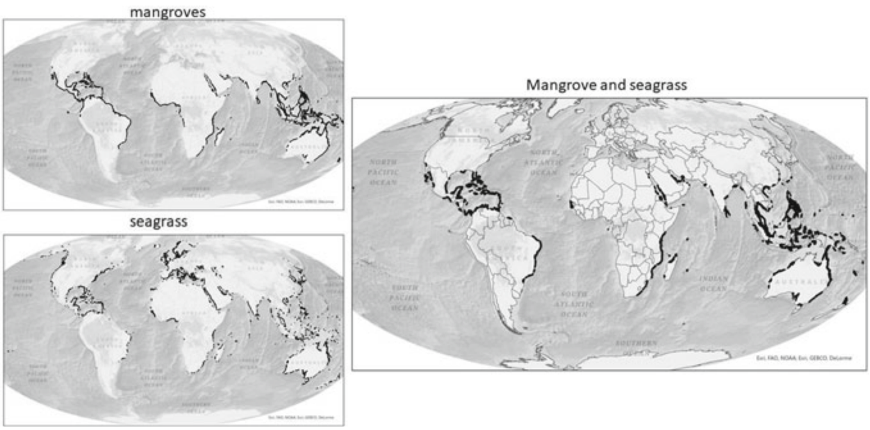


Fig. 3.3 Mangrove and seagrass global distribution maps (and overlapping areas): Several data on global ecosystem distributions are available as georeferenced files as in the case of UNEP (2020) and Bunting et al. (2018)

have discrepancies that can lead to uncertainties and inaccuracies, especially when detailed analysis is needed. These limitations indicate the importance of developing work at higher resolutions to complement these data with local analyses (and improve training data in the case of machine-learning models).

Although the specific methods used to derive habitat maps vary considerably, studies can generally be categorized into one of three overarching strategies: (1) abiotic surrogate mapping; (2) assemble first, predict later (unsupervised classification); and (3) predict first, assemble later (supervised classification). While there is still no widely accepted agreement on the best way to produce benthic habitat maps, all three strategies provide valuable map resources to support management objectives (Brown et al. 2011).

3.4.2 Conservation

The United Nations Decade on Ecosystem Restoration (2021–2030) aims to prevent, halt and reverse the degradation of ecosystems on every continent and in every ocean. The UN Decade proposes a strategy with ten actions, such as empowering a global movement, investing in research, building up capacity, and stimulating youth participation, among others.

Responding to Sustainable Development Goals (SDGs), restoration projects can help to end poverty in all its forms everywhere (SDG 1), end hunger, achieve food security and improved nutrition (SDG 2), ensure availability and sustainable management of water and sanitation for all (SDG 6) and take urgent action to combat climate change and its impacts (SDG 13).[2]

Increasing recognition of the importance of mangrove ecosystems for both biodiversity and human well-being is driving efforts around the world to conserve, better manage and restore these ecosystems. Many of these have been successful at local scales, often supported by national policies that recognize the significant long-term benefits of mangroves over short-term financial gains (UNEP 2014).

Restoration projects of seagrasses and mangrove areas will mitigate climate change, safeguard biodiversity and increase food security. Although much effort is needed and decline is still going on, different projects are gaining space with restoration programs such as “Project Seagrasses: making waves to save our seas”[3] that proposes to restore 30 km^2 of seagrasses in the UK. The project from Wetlands International “To plant or not to Plant?”[4] proposes to use best practice in mangrove restoration, considering biophysical (hydrological flows) and socio-economic conditions, empowering communities, engaging local government, and ensuring that local actions are strengthened by policies and planning.

[2] https://www.decadeonrestoration.org/.

[3] https://www.projectseagrass.org/.

[4] https://www.wetlands.org/publications/mangrove-restoration-to-plant-or-not-to-plant/.

Rehabilitation projects are planned, conceived, executed, and managed by people with diverse backgrounds and different scientific and socio-political agendas. These projects need to be responsive to various stakeholders and actors who have different values. In general, the projects are influenced by laws that span local and international scales and must be able to adapt and evolve geomorphologically and socioeconomically over decades to centuries in the context of a rapidly changing climate (Ellison et al. 2020).

Natural regeneration gained worldwide relevance with the "Ecological Restoration of Mangroves" approach, which emphasizes the management of hydrology and topography (Lewis 2005). Subsequently, local human communities and other social actors have been included in the process as a central element in the planning and implementation of actions, with the approach of "Community Based Ecological Mangrove Restoration" (CBEMR) (Brown et al. 2014), in which women have been considered having fundamental roles in mangrove restoration projects.[5] Restoration projects have to consider some important context. It is necessary to avoid planting in areas where the local community is not involved, and avoiding mono-species planting, leading to mangroves with low resilience and planting in places that are too exposed to erosion processes, among others.

3.4.3 Awareness (Perceptions) and Citizen Science

Historically, mangrove forests have been cast in a negative light due to their (often perceived) ecosystem disservices (Friess et al. 2020a), such as being habitats for dangerous animals (like crocodiles, tigers, and snakes) and insects (like mosquitoes and sandflies) that act as vectors for disease. Dahdouh-Guebas et al. (2020a, b) highlighted the dangers of recurrent public misperceptions about mangroves and how they can be countered. Mangrove conservation has recently shifted from a pessimistic to a more optimistic trajectory. Management and governance success stories have helped to protect mangroves and build upon international interest in sustainable blue economies. Conservation Optimism is an emerging paradigm that can unite stakeholders and the public and increase their engagement with conservation and inspire local action. Capitalizing on successes in one ecosystem and transferring this knowledge can help us limit broader environmental degradation, making mangroves an important and positive case study for the Conservation Optimism movement (Friess et al. 2020b). Promoting positive perceptions by highlighting the valuable functions, goods and services and the long-term economic and social benefits that these endangered ecosystems provide will ultimately underpin successful conservation (Bennett 2016).

Unlike mangrove forests, seagrass meadows are not always seen with a negative point of view since they can really be "invisible" for the general public and the stakeholders due to their submersed nature in most of their distribution areas. Raising

[5] https://www.iucn.org/news/forests/201707/gender-equity-key-mangrove-restoration.

public awareness and communicating the seagrass contribution to human livelihoods and well-being, as well as the consequences of their loss, are key for any development towards a sustainable blue economy involving them.

Involving the public without formal scientific background in scientific studies—citizen science—is one of practices that has been working to both achieve conservation and gather data on a large spatial scale and long time scales. Jones et al. (2018) listed seagrass projects using citizen science around the world, but point out that only two of them are real examples of programs that cover a wide spatial scale involving a large number of participants: Seagrass-Watch and SeagrassSpotter. The use of technology seems to be essential for this kind of research (Dalby et al. 2021) but, even so, citizen participation as a tool in science for coastal ecosystems may be limited by intertidal access.

Highlighting the role of indigenous/traditional communities is fundamental to understanding seagrass potential, but also for the effectiveness of any protection or intervention, and even to coping with global changes. A good way to involve communities is to incentivize the people who work daily on the meadows, increasing their awareness of the importance of the conservation of these marine environments; communities are also able to perceive threats to the ecosystems and propose alternatives to mitigate anthropogenic pressures (Nordlund et al. 2018; McKenzie et al. 2021).

3.4.4 Marine Protected Area and Legislation

Mangroves need to be appreciated for the valuable socio-economic and ecological resources they provide, and to be conserved and managed sustainably. This requires a commitment by governments to make policy decisions and enforce existing protective measures to curb widespread losses from human activities.

In several parts of the world, mangroves and seagrasses are protected by law, being areas of strict protection. But even with such protections, these systems are being destroyed, mainly due to the expansion of urban areas, as well as large enterprises, such as ports and aquaculture. In Brazil, where there is vast environmental protection legislation, any intervention on these areas is only considered in exceptional cases, requiring a technical and legal assessment for intervention purposes in these specially protected areas.

3.4.5 Valuation

Although in some cultures, people strongly identify with seagrass meadows because they provide food security, livelihood, and spiritual fulfillment, valuing seagrass services is one of the most significant challenges in seagrass conservation. Monetizing goods and services derived from seagrass meadows may be essential to represent the ecosystem in management and policy decisions. Together with macroalgae banks, economical services of seagrass meadows were estimated to amount to US$29,000 ha^{-1} yr^{-1}, a value 27 times greater than the average of marine ecosystems as a whole and 7–23 times greater than terrestrial ecosystems, being almost 6 times most productive than tropical forests, making seagrass meadows one of the most valuable biomes on Earth (Costanza et al. 1997, 2014; Björk et al. 2008). For mangrove forests, the calculated value, together with tidal marshes, is even higher, around US$194,000 ha^{-1} yr^{-1} (Costanza et al. 2014).

3.5 Summary

This chapter serves as a call to action to decision makers and highlights the unique range of values of mangroves to people around the world. It aims to provide a science-based synthesis of the different types of goods and services provided by mangroves and the associated risks in losing these services in the face of ongoing global habitat loss and degradation. Mangrove and seagrass ecosystems have enormous potential as components of blue economies, but these systems are in danger. The growing human occupation in coastal areas around the world brings great pressure, with reduction and fragmentation of these ecosystems. Measures for the conservation and protection of mangroves and seagrasses have increased and involved communities worldwide. We are still learning to value these systems and to promote their ecosystem services more effectively; improving the mapping of seagrass and mangrove ecosystems is critical. In addition, it is essential to involve stakeholders and local communities at all stages of the process. We need to increase knowledge about these ecosystems, to protect and restore them, and in this way, we can fully exploit them in a sustainable way and achieve the goals of the Blue Economy, promoting alternative economic improvements for coastal populations and consequently increasing the quality of human life.

References

Ali MS, Ravikumar S, Beula JM (2012) Bioactivity of seagrass against the dengue fever mosquito Aedes aegypti larvae. Asian Pac J Trop Biomed 2:570–573

Avau J, Cunha-Lignon M, De Myttenaere B et al (2011) The commercial images promoting Caribbean mangroves to tourists. J Coastal Res 64:1277–1281

Alongi D (2014) Carbon cycling and storage in mangrove forests. Ann Rev Mar Sci 6:195–219
Alongi D (2020) Carbon balance in salt marsh and mangrove. J Marine Sci Eng 8:767. https://doi.org/10.3390/jmse810076
Barañano C, Fernández E, Méndez G (2018) Clam harvesting decreases the sedimentary carbon stock of a Zostera marina meadow. Aquat Bot 146:48–57
Barros KVS, Rocha-Barreira CA, Magalhães KM (2016) Seagrass meadows on the northeast coast of Brazil: Habitat influence on the spatial and seasonal variations. In: Snyder M (ed) Aquatic ecosystems: influences, interactions and impact on the environment. Nova Science Publishers, New Jersey, pp 1–29
Bennett NJ (2016) Using perceptions as evidence to improve conservation and environmental management. Conserv Biol 30:582–592
Bertram C, Quaas M, Reusch TB et al (2021) The blue carbon wealth of nations. Nat Clim Change 11(8):704–709
Bezerra DS (2014) Modelagem da dinâmica do manguezal frente à elevação do nível do mar. Tese de Doutorado do Curso de Pós-Graduação em Ciência do Sistema Terrestre, INPE/MCT. São José dos Campos, SP. 158p
Björk M, Short F, Mcleod E et al (2008) Managing seagrasses for resilience to climate change. World Conservation Union Global Marine Programme, Gland, Switzerland, 55p
Breithaupt JL, Smoak JM, Smith III TJ et al (2012) Organic carbon burial rates in mangrove sediments: strengthening the global budget. Global Biogeochem Cycles 26:GB3011
Breithaupt JL, Smoak J, Bianchi T et al (2020) Increasing rates of carbon burial in Southwest Florida coastal wetlands. J Geophys Res: Biogeosci 125(2):e2019JG005349
Brown CJ, Smith SJ, Lawton P et al (2011) Benthic habitat mapping: a review of progress towards improved understanding of the spatial ecology of the seafloor using acoustic techniques. Estuarine, Coastal Shelf Sci 92(3):502–520
Brown B, Fadillah R, Nurdin Y et al (2014) Case study: Community based ecological mangrove rehabilitation (CBEMR) in Indonesia. Surv Persp Integr Environ Soc 7:53–64
Bunting P, Rosenqvist A, Lucas R et al (2018) The global mangrove watch—a new 2010 global baseline of mangrove extent. Remote Sens 10(10):1669
Celeri MJ, Mendes LET, Lima RMBF et al (2019) A cidade, o mangue e os resíduos sólidos: estudo de caso do manguezal Vinhais, São Luís - MA. Revista Geografia Em Atos, Presidente Prudente 3(10):163–186
Connolly R, Collier C, O'Leary J et al (2020) Threats to seagrasses and ecosystem resilience. In: Dos Santos CB, et al. Out of the blue: the value of seagrasses to the environment and to people, UNEP, p 36
Costanza R, d'Arge R, De Groot R et al (1997) The value of the world's ecosystem services and natural capital. Nature 387(6630):253–260
Costanza R, De Groot R, Sutton P et al (2014) Changes in the global value of ecosystem services. Glob Environ Chang 26:152–158
Costa SPC, Pegado EAC (2016) Análise da degradação nos manguezais norte-rio-grandenses: o caso de Canguaretama. In: VII Congresso Brasileiro de Gestão Ambiental, Campina Grande, PB, 21 a 24 de novembro de 2016, 9p
Cragg SM, Friess DA, Gillis LG et al (2020) Vascular plants are globally significant contributors to marine carbon fluxes and sinks. Annu Rev Mar Sci 12:469–497
Cunha-Lignon M, Mendonça JT (2021) Ecossistema manguezal: seus recursos naturais e pesca. In: Cunha-Lignon, M, Bertini, G, Montealegre-Quijano, S (ed) Manguezais, camarões-de-água-doce e manjuba-de-iguape: patrimônios natural e cultural do Vale do Ribeira e Litoral Sul do Estado de São Paulo. Unesp, Registro, pp 23–65
Cullen-Unsworth LC, Nordlund LM, Paddock J et al (2014) Seagrass meadows globally as a coupled social–ecological system: implications for human wellbeing. Mar Pollut Bull 83(2):387–397
Dahdouh-Guebas F, Ajonina GN, Amir AA et al (2020a) Public perceptions of mangrove forests matter for their conservation. Front Mar Sci 7:603651

Dahdouh-Guebas F, Hugé J, Abuchahla GMO et al (2020b) Reconciling nature, people and policy in the mangrove social-ecological system through the adaptive cycle heuristic. Estuarine, Coastal Shelf Sci 248:106942

Dalby O, Sinha I, Unsworth RK, McKenzie LJ et al (2021) Citizen science driven big data collection requires improved and inclusive societal engagement. Front Mar Sci 8:610397. https://doi.org/10.3389/fmars.2021.610397

Duarte CM, Middelburg JJ, Caraco N (2005) Major role of marine vegetation on the oceanic carbon cycle. Biogeosciences 1:659–679

Duarte CM, Dennison WC, Orth RJW et al (2008) The charisma of coastal ecosystems: addressing the imbalance. Estuaries Coasts 31:233–238

Duarte CM, Krause-Jensen D (2017) Export from seagrass meadows contributes to marine carbon sequestration. Front Marine Sci 4:13

Duke NC, Meynecke J-O, Dittmann AM et al (2007) A world without mangroves? Science 317:41–42

Ellison AM, Felson AJ, Friess DA (2020) Mangrove rehabilitation and restoration as experimental adaptive management. Front Mar Sci 7:327. https://doi.org/10.3389/fmars.2020.00327

Erwiantono (2006) The community participation in mangrove ecosystem management in Pangpang Bay, Muncar—Banyuwangi. Jurnal Ekonomi Pembangunan Dan Perencanaan (EPP) 3(1):44–50

Fatoyinbo T, Feliciano EA, Lagomasino D et al (2018) Estimating mangrove aboveground biomass from airborne LiDAR data: a case study from the Zambezi River delta. Environ Res Lett 13:025012

FAO (2010) Global forest resources assessment 2010. FAO Forestry Paper 163. Food and Agriculture Organization of the United Nations Rome, Italy

Fourqurean JW, Duarte CM, Kennedy H et al (2012) Seagrass ecosystems as a globally significant carbon stock. Nat Geosci 5(7):505–509

Freire KMF, Aragão JAN, Ávila-da-silva AO et al (2015) Reconstruction of catch statistics for Brazilian marine waters (1950–2010). Fish Centre Res Rep 23:3–30

Friess DA, Yando ES, Alemu JB et al (2020a) Ecosystem services and disservices of mangrove forests and saltmarshes. Oceanogr Mar Biol 58:107–142

Friess DA, Yando ES, Abuchahla GMO et al (2020b) Mangroves give cause for conservation optimism, for now. Curr Biol 30:R135–R158

Furkon NN, Ambo-Rappe R, Cullen-Unsworth LC et al (2020) Social-ecological drivers and dynamics of seagrass gleaning fisheries. Ambio 49:1271–1281

Gajula H, Kumar V, Vijendra PD et al (2020) Secondary metabolites from mangrove plants and their biological activities. In: Biotechnological utilization of mangrove resources. Academic Press, pp 117–134

Ganguly D, Singh G, Ramachandran P et al (2017) Seagrass metabolism and carbon dynamics in a tropical coastal embayment. Ambio 46:667–679

Gillanders, BM (2006) Seagrass, fish and fisheries. In: Larkun, AWD et al (eds) Seagrass: biology, ecology and conservation. Printed in the Netherlands, Springer. Chapter 21:503–536 pp

Gilman EL, Ellison J, Duke NC et al (2008) Threats to mangroves from climate change and adaptation options. Aquat Bot 89(2):237–250. https://doi.org/10.1016/j.aquabot.2007.12.009

Hamilton S, Casey D (2016) Creation of a high spatiotemporal resolution global database of continuous mangrove forest cover for the 21st Century (CGMFC-21). Glob Ecol Biogeogr 25:729–738

Howard J, Hoyt S, Isensee K et al (eds) (2014) Coastal blue carbon: methods for assessing carbon stocks and emissions factors in mangroves, tidal salt marshes, and seagrasses. Conservation International, Intergovernmental Oceanographic Commission of UNESCO, International Union for Conservation of Nature, Arlington, Virginia, USA

Hu T, Zhang Y, Su Y et al (2020) Mapping the global mangrove forest aboveground biomass using multisource remote sensing data. Remote Sens 12:1690

Hutchison J, Manica A, Swetnam R et al (2014a) Predicting global patterns in mangrove forest biomass. Conserv Lett 7(3):233–240

Hutchison J, Spalding M, Zu Ermgassen P (2014b) The role of mangroves in fisheries enhancement. The Nat Conservancy Wetlands Int, 54p

Intergovernmental Panel on Climate Change—IPCC (2014) Supplement to the 2006 IPCC guidelines for national greenhouse gas inventories: Wetlands. In: Hiraishi T, Krug T, Tanabe K et al, IPCC, Switzerland

Jones BL, Unsworth RKF, McKenzie LJ et al (2018) Crowdsourcing conservation: the role of citizen science in securing a future for seagrass. Mar Pollut Bull 134:210–215. https://doi.org/10.1016/j.marpolbul.2017.11.005

Kannan RRR, Arumugam R, Anantharaman P (2010) Antibacterial potential of three seagrasses against human pathogens. Asian Pac J Trop Med 3(11):890–893

Kennedy H, Beggins J, Duarte CM et al (2010) Seagrass sediments as a global carbon sink: Isotopic constraints. Global Biogeochem Cycles 24:GB4026. https://doi.org/10.1029/2010GB003848

Kim DH, Mahomoodally MF, Sadeer NB et al (2021) Nutritional and bioactive potential of seagrasses: a review. S Afr J Bot 137:216–227

Kusumaningtyasa MA, Hutahaean AA, Fischer HW et al (2019) Variability in the organic carbon stocks, sources, and accumulation rates of Indonesian mangrove ecosystem. Estuarine, Coastal Shelf Sci 218:310–323

Kyoto Protocol (1998) Kyoto protocol to the United Nations framework convention on climate change. United Nations, 21p

Kissinger NAS, Rina Muhayah NP, Violet, (2020) The potential of mangrove forest as natural tourism area based on the Flora-Fauna characteristics and social aspect case study: Mangrove forest in Angsana village. BIO Web of Conferences 20:02004. https://doi.org/10.1051/bioconf/20202002004

Lacerda LD, Ward R, Godoy MP et al (2021) 20-years cumulative impact from shrimp farming on mangroves of Northeast Brazil. Front For Global Change 4:653096

Lewis R III (2005) Ecological engineering for successful management and restoration of mangrove forests. Ecol Eng 24:403–418

Lovelock CE, Reef R (2020) Variable impacts of climate change on blue carbon. One Earth 3(2):195–211

Macreadie PI, Costa MD, Atwood TB et al (2021) Blue carbon as a natural climate solution. Nat Rev Earth Environ 2:826–839

Magalhães KM, de Souza Barros KV, de Lima MCS et al (2021) Oil spill+ COVID-19: a disastrous year for Brazilian seagrass conservation. Sci Total Environ 764:142872

Mateo MA, Cebrián J, Dunton K et al (2006) Carbon flux in seagrass ecosystems. In: Larkun AWD, Orth RJ, Duarte CM (eds) Seagrass: biology, ecology and conservation. Springer, Printed in the Netherlands, pp 159–192

McKenzie LJ, Nordlund LM, Jones BL et al (2020) The global distribution of seagrass meadows. Environ Res Lett 15:0740418

McKenzie LJ, Yoshida RL, Aini JW et al (2021) Seagrass ecosystem contributions to people's quality of life in the Pacific Island countries and territories. Mar Pollut Bull 167:112307

McLeod E, Chmura GL, Bouillon S et al (2011) A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO_2. Front Ecol Environ 9:552–560

Mcowen C, Weatherdon L, Bochove J et al (2017) A global map of saltmarshes. Biodiversity Data J 5:e11764

Mitra A (2013) Sensitivity of mangrove ecosystem to changing climate. Springer, New Delhi, 338p

MMA—Ministério do Meio Ambiente (Brazilian Ministry of the Environment) (2018) Atlas dos Manguezais do Brasil. Instituto Chico Mendes de Conservação da Biodiversidade, Ministério do Meio Ambiente—Brasília, 176p

Montaño MNE, Bonifacio RS, Rumbaoa RGO (1999) Proximate analysis of the flour and starch from Enhalus acoroides (Lf) Royle seeds. Aquat Bot 65(1–4):321–325

Musembi P, Fulanda B, Kairo J et al (2019) Species composition, abundance and fishing methods of small-scale fisheries in the seagrass meadows of Gazi Bay, Kenya. Journal of the Indian Ocean Region 15(2):139–156. https://doi.org/10.1080/19480881.2019.1603608

Newmaster AF, Berg KJ, Ragupathy S et al (2011) Local knowledge and conservation of seagrasses in the Tamil Nadu State of India. J Ethnobiol Ethnomed 7(1):1–17. https://doi.org/10.1186/1746-4269-7-37

Nindatu M, Noya FC, Lantang D et al (2018) Seagrass (*Enhalus acoroides*) seeds as complementary food for people living with HIV-AIDS in Ambon-Maluku. Asian J Microbiol Biotech Environ Sci 20(1):76–81

Nordlund M, Koch EW, Barbier EB et al (2016) Seagrass ecosystem services and their variability across genera and geographical regions. PLoS One 11(10):e0163091

Nordlund ML, Jackson EL, Nakaoka M et al (2018) Seagrass ecosystem services—what's next? Mar Pollut Bull 134:145–151

Patra JK, Mishra RR, Thatoi H (eds) (2020) Biotechnological utilization of mangrove resources. Academic Press

Patil PG, Virdin J, Diez SM et al (2016) Toward a blue economy: a promise for sustainable growth in the Caribbean: an overview. The World Bank, Washington, DC

Pendleton L, Donato DC, Murray BC et al (2012) Estimating global "blue carbon" emissions from conversion and degradation of vegetated coastal ecosystems. PLoS One 7(9):e43542. https://doi.org/10.1371/journal.pone.0043542

Perdan S, Azapagic A (2011) Carbon trading: current schemes and future developments. Energy Policy 39(10):6040–6054

Pham TD, Xia J, Ha NT et al (2019) A review of remote sensing approaches for monitoring blue carbon ecosystems: Mangroves, seagrasses and salt marshes during 2010–2018. Sensors 19(8):1933

Ravikumar S, Gnanadesigan M, Saravanan A et al (2012) Antagonistic properties of seagrass associated *Streptomyces* sp. RAUACT-1: a source for anthraquinone rich compound. Asian Pac J Trop Med 5(11):887–890

Richieri, SMM (2006) Estudo do impacto das mudanças climáticas globais nos mangues tropicais. Dissertação apresentada à Escola de Engenharia Mauá do Centro Universitário do Instituto Mauá de Tecnologia. São Caetano do Sul, 117p

Rovai AS, Twilley RR (2021) Gaps, challenges, and opportunities in mangrove blue carbon research: a biogeographic perspective. In: Dynamic sedimentary environments of mangrove coasts. Elsevier, pp 295–334

Ruiz-Frau A, Krause T, Marbà N (2019) In the blind-spot of governance—stakeholder perceptions on seagrasses to guide the management of an important ecosystem services provider. Sci Total Environ 688:1081–1091

Santos MCF, Santos CF, Branco, JO, Barbieri, E (2016) Caracterização da pesca e dos pescadores artesanais de camarões Penaeidae em salina no município de Macau - Rio Grande do Norte. Bol. Inst. Pesca, São Paulo 42(2):465–478. https://doi.org/10.20950/1678-2305.2016v42n2p465

Satyanarayana B, Bhanderi P, Debry M et al (2012) A socio-ecological assessment aiming at improved forest resource management and sustainable ecotourism development in the mangroves of Tanbi Wetland National Park, The Gambia, West Africa. Ambio 41:513–526

Save Posidonia Project (2021) Save Posidonia Project és un projecte pioner en el mar Mediterrani occidental. Available on line at: https://www.saveposidoniaproject.org/sobre-el-proyecto/. Accessed 6 July 2021

Silva EES, Almeida LQ, Macedo YM (2017) Impactos ambientais e serviços ecossistêmicos em áreas de manguezal. In: XVII Simpósio Brasileiro de Geografia Física Aplicada. UNICAMP, Instituto de Geociências, 28 de junho a 02 de julho de 2017. Campinas, SP. P. 7305–7310

Silva SL, de Carvalho R, Magalhães KM (2021) Chromosomal evolution in seagrasses: is the chromosome number decreasing? Aquat Bot 273:103410

Simard M, Fatoyinbo T, Smetanka C et al (2019) Global mangrove distribution, aboveground biomass, and canopy height. ORNL DAAC

Spalding M, Parret CL (2019) Global patterns in mangrove recreation and tourism. Mar Policy 110:103540
Stankovic M, Ambo-Rappe R, Carly F et al (2021) Quantification of blue carbon in seagrass ecosystems of Southeast Asia and their potential for climate change mitigation. Sci Total Environ 783:146858
Steven ADL, Vanderklift MA, Bohler-Muller N (2019) A new narrative for the blue economy and blue carbon. J Indian Ocean Reg 15(2):123–128. https://doi.org/10.1080/19480881.2019.1625215
Syukur A, Al-Idrus A, Zulkifli L et al (2019) The potential of seagrass ecotourism as an indicator of conservation in the coastal waters of East Lombok. Journal of Science and Science Education 1(1):41–63
Sukardjo S (2004) Fisheries associated with mangrove ecosystem in Indonesia: a view from a mangrove ecologist. Biotropia 23:13–39
Sulochanan B (2013) Mangrove ecosystem and its impact on fisheries. Central Marine Fisheries Research Institute | R.C. Mangalore, pp 57–62
Tioti R, Li O, Delisle A (2021) Seagrass, culture, women and hard decisions: a case study from Kiribati. SPC • Women in Fish Inf Bull N. 33:12–15
Thompson BS, Rog SM (2019) Beyond ecosystem services: using charismatic megafauna as flagship species for mangrove forest conservation. Environ Sci Policy 102:9–17
Tsabang N, Ngah N, Estella FT et al (2016) Herbal medicine and treatment of diabetes in Africa: case study in Cameroon. Diabetes Case Rep 1(112):2
Twilley RR, Rovai AS, Riul P (2018) Coastal morphology explains global blue carbon distributions. Front Ecol Environ 16:1–6
Uchida M, Miyoshi T, Kaneniwa M et al (2014) Production of 16.5% v/v ethanol from seagrass seeds. J Biosci Bioeng 6:646–650
UNEP—United Nations Environment Programme (2014) The importance of Mangroves to people: a call to action. In: van Bochove J, Sullivan E, Nakamura T (eds) United Nations environment programme. World Conservation Monitoring Centre, Cambridge, 128p
UNEP—United Nations Environment Programme (2020) Opportunities and challenges for community-based seagrass conservation, UNEP, Nairobi, Kenya, 46p
Unsworth RKF, Nordlund LM, Cullen-Unsworth LC (2018) Seagrass meadows support global fisheries production. Conserv Lett 12(1):e12566. https://doi.org/10.1111/conl.12566
Valiela I, Bowen JL, York JK (2001) Mangrove forests: one of the world's threatened major tropical environments. Bioscience 51(10):807–815
Vanderklift MA, Gorman D, Steven ADL (2019) Blue carbon in the Indian Ocean: a review and research agenda. J Indian Ocean Res 15(2):129–138
Veitayaki J, Ram-Bidesi V, Matthews E et al (1995) Overview of destructive fishing practices in the pacific islands region. SPREP Reports and Studies series: no. 93, Apia, Western Samoa, 32p
Waycott M, Duarte CM, Carruthers TJB et al (2009) Accelerating loss of seagrasses across the globe threatens coastal ecosystems. Proc Natl Acad Sci USA 106(30):12377–12381
Wylie L, Sutton-Grier AE, Moore A (2016) Keys to successful blue carbon projects: lessons learned from global case studies. Mar Policy 65:76–84
Wojciechowski MJ, Melo KSG, Nascimento AF (2014) Caracterização da cadeia produtiva de moluscos bivalves nos estados de Pernambuco e Rio Grande do Norte. In: Silva GHG, Carolsfeld, J, Gálvez, AO (orgs) Gente da Maré, Aspectos ecológicos e socioeconômicos da mariscagem no nordeste brasileiro. EDUFERSA, Mossoró, RN, 420p, p 271–314
World Bank (2016) Blue economy development framework. Ocean 2030: Financing the Blue Economy for Sustainable Development, 8p. https://www.worldbank.org/en/topic
World Bank (2017) The potential of the blue economy: increasing long-term benefits of the sustainable use of marine resources for small island developing states and coastal least developed countries. World Bank, Washington, DC, p 50p
Wu J, Xiao Q, Xu J et al (2008) Natural products from true mangrove flora: Source, chemistry and bioactivities. Nat Prod Rep 25(5):955. https://doi.org/10.1039/b807365a

Yuvaraj N, Kanmani P, Satishkumar R et al (2012) Seagrass as a potential source of natural antioxidant and anti-inflammatory agents. Pharm Biol 50(4):458–467

Zeng Y, Friess DA, Sarira TV et al (2021) Global potential and limits of mangrove blue carbon for climate change mitigation. Curr Biol 31:1737–1743

Zu Ermgassen P, Mukherjee N, Worthington TA et al (2020) Fishers who rely on mangroves: modelling and mapping the global intensity of mangrove-associated fisheries. Estuar Coast Shelf Sci 247:106975

Zuidema C, Plate R, Dikou A (2011) To preserve or to develop? East bay dredging project, South Caicos, Turks and Caicos Islands. J Coast Conserv 15(4):555–563

Chapter 4
Coastal Fisheries

Teresa C. Borges, Joeli Veitayaki, Marcia Moreno-Báez, Andrés M. Cisneros-Montemayor, and Jorge Santos

Abstract The essential role of coastal fisheries in the Blue Economy is discussed, highlighting the importance of science and technology in their economic and social contexts, as well as that of good governance for their sustainability. The evolution and present situation of global fishery activities are discussed, as well as the effects of fishing on the environment. The worldwide problem of "seafood fraud" by mislabelling is also presented, together with recent technologies and methods to counteract it. Fisheries development trends observed in an industrialized country are presented to illustrate the long steps leading to a new fishing regime after the depletion of fishery stocks. Biological, economic, social and political considerations are discussed together with the importance of stakeholder participation in local and international fishery settings. The main effects of climate change on fisheries are discussed, emphasizing the vital need for adaptation strategies to reduce their impacts. The application of the targets of the Sustainable Development Goal 14 (Life Below Water) is illustrated from a global perspective, stressing the contribution of science and technology. Finally, the importance of fisheries for the Blue Economy is discussed, focusing on the need for equity, an essential factor for support and success.

T. C. Borges (✉)
Centre of Marine Sciences (CCMAR), University of Algarve, Faro, Portugal
e-mail: tborges@ualg.pt

J. Veitayaki
University of South Pacific, Suva, Fiji

M. Moreno-Báez
The Fletcher School, Tufts University, Medford, MA, USA
e-mail: marcia.morenobaez@tufts.edu

A. M. Cisneros-Montemayor
Ocean Nexus, School of Resource and Environmental Management, Simon Fraser University, Burnaby, BC, Canada
e-mail: a_cisneros@sfu.ca

J. Santos
UiT—The Arctic University of Norway, University of Tromsø, Tromsø, Norway
e-mail: jorge.santos@uit.no

E. R. Urban Jr. and V. Ittekkot (eds.), *Blue Economy*,
https://doi.org/10.1007/978-981-19-5065-0_4

Keywords Coastal fisheries · Sustainable fisheries · Seafood fraud · Fisheries subsidies · Fisheries governance · SDG 14

4.1 Introduction

It took over 200,000 years of human history for the world's population to reach 1 billion, and only 200 years more to reach 7 billion (Roser et al. 2013). Nowadays, one billion people live in coastal areas, within 20 m above sea level (UN 2016), very dependent on sea resources, which puts intense pressure on the sustainability of coastal ecosystems, of which humans are a part. Marine resources are materials and attributes from the ocean, considered to have intrinsic or monetary value, and include physical (minerals, oil, natural gas), biological (live animals and plants), and non-extractive resources (transport, tourism). Biological resources have probably been the most important to date and, as elaborated below, provide a high percentage of protein essential to humankind. These resources include algae and other sea plants, and sea animals such as fish, molluscs, crustaceans, sponges, reptiles, and mammals. They are important as human and animal food but also for pharmaceutical and cosmetic industries, and other uses (e.g., clothes, jewelry).

The definition of coastal fisheries used in this chapter is the one discussed in Palomares and Pauly (2019): fisheries that occur in the areas up to 50 km from inhabited coastlines or down to a depth of 200 m, whichever comes first. This wide definition includes the catches of industrial and small-scale fisheries—that is, subsistence, artisanal, and recreational fisheries—which make up to an average of 55% of annual global marine fisheries catches and contributes 36% of the marine catches consumed directly by people (Palomares and Pauly 2019). We note here that, although this chapter focuses on commercial fisheries, recreational fisheries can significantly contribute to fish mortality, and are often very important local industries (Kadagi et al. 2021). The accessibility of these fisheries has implications for sustainability but also helps underpin their importance for traditional livelihoods, cultures and food sovereignty.

Over time, scientific advancement and development have broadened the use of coastal areas and resources, which place even more pressure on coastal fisheries. Ports, airports, coastal installations, infrastructure, mining, shipping, tourism, aquaculture, submarine cables, pipelines and marine renewable energy are displacing fishing from coastal areas. The alteration of coastal habitats through natural and anthropogenic changes, pollution and over-exploitation are now threatening the health and productivity of coastal resources that endanger food security and sources of livelihood.

4.2 Fishing Over Time

An historical perspective on human source of food from the wild (hunting, gathering, and fishing) helps to understand our present, and prepares us for a better future.

Fishing is not only one of the most important human activities, but also one of the oldest, since it may have been practiced already by pre-hominids, enabling our species to survive hostile global conditions around 150 thousand years ago (Gabriel et al. 2005; Marean et al. 2007). At the beginning, fishing was opportunistic, mainly for subsistence, based on careful observation and patience, probably involved hominids simply using their hands to catch plants, molluscs or even gather fish. Soon, however, simple tools were invented or adapted from hunting for more efficient catching methods (Fagan 2017).

Throughout history, fishing technology has developed continuously, with improved and bigger vessels, more sophisticated equipment, and better preservation techniques, representing the three fundamental basics of fishing: boats, catching gear, and catch preservation. However, the Twentieth Century World Wars (1914–1918 and 1939–1945) changed everything dramatically: boats became larger, faster, and more numerous, and many war-developed technologies were transferred to fisheries. This amounted to a large improvement in economic efficiency and fisher safety and welfare, but it also gave rise to a large increase in fishing power, leading to unsustainable levels of catch in some fisheries (Smylie 2015).

World War II deeply changed knowledge of the ocean; soldiers returned home with new experiences and knowledge; new and improved technologies were used (e.g., radio and echo-sounding equipment, food preservation, diesel engines, etc.); and marine shipbuilding developed at a rapid pace, using all the experience and technology gained during the war, to build larger and faster fishing vessels. Social importance was devoted to giving jobs to returned soldiers, and designing boats with more comfortable crew accommodations (FAO 1955). War pilots, for example, were redirected to look for whales (Japan) or to hunt bluefin tuna (Greenberg and Worm 2015). All these improved the old forms of fishing, leading to greater fishing efficiency; an increase in fishing fleets, fishing operations, fishing catches; and improvement and adoption of better preservation systems. These developments led to a greater need for updated legislation and stronger control. Later, improved distribution of fishery products (by airplane), liaison between fishing companies and food companies, and increased international trade, gave to the fishing industry a new and powerful importance for humankind.

But the two World Wars also gave to humans the awareness of the importance of protecting the ocean and preserving its resources. In the middle of the 1950s, FAO (1955) recognized the main difficulties in the post-World War II development of the fishery industries and the increased need for research on the exploitation of marine resources. Following the war, the concept of rational exploitation and of sustainability of fishery resources became an important concern, with due regard for economic priorities in the fishery industry. Although some international scientific councils were already established before World War II, only after the war they were encouraged and supported to be actively engaged in fishery management (FAO 1955).

Traditionally, the ocean was considered to be common property, with the perception that the ocean was open to all, and little restriction existed on where, when, and how fishing was done. These arguments prevailed and were only overcome after World War II and several United Nations (UN) conferences, when the right of 200-nautical-mile Exclusive Economic Zones (EEZs) were formalized in the 1973 UN Conference on the Law of the Sea (Jennings et al. 2001). The result was the decrease of high-seas catches, and the sudden control of vast sea areas and their resources by small island states, which could receive payments for licenses to fish in their EEZs from richer countries (Burke 1994). This also led to more responsibility for knowledge and management of resources in national waters, leading to the need of a stronger international cooperation.

Take-Home Messages:

- Fishing methods have been conservative for thousands of years, but the development and adoption of new technology and markets in the 1950s radically drove up the yields of fisheries.
- Concerns about rational exploitation and sustainability of important fish and whale stocks arose at the same time.
- The United Nations Convention on the Law of the Sea (UNCLOS) gave all coastal nations the right to set Exclusive Economic Zones (EEZs), 200-nautical-miles from the shore, to manage their resources.

4.3 World Fisheries

The result of improved technology, increased human population, and increased mobility had an enormous impact of world marine catches, which increased from 17 million metric tons in 1950 to 58 million metric tons in 1970. This led to 90% of important stocks to be fished to low levels, other started supplying less than expected and many non-commercial species entered the markets (FAO 2020). The latest global fish[1] production (fishery and aquaculture) estimated by the Food and Agriculture Organization (FAO) of the UN (FAO 2020) is almost 179 million metric tons in 2018, the highest ever recorded. The marine capture fisheries seem to have reached a threshold at 84 million metric tons, while inland capture fisheries contribute with 12 million metric tons, marine aquaculture 31 million metric tons, and inland aquaculture 51 million metric tons.

Based on the most recent FAO estimates (FAO 2020), there was a decrease in the fraction of fish stocks that are thought to be within biologically sustainable levels, from 90% in 1974 to 66% in 2017. A concern is also the percentage of overfished stocks, which increased from 10 to 34% in the same period, while the underfished

[1] As in FAO (2020) the term “fish” indicates fish, crustaceans, molluscs, and other aquatic animals, but excludes marine mammals, reptiles, corals, pearls, sponges, seaweeds, and other aquatic plants.

stocks decreased from 39 to 6%, in the same timeframe. Therefore, it is urgent to develop (with local governments) adaptive management approaches; discontinue harmful fisheries subsidies (Cisneros-Montemayor, Ota, et al. 2020b; Sumaila et al. 2021); avoid negative environmental, economic, and social impacts; and implement management policies for some fish stocks in some countries and regions, which lack proper management (FAO 2020).

4.3.1 Coastal Fisheries Capture Evolution by Country Economic Class

Most coastal capture fisheries consist of fish and shellfish (crustaceans and molluscs), and account for more than half of the global marine fisheries (Palomares and Pauly 2019). Based on data and definitions of FishStat FAO (2021a), Fig. 4.1 shows the global capture of marine fish and shellfish from 1950 to 2018, by country economic class: developed and developing countries (the latter includes the least developing countries).

Although global marine capture fisheries continued to increase over time, by the late 1980s they had stabilized, reaching their peak in the mid-1990s (85 million metric tons). However, in 2018 there was a sharp increase in global fish capture of about 6% from the average of the previous three years.

In 1988, there was a turning point in marine capture fisheries, with an abrupt decrease in the captures by developed countries, while the captures by developing

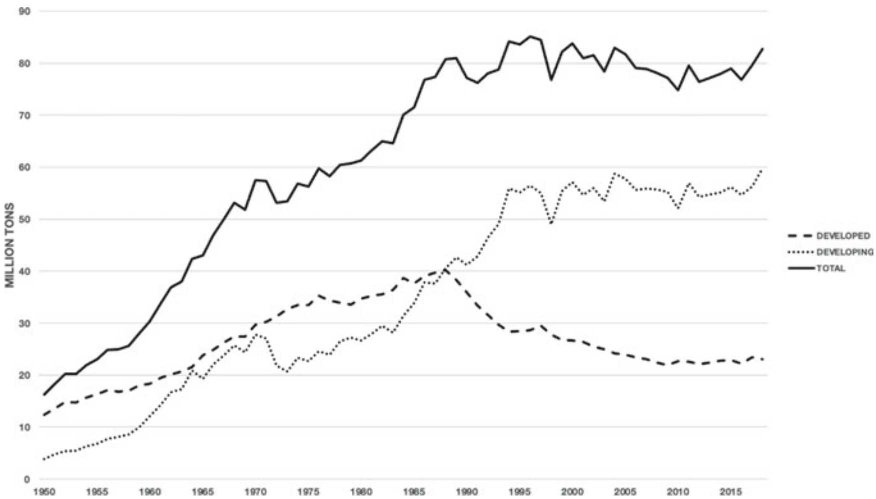


Fig. 4.1 Marine fish and shellfish (crustaceans and molluscs) captures, in million tons, by developed and developing countries (least developing countries included in the latter), from 1950 to 2018 (Data and definitions from FishStat FAO 2021a)

countries continued to rise, reaching in 2018 three times more than those from developed countries (Fig. 4.1). As possible reasons for this shift, the following factors may apply:

(a) Overcapacity in fishing fleets, particularly owing to technological advances starting in the 1950s, gradually led to overfishing of many fish stocks in the developed world, where fleets had more access to these technologies. This included notable collapses, including Atlantic cod and North Sea herring stocks, which were then some the world's largest fisheries by volume. Some of these stocks have since recovered, but there remains a gradual decline in global catches by industrial fisheries as stocks either become overexploited or their allowable quotas are decreased to avoid their overexploitation (Pauly and Zeller 2016).
(b) While developed country fleets were losing access to distant fishing areas, due to the implementation of the 200-nautical-mile EEZs as a result of UNCLOS (UN 1982), motorization of fisheries was widespread in developing countries, resulting in the emergence of boats with outboard engines and more powerful trawlers, both equipped with increasingly sophisticated technology, which led to increased captures. In some developing countries, the trend was difficult to notice, either because the changes in the vessel's technology were not reported or the statistics were unreliable, but the changes were evident (Zeller and Pauly 2019).
(c) The global number of fishing vessels has been drastically increasing, mainly from developing countries (FAO 2020). More recently, there have been strong efforts to reduce fishing fleet sizes, mainly from developed countries (e.g., Europe since 2000).

4.3.2 Global Fishing Fleets and Employment

As a measure of abundance of a fish stock and knowledge of its health, catch per unit of effort (CPUE) is the most widely used measure, but information on the fishing capacity, defined as the size and power of a fishing fleet, is also essential (Rousseau et al. 2019). Although several studies have been made to document more accurately the size and power of world fishing fleets, results always show some inconsistencies, mostly due to aggregation of completely different types of fishing fleets, which according to Rousseau et al. (2019), should be aggregated into three main groups: "artisanal motorised", "artisanal unmotorised" and "industrial".

Although the industrial fleet is better documented and reported, due to recent electronic monitoring systems (e.g., VMS—Vessel Monitoring System), in some countries or regions the impact of artisanal fishing fleet is underestimated, especially the unmotorized segment of the fleet (Rousseau et al. 2019). Most scientific studies only include registered and licensed fishing boats, not considering sometimes a substantial number of unlicensed ones. This leads to underestimates of national fleets and their efforts, an increase of illegal, unreported, and unregulated (IUU) fishing, and consequently inaccurate assessments of fish stocks and catches. Although the effect of the unmotorized fishing boats on global overfishing may be arguable, studies suggest that artisanal fleets may play an important role (Rousseau et al. 2019). However, it very much depends on definitions of artisanal and industrial fleets, for example, based on the use of vessel length classes (FAO 2018), or engine power (Rousseau et al. 2019).

Recent data indicate a world total of 4.6 million fishing vessels in 2018 (FAO 2020), more than twice the number reported in 1950 (1.7 million), particularly the motorized fleet, both artisanal and industrial, which increased more than six times over the same period (Rousseau et al. 2019). Thus, by 2015, the motorized artisanal fleet (<12 m) become nearly twice as large as the non-motorized fleet. Asia continues to have the largest fleet—3.1 million fishing vessels, equivalent to 68% of the global total. Although the number of fishing vessels has been drastically increasing, 2018 data show a global decrease in vessel number of nearly 3% from 2016, due to efforts to reduce fleet sizes, mainly from Europe since 2000, and from China from 2013 (FAO 2020).

Worldwide, the fisheries sector is a major source of jobs, employing over 39 million people, followed by the aquaculture sector with more than 20 million people, in 2018. Asia is the region with highest employment in both sectors, accounting for 85% of the world total, Africa 9%, the Americas 4%, and Europe and Oceania 1% each. Europe has the lowest employment in both sectors, with a marked decrease in the number of people in the fisheries sector in recent years (679,000 people in 2000 and 272,000 in 2018), while in the aquaculture sector the number of people involved has been slowly increasing (104,000 people in 2000 and 129,000 in 2018) (FAO 2020). This is the result of the efforts of Europe to decrease the capture fishing effort since 2000. Although still important in terms of employment, extraction of living resources ranks fourth after coastal tourism, maritime transport and port activities for the gross value added in the European blue economy (EC 2021). Similar statistics are hard to find for other regions. However, coastal fisheries are essential for some countries, especially for Small Island Developing States (SIDS), with an extreme social and economic importance. For example, in 2014, coastal fisheries contributed more than US$300 million annually to the GDP of Pacific SIDS (Gillett 2016), and employed around 100,000 people, with subsistence fisheries engaging 10–20 times more people than commercial fisheries (Hanich et al. 2018). Women constituted approximately 25% of the small-scale fishers and accounted for 56% of all landings (Harper et al. 2013).

4.3.3 Fish Utilization and Consumption

Of the global fish production (fishery and aquaculture) in 2018 (179 million metric tons), 88% was used for direct human consumption (44% are live, fresh, or chilled fish), which makes an average of 20.5 kg per capita per year (FAO 2020). While FAO reported that (2020) 12% of the total fish production are used for non-food purposes, Cashion et al. (2017) reported that a third of global marine landings, are mostly used for fishmeal or animal feed, including to produce food for pets and to farm carnivorous fish for humans. Although this is a reduction in the percentage of fish used for non-human consumption compared to previous decades, it would be more efficient to use fish biomass to feed humans, rather than to use these fish as food for carnivorous fish or other animals. It is mostly the consumer markets in rich developed countries, which have low acceptance for small pelagic fish, that create this demand for processed products. This creates an ethical dilemma as wealthy buyers raise the market prices above what the poor can pay for fish as a dietary staple.

The average figures of fish consumption hide large regional and even national discrepancies. As in many coastal areas and islands, 59–100% of Pacific Islanders consume fish weekly (SPC 2008). Per-capita fish consumption is 37 kg per year, ranging between 20 kg and 110 kg (2001–2006). Fish provided 50–90% of the animal protein intake in rural communities in Pacific Island Countries and 40–80% in urban centers (Hanich et al. 2018). This high dependence and demand for fish products, combined with increasing human populations, gave rise to degraded fisheries resources. Forecasts of fish requirements in 2030 indicate that only 6 of the 22 Pacific SIDS will be able to meet the necessary fish demands (SPC 2008; Bell et al. 2009).

Eating seafood is part of the cultural traditions of many countries, and plays a vital role in global food security, particularly in developing countries, as an important source of protein, but it is also highly recommended for the beneficial effects of its content, like Omega-3 fatty acids, vitamin A, iron, vitamin B_{12} and calcium. Among the general adult population, consumption of fish, particularly fatty fish, lowers the risk of mortality from coronary heart disease (FAO/WHO 2011). Fish consumption globally has increased annually at around 3% since the 1960s, a rate twice that of annual population growth (1.6%) and higher than other animal protein (meat, milk: 2% per year). Globally, fish provides more than 3.3 billion people with 20% of their average per capita intake of animal proteins, reaching 50% or more in some countries (FAO 2020).

In today's globalized world and economy, marine fish and other seafood easily crosses borders, mainly due to the ever-increasing demand of consumers for specific seafood and seafood products. International trade of fish products is an essential and important driver of economic growth and contributes to global food security. Exports of fish products are essential to the economies of many countries and the total of fish and fish products traded in 2018 was equivalent to 38% of all fish caught or farmed worldwide (FAO 2020).

4.3.4 Fisheries Subsidies

The Blue Economy gives rise to an escalating competition for space and resources among different economic sectors along the coast. However, the most significant competitor of fisheries in this scenario are the fisheries themselves, particularly the old conflict between the small-scale and industrial sub-sectors. Industrial fisheries are often subsidized, especially those that operate in distant waters. This can take the form of fuel subsidies, construction subsidies, other subsidies to employ or expand fishing capacity, or payment of access fees. Without these subsidies, distant-water fleets would not be able to operate in the same scale in a fair playing field with the small-scale fisheries, which only receive about 16% of all subsidies (Schuhbauer et al. 2017; Sala et al. 2018). In the opinion of Zeller and Pauly (2019), subsidies to industrial fisheries should stop, to decrease fishing fleets to more viable levels, and to reach economic and ecological sustainability, as well as social equity. The main reasons to stop subsidies are that (1) industrial fisheries employ fewer people than small-scale fisheries; (2) industrial fisheries use more fuel per metric ton of fish landed; (3) industrial fisheries generate around 10 million metric tons per year of discards (Zeller et al. 2018); and (4) a third of industrial fisheries catches is for animal feed (Cashion et al. 2017). Irrespective of fleet, subsidies need clear goals, co-design, transparency and fair implementation, to avoid harmful practices, and support communities that are highly dependent on ocean-based protein (Cisneros-Montemayor, Ota, et al. 2020).

4.3.5 The Modern Cycle of Fisheries Development (An Example)

It is difficult to make predictions about the future of fisheries in developing countries. However, there may be some lessons from the trends observed in developed countries in the last 80 years and draw the contours of a typical investment/disinvestment cycle. FAO also follows the narrative of a boom-and-bust model to categorize the state of aggregated world fisheries. That and the simplification presented herein should thereby be used with care. We use information from Norway, the dominant fish producer in Europe, to illustrate the point. The aggregated numbers of vessels, people employed and yields, presented here obscure much of the detail and diversity in the fisheries, but are still useful.

Following the technological advances after World War II, a growing population and an expanding economy, the number of fishing vessels increased in Norwegian fisheries. These vessels became more efficient owing to widespread technological and social innovations. This included better construction methods and materials, bigger vessels, and better equipment, such as echosounders, electronic navigation, better communication, and rescue services.

Simultaneously, as vessels increased in fishing power, UNCLOS ensured the adoption of exclusive fishing areas, a minimum price guarantee was negotiated by the fisher associations and cooperatives, which were becoming increasingly consolidated, and fishers were getting more trained in the use of technology. Together, these developments brought the major fish stocks to precarious conditions in a sequential process. The largest fishery, the purse-seine fishery for herring, collapsed around 1970 and was closed for nearly 20 years. The herring fleet soon turned its attention to other small pelagic fish, particularly the capelin. This is, however, the main prey of Atlantic cod, which was already under strong fishing pressure. By 1990, all major stocks needed re-building, and the strategy since then has been to sacrifice the fishery targeting prey species to obtain higher yields of the predators, which are usually more valuable. Thus, from a policy of maximum yield, the national fishery has moved to a policy of profitability, which has diminished the aggregated yield by only about 10%.

Rationalization of the fishery was a long and sometimes painful process for some. To remove the excessive effort from the fishery, quota regimes were introduced, and, since the new millennium, regulations have allowed the accumulation of quotas in single vessels, provided that other vessels are immobilized or abated. Subsidies to the fishing fleets were halted in 1995. The number of vessels and people in the fishery consequently dropped dramatically, and today is only about 10 and 25%, respectively, of the levels in the 1960s (Fig. 4.2). The displacement of people from the fishery was made possible by favorable welfare benefits for retiring fishers. Alternative employment for younger fishers was partly to be found in a bourgeoning aquaculture industry along the coast. Others moved away and engaged in other types of jobs, often in the civil services. Vessels have been replaced by more modern and powerful vessels, and the immediate challenge now is to deal with the energy transition until 2030.

Many developing countries are in state of maximum labor inclusion in their capture fisheries owing to large population growth and lack of alternative employment, which

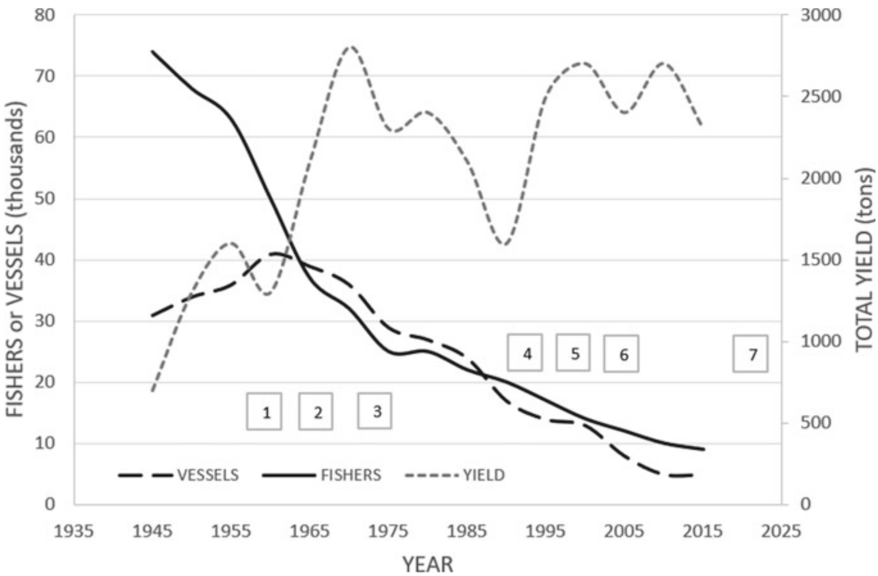


Fig. 4.2 Development of the aggregate Norwegian fisheries in national waters, with respect to input factors and yield. Significant trends (see text): 1—new technology; 2—increased vessel size; 3—establishment of 200 nm EEZ; 4—stricter quotas; 5—end of subsidies; 6—consolidation of quotas; 7—energy transition (*Credit* Based on data from the Norwegian Directorate of Fisheries)

raise social and ecological challenges. The disinvestment cycle will certainly occur, but the extent of it will probably be longer. Disinvestment in Norway has been enabled by proactive government policies, which were possible in an unusually long period of peace in Europe, good collaboration with neighboring states even in times of cold war, international market development and integration, and a generally wealthy economy. Such propitious conditions are not guaranteed to last long worldwide and are rare in most developing countries. The COVID-19 pandemic may have been positive for natural resources, but has demonstrated the fragility of fishery communities in face of trade barriers. Investment in social welfare, training and alternative blue industries (Sect. 4.7) is, nevertheless, the way forward for sustainable living along the coasts.

Take-Home Messages:

- The annual production of marine capture fisheries has stabilized at around 80–90 million metric tons in the last decades, presumably close to its maximum output.
- Seafood provides for much of the protein for humans, who consume an annual average of 20.5 kg per capita per year, and feed for other animals. Seafood is rich in micro-nutrients. The dependence of humans on seafood is much higher in coastal areas, and particularly in island states.
- Asia is the continent experiencing the most growth in terms of vessels, yield, consumption, employment, and exports in fisheries. Developed countries have become important markets, rather than producers.
- Many industrial fleets, particularly distant-water fleets, where they still exist, tend to be subsidized. This is economically inefficient and creates an uneven playing field for small-scale fisheries where the two compete for the same resources.
- Many fisheries in developing countries, including small-scale fisheries, are in a state of maximum labor inclusion. Disinvestment in fisheries will re-distribute wealth among the remaining fishers and will probably shift future yields among different species.
- Disinvestment in fisheries is only possible if alternative livelihoods are found for the younger labor force and welfare solutions exist for the retiring people.

4.4 Fishery Science and Technology

Science and technology are distinct but interdependent activities, contributing to each other in different but complementary ways. They both are intrinsically linked to development, the success of which is dependent on scientific research.

Marine scientific research may be logistically challenging, requiring resources (e.g., research vessels and other advanced equipment) that makes it expensive. However, funding for marine research is minor in comparison to the enormous economic contribution of the world's ocean. An average of 1.2% of national research budgets were allocated for ocean science between 2013 and 2017. This is a miniscule contribution compared with the estimated US $1.5 trillion contribution of the ocean to the global economy in 2010 (UN 2021).

Research in fisheries constitutes so-called “fisheries science”, a multidisciplinary science, which involves disciplines in the areas of biology, genetics, stock assessment, economics, sociology, marketing, and technology, to provide an integrated view of fisheries (Royce 1996). However, for a more holistic perspective of fisheries, interdisciplinary methodologies and practices are essential to fully integrate knowledge from different disciplines. Therefore, natural scientists, social scientists and environmental economists need to better understand the complexities and uncertainties inherent to fisheries to support science-based decision making (Haapasaari et al. 2012). Although traditionally dominated by the views of natural scientists, fisheries are increasingly recognized as social-ecological complex adaptive systems. They couple a human sub-system with a natural one (Weber et al. 2019).

4.4.1 The Effects of Fishing

The effects of fishing on the environment have been well described and documented over time (e.g., Goñi 1998; Garcia et al. 2003). Based on several scientific reviews published on this subject, the effects of fishing on ecosystems may be divided into direct and indirect. Direct fishing effects are primarily on the target species’ populations by reducing their abundance (overfishing), and on other co-habiting species, which may be captured or killed (bycatch and discards), as well as the physical impacts on the seabed and benthic organisms caused by fishing gear. Indirect effects include changes in biological interactions between species in the ecosystem (competition and predation), changes in the structure of communities (biodiversity), and the mortality caused by lost fishing gear (ghost-fishing) (Goñi 1998). Fishing also contributes to other important problems, such as the environmental effects of discard dumping and marine litter.

At the level of target and non-target species’ populations, fishing decreases abundance (overfishing), modifies their population parameters (size and age structure, fecundity, sex-ratio, etc.), as well as genetic diversity. Since fishing is mostly selective on size and age, it alters the genetic structure of exploited populations. Experimental studies on some marine species have demonstrated that fishing selectivity may change life strategies of populations within a few generations (Smith 1994), but often not irreversibly. As an example, a study done on the population of orange roughy (*Hoplostetus atlanticus*) off New Zealand showed significant loss of genetic diversity after a 70% reduction of the population over six years of intense fishing. This study also suggests that in unfished populations, the largest and older individuals are the most genetically diverse, which makes a case for the protection of large rather than small sized individuals, as commonly advocated in selective fisheries (Smith 1994).

Fishing effects on seabed habitats are mainly through fishing gear and fishing effort, and vary with time and place, type of habitat and environment where they occur. Studies show that the spatial footprint of industrial fishing extend more than four times that of agriculture. Although different estimations have been published of

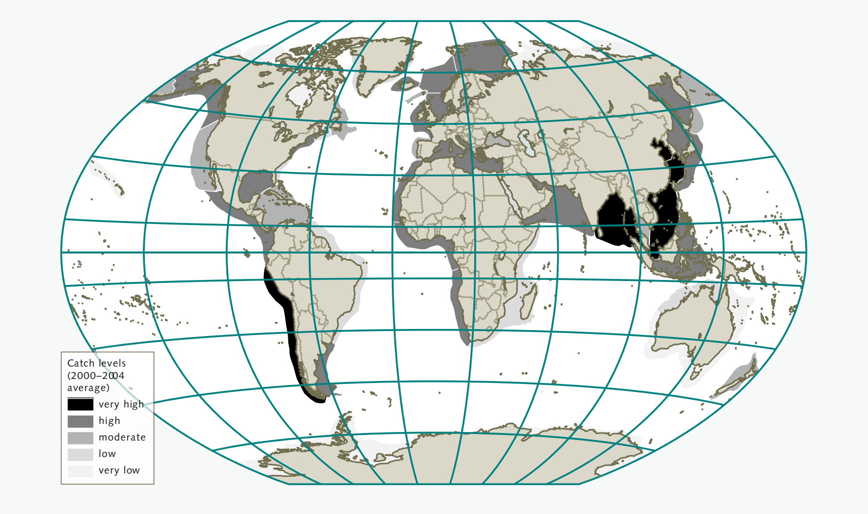


Fig. 4.3 World coastal regions and intensity of fishing from 2000 to 2004 (Adapted from WOR 2013)

the percentage of the ocean fished (95% by Watson [2017] versus 73% by Kroodsma et al. [2018]), the spatial footprint of fishing seems undoubtedly much larger than agriculture—200 million km^2 of the ocean fished, compared with 50 million km^2 for agriculture (Kroodsma et al. 2018). However, according to the same study, only limited coastal systems are exploited intensively worldwide, and oceanic areas tend to be exploited seasonally for large migratory species only (Fig. 4.3).

Apart from the spatial coverage of industrial (and some artisanal) fishing, the use of habitat damaging gear (mainly trawls) not only has an impact on coastal marine grounds (Jennings and Kaiser 1998; Morais et al. 2007; Mazor et al. 2021) but also threatens the integrity of livelihoods and the fishing traditions and heritage of coastal communities (Aburto-Oropeza et al. 2018; Giron-Nava et al. 2021). Although these grounds are only a minuscule part of the world ocean, they may suffer impacting changes in habitat structure and biodiversity (Schwinghamer et al. 1998; Smith et al. 2003).

Uncontrolled small-scale fisheries can also contribute to depletion of coastal stocks, due to increasing fishing effort or use of damaging fishing gear and methods. In some areas of the world (e.g., East and West Africa, Madagascar), the use of small-meshed nets for fishing is a common practice. This unselective type of fishery tends to target and be locked into a small pelagic fish cycle, mostly through an ecological cascading mechanism of predator exclusion and prey release (Santos et al., in press). The small pelagic fish are also the most productive and resilient species in these assemblages, and often they compose the only protein source of the coastal dwellers. However, the widespread use of mosquito nets, for example, is environmentally damaging, not only due to the very small mesh size net (fishing small species or larval stages), but also due to these nets being dip-treated with insecticides, which are environmentally toxic (Short et al. 2018).

Other very damaging fishing practices in coastal waters are blast fishing (or fish bombing), and cyanide fishing, two of the most destructive fishing practices. Although its prohibition is well stated in the FAO Code of Conduct for Responsible Fisheries (FAO 1995), these methods are still currently used in many countries (e.g., Indonesia, Philippines, Tanzania, Brazil, among others). Both methods intend to stun or kill fish for easy collection, but both are extremely destructive to surrounding ecosystems, as they damage or destroy habitats, and many other marine organisms, such as coral, which are very slow-growing species, and vulnerable to extirpation (local extinction). These destructive fishing methods need to be stopped, and the only way to do so is through legislation, competent surveillance and law enforcement, although culturally adapted education and communication are fundamental as preventive methodologies.

4.4.2 Bycatch and Discards

Most fishing gear are not selective enough to capture only the desired target species, which leads to the incidental capture of non-target species (bycatch). This bycatch may have some economic value, although usually little or none, in which case it is discarded overboard, mostly dead. Bycatch has caught full public attention because of its effects on charismatic species, like mammals and birds. However, the problem of mortality of non-target species is broader, and affects all animal species, including endangered, threatened, and protected species (e.g., sharks). Moreover, since most bycatch is discarded, all this biomass is unaccounted and fishing mortality is, therefore, underestimated. Bycatch and discards are a problem that permeates quota-based fisheries of developed countries, oceanic pelagic longline fisheries, and bottom trawl fisheries that target high-value species worldwide. In coastal fisheries of developing countries, and in developed countries with strong traditions of fish consumption, most species captured are commercialized, therefore, less are discarded.

The main reason for bycatch is ecological (different species live in the same habitat), and for discards the reasons are technological (gear selectivity, storage capacity), economic (species with no or low commercial value), and regulatory (minimum size, catch quotas, seasonal closures). The main effects of discards are on fisheries management, due to the underestimated fishing mortality, economic costs from the loss of raw material, and ecological (biodiversity, impacts on food webs). Discards are a waste of natural resources, and a threat to the health and stability of marine ecosystems.

Bycatch may be considered unavoidable, as most fishing gear are generally not very species-selective, but mostly size-selective. Size selection in net fisheries is mainly determined by the size and orientation of the net meshes or other escape mechanisms. Bottom trawls are probably the most unselective fishing gear used in fisheries because they capture most organisms in their paths. However, trawls may also capture birds and turtles incidentally when hauling the net, as in the case of the shrimp trawling in the Gulf of Mexico (Dayton et al. 1995), or capture other "charismatic" species, such as sharks (Costa et al. 2008). Pelagic trawls, which are designed to work in midwater, may be considered more selective for the target species, but they also have considerable incidental capture of cetaceans and seals due to their relatively large dimension and fast towing speed (Alverson et al. 1994).

Sometimes, unwanted catch of accompanying species comes out of ignorance of better operative methods. Change of the depth of the longline sets, and utilization of streamers can spare the lives of tenths of thousands of sharks and seabirds annually in a single tuna fishery (Jordaan et al. 2020). Selectivity in trawls may also be improved through the use of different mesh shapes (e.g., square mesh windows), species sorting grids, and other devices (i.e., Bycatch Reducing Devices—BRDs) which can be fitted to existing gear to enable unwanted catch to escape (Fonseca et al. 2005; Campos et al. 2015). There is, thus, a role for continuing education of the fishers in a well-governed fishery.

All fishing gear types capture non-target species, even the gear considered to be selective, like purse-seines, gillnets and longlines. Several studies done in Portuguese waters show that they all have considerable impact on bycatch species, not only birds and mammals but also on other species of fish and invertebrates (Borges et al. 2001; Erzini et al. 2002; Gonçalves et al. 2008). The removal of predators always has considerable impact on community interactions in marine food webs.

Most bycatch is discarded, particularly in industrial fisheries (although in artisanal fisheries quantities may also be considerable), and most organisms are already dead when brought on board. The first study on the average world fisheries discard rates was by Saila (1983), with an estimation around 6.7 million metric tons. Later, Alverson et al. (1994) estimated the average global discards at about 27 million metric tons per year, followed by Kelleher (2005) with annual estimations of about 7.3 million metric tons. More recently, Pérez-Roda et al. (2019) estimated that the annual discards from global marine capture fisheries was 9.1 million metric tons. In all studies, bottom trawls, particularly shrimp trawls, generate the most discards. Research on the probable fate of discards is important to understand the extent to which fishing activities alter the trophic webs in the marine environment (Castro et al. 2005). Survival assessments of bycatch species can be conducted using different methods, some more accessible and less costly, like vitality assessments (Adão et al. 2018); other methods are technically more difficult and costly, like captive observation and tagging/biotelemetry (Campos et al. 2015).

Since it is not possible to completely avoid bycatch, there is a need for technological solutions, as well as economic and social incentives, to reduce bycatch, with the goal of gradually eliminating discards. The European Commission Common Fisheries Policy (CFP) established in 2013 a phased introduction of the so-called "landing obligation" or "discard ban" (EC 2013b). The landing obligation was a major shift in EU fisheries management, and quotas are now controlled by what is caught at sea, rather than what is landed onshore. Such measures require, however, good control of catches at sea to be effective. This is normally a costly exercise unless there is full cooperation from the industry.

To effectively implement and control policies on discards, monitoring on-board activities is important. Traditionally, monitoring is done by aerial and boat surveillance, dockside checks, and observers on-board fishing vessels, which is difficult in small vessels and very costly. Taking advantage of modern technologies, remote electronic monitoring (REM) can offer more efficient and cost-effective monitoring of fishing activities. Several electronic systems are already in use, like E-logs (electronic logbooks, where fishermen record their catches at sea), and electronic tracking systems, like AIS (Automatic Identification System), and VMS (Vessel Monitoring Systems). Both systems record the position of the vessel and broadcast positions in real-time online to fishery management centers, but they work on different types of technology. AIS uses VHF radio signals and transmits a vessel's identity and location to other vessels in its area. VMS uses satellite communications to transmit the identity and position of the vessel to a shore-based data hub. While AIS is mainly used for safety reasons, and the public has access to the positioning and identity data, VMS data are usually hosted by compliance departments to monitor vessels movements and data are not available to the public (Course et al. 2020).

4.4.3 Ghost Fishing and Marine Litter

Another strong impact of fishing on the environment is the abandoned, lost, and discarded fishing gear in the ocean. Apart from being the main type of fishery litter, these fishing gears continue to fish by trapping and entangling animals, and potentially kill most of them. This is called "ghost fishing". Species affected by ghost gear include not only fish and invertebrates but sea birds, marine mammals, and turtles.

Ghost fishing is most problematic in gillnets, trammel nets and other passive fishing gear—fishing gear where the capture depends on the movement of animals into the gear. Used worldwide primarily by coastal small-scale fisheries, gillnet and trammel net fisheries are responsible for about one-fifth of global marine fishery landings. Abandoned, lost, and discarded fishing gear (also known as "ghost gear") have important and long-lasting effects on the marine environment, particularly on animals, continuing to catch different species, until the nets curl and sink, due to the weight of encrusting species, or are destroyed by currents or another oceanic phenomena. Although more studies are needed on how to prevent ghost fishing, results on the scale of the impacts of ghost-fishing indicate that the effects are not negligible (e.g., Erzini et al. 1997, 2008; Gilman et al. 2016). The change from natural to synthetic manufactured materials has increased ghost fishing. Every year 640,000 tons of ghost gear are estimated to enter the ocean, and by weight it is estimated to be between 46 and 70% of all macroplastic marine debris (Nguyen 2020), which constitute a significant impact on marine life.

Several programs and policies have already been implemented in different countries and regions to prevent the purposeful discard and accidental loss of fishing gear. The Government of Canada, for example, created programs to financially support the retrieval and disposal of lost gear, as well as to develop innovative technologies and strategies to prevent the loss of fishing gear. An example of a new technology implemented is a low-cost acoustically activated rope-less fishing system and gear-tracking system, for use in the lobster and crab fisheries. At the same time, Canadian policies have made reporting lost and retrieved fishing gear compulsory (Nguyen 2020).

4.4.4 Seafood Fraud

Trade in fish and fish products is greatly diverse, reflecting diversity in consumers' taste and preferences. Yet, increased demand created the opportunity for so-called "seafood fraud" by mislabeling. This problem has been attracting much attention because species authenticity cannot be determined visually, particularly for fillets and processed seafood products (e.g., Carvalho et al. 2017; Veneza et al. 2018; Boughattas et al. 2019). Although unintentional mislabeling may occur (species misidentification, loss of information along the supply chain), the main reason for this fraud is to maximize profit, which can be significantly increased by substituting expensive or more desirable species with cheaper or less desirable ones. For example, tilapia (*Oreochromis spp.*) or pangasius (*Pangasianodon hypophthalmus*) are occasionally sold as snapper or cod, or farmed Atlantic salmon (*Salmo salar*), as wild Pacific salmon (*Onchorhynchus spp.*). But seafood fraud can also be committed with the intention to disguise the sale of protected or over-quota species (Ho et al. 2020; Marchetti et al. 2020).

Mislabeling of seafood products is not only a problem of a simple "fraud" since it may have several serious implications: (1) deception of consumers, lowering the quality of the product; (2) risk to consumer's health, for example, introduction of toxic fish; (3) impact on the conservation of species and populations, such as protected species, and contribution to IUU fishing; and (4) religious and ethical, when containing ingredients that are not allowed or recommended (Griffiths et al. 2014; Huang et al. 2014; Wainwright et al. 2018; Ho et al. 2020).

To prevent food fraud and mislabeling, some countries, for example, in the European Union (EU), have detailed and robust seafood legislation, which requires on retail seafood products (raw, thawed, unprocessed or slightly processed) a declaration of the commercial designation, scientific name, production method, geographical origin, and fishing gear category, complemented with comprehensive traceability requirements (EC 2013a). However, integrity and transparency of information are not guaranteed, and mislabeling may happen at any stage of the process, which requires constant inspection by government authorities. Also, different countries have different seafood naming lists, lacking harmony between countries, and frequently several species are under a generic market name, introducing even more confusion (Cawthorn et al. 2018). Therefore, weak, or poorly enforced regulations, and confused seafood naming lists, promote the proliferation of seafood fraud, with all its implications.

Mislabeling is common everywhere—in restaurants, fishmongers, and supermarkets—all over the world, and is rarely accidental. Science and technology play here an important and essential role, with an increasing number of studies examining seafood fraud in recent years (e.g., Carvalho et al. 2017; Boughattas et al. 2019; Ho et al. 2020; Munguia-Vega et al. 2021). Several methods have been developed that are able to identify the ingredients of commercially sold seafood (chromatographic, spectroscopic, proteomic, and genetic methods). Food standard authorities of some countries, for example, can now use DNA testing to identify seafood species by comparing a specific section of a specific gene from a sample with a library of "barcodes" from known species. However, all these methodologies are time consuming and costly, and not available to average consumers.

After capture, seafood enters a so-called "fishery value chain". A value chain is the full range of activities (such as production, marketing, distribution, and support services) that are required to bring a product or service from its conception to the final consumer, which includes local, regional, and global markets. Key activities in a fisheries value chain can include fishing or aquaculture production, processing, transport, wholesale, and retail marketing (FAO 2021b).

In a fishery value chain, safety and traceability are essential to ensure transparency, integrity, and food safety, but do not guarantee these results. It is important not to confuse traceability and verification, while the first is a system, the second is an action. Yet, traceability is not only a numeric code attached to a product, ensuring that information is true, but is the ability to trace the history, application, or location of an entity by means of recorded identifications (Blaha and Katafono 2020). A very important criterion associated with traceability is eligibility of products, and that is when blockchain technology can be useful.

A blockchain database consists of blocks containing batches of transactions that are hashed and encoded. The blocks are all linked by the hash of the block before, which forms the chain. When a block of data is added to the chain it cannot be changed or removed. This process validates each block and is integral to the database's security (Blaha and Katafono 2020). This technology in fisheries provides traceability from the point of production (capture or culture) to the final consumer. Therefore, by reviewing a blockchain, one may know with certainty that a specific fish had been caught or cultured in a particular place, arrived or left at a particular time, and since the records cannot be manipulated, seafood fraud may drop sharply.

Although the results are very promising, several challenges have been identified. For example, the costs of building a blockchain solution from scratch can be costly since there are still few experienced blockchain developers, even less with deep knowledge of seafood value chains (Blaha and Katafono 2020). Also, seafood has the longest supply chain of any food product, from catch or farming to the consumer, but also geographically complex, with people speaking different languages, and where species' common names are different in different countries. At the same time, blockchain technology is probably more relevant to industrial fisheries and to more expensive seafood. Therefore, although very attractive and promising technology, it still needs more pilot studies to learn how to avoid operational difficulties.

The combination of DNA testing (to prove the species of fish), with blockchain technology (to improve fish traceability) has the potential to improve control of fishery products. Yet, blockchain technology will not per se stop or prevent IUU fishing, will not stop overfishing or discarding, but will enhance transparency in seafood supply chains, improve food safety, and reduce seafood fraud. Blockchain technology may also allow government authorities to improve surveillance of industry compliance, and consumers to make better informed decisions on which product they would like to purchase. Data within blockchains could also become a valuable source for enforcement agencies, fishers, traders, and scientists (Probst 2019).

Take-Home Messages:

- Fishery science is an applied inter-disciplinary field. Fishery scientists must grasp and integrate different disciplinary knowledge. However, the political implementation of scientific recommendations is often a problem in both developing and developed countries.
- The most urgent and universal mission of fisheries management is to deter the permanent destruction of habitats and local extinction of slow-growing species, while aiming for broad sustainability. Apart from that, management policies may vary with the ecological and social settings.
- Fishing methods that destroy habitat need to be stopped, and the only way to do so is through legislation and competent surveillance, although culturally adapted education and communication are fundamental as preventive methodologies.
- Some fisheries practices are wasteful of seafood resources. Sometimes, smart changes of regulations, fishing gear or fishing operations have little costs and avoid bycatch and discards to a great extent.
- Fisheries are some of the main contributors of marine litter, particularly plastics, to the sea environment in many parts of the world. New degradable materials are being tested. But while we wait for this, smart changes in the operations, monitoring and education of the stakeholders (fishers, fish processors, consumers, etc.) are a great help in the mitigation of the problem.
- Mislabeling of seafood products occurs particularly in the international trade of valuable fish products. The first line of defense is a well-documented value chain that follows the product from the sea to the consumer.

4.5 Fisheries Management

There are many challenges to achieving sustainable fisheries, starting by an objective definition of its goals. Accordingly, a wide variety of fisheries management objectives and tools have been developed and implemented throughout the world; these were largely developed based on principles of natural population dynamics, though their implementation has frequently faced challenges related to social and economic dynamics. Traditional fisheries management aimed to maximize sustainable catches, and the concept of Maximum Sustainable Yield (MSY) is enshrined in the UNCLOS (UN 1982), and guidelines such as the FAO's Code of Conduct (FAO 1995). Although the concept of MSY is outdated in ecological thinking and known to have been prescribed based on international political interests (Larkin 1977; Finley and Oreskes 2013), it still permeates the practice of biological fisheries management. Estimating and achieving maximum sustainable yearly catch is the most important objective in this context. However, because focus on catches alone would often lead to overfishing, fisheries management aims instead to monitor and control mortality and allow adequate reproduction in the harvested populations and, sometimes, in bycatch species (Walters and Martell 2020). Fish populations have specific ages, sizes, seasons, and areas in which they reproduce and recruit (grow and become available to the fishery). Consequently, mesh sizes of nets, minimum (and sometimes, maximum) size limits, seasonal area closures and landing quotas are all designed to protect wild populations so that they may replenish. This makes some sense in the case of fisheries targeting one or only a few species, but is of limited value elsewhere. Fisheries in warm temperate and tropical areas that target multiple species must have broader ecological reference points (Garcia et al. 2003).

Overall limits to capacity, for example, the total number of fishers or vessels of a given size, also intend to limit mortality and prevent overfishing. However, these limits have also come to be used to achieve economic objectives for the fishery, for example, by increasing or sustaining fishing profit, even if it means that not everyone has the opportunity to fish (because if they did, everyone's profits would decrease) (Clark and Clark 2006). More recently, there has been increasing interest in reconciling the bioeconomic assumptions and goals of fisheries (i.e., maintaining sustainable and profitable fisheries), with equity and social justice considerations (Bennett et al. 2021b), which makes more sense than managing theoretically isolated populations. One prominent example is the management of small-scale (artisanal) fisheries around the world. These have often been considered particularly challenging because of the large number of fishers and many different types of species and gears involved, which does not suit the intensive monoculture paradigm. This perception of artisanal fisheries as mainly a challenge, however, ignores their essential role for local livelihoods, traditions, and food security, and indeed for global seafood markets which they help supply. Environmental sustainability, which is a very loosely defined term as a consequence of our limited ecological insight, will continue to be at the core of fisheries management. But employment and social equity objectives must also be fully integrated to truly contribute to overarching well-being goals (FAO 2015; Jentoft et al. 2017).

4.5.1 Importance of Marine Protected Areas (MPAs)

In face of the ultimate variety and complexity of fisheries and other anthropogenic pressures on marine and coastal habitats, marine protected areas (MPAs) have been proposed as a universal, no frills, spatial conservation tool worldwide. This management approach warrants specific mention since the adoption of specific area targets as part of the Aichi Biodiversity Targets and the UN Sustainable Development Goals (10% of marine areas), and the more recent '30 × 30' campaign led by a coalition of conservation NGOs aiming to establish marine protected areas in 30% of the ocean by 2030. From a practical standpoint, the protection of marine areas from direct human impacts is a straight forward endeavor, particularly in small, easily monitored areas, and does address management and conservation goals (Hilborn et al. 2021). There is evidence showing significant recoveries in species abundance and ecosystem function as a result of such protections (Grorud-Colvert et al. 2021), particularly for sedentary species but also for a wide variety of fishes. Recent work also shows that MPAs support greater genetic diversity and vigor, potentially enabling mitigation of species to compensate for the ecosystem effects of climate change (Duncan et al. 2019). Given appropriate guidelines, it is possible to use areas in the littoral zone of MPAs for ecotourism activities with some economic benefits (Cisneros-Montemayor, Becerril-García, et al. 2020) or in Territorial Use Rights for Fishing programs. The main negative social impact of MPAs is usually the exclusion of fishing activities, traditional or modern, in the proposed areas. While there can be multiple sub-areas allowing for different uses within MPAs, this carries the risk of decreasing overall protection or resulting in "paper-parks" with limited ecosystem protection. It is commonly argued, not without logic, that increased biomass and biodiversity within MPAs can spill over into areas outside of the MPA itself, thus supporting local fisheries. Evidence on this point is mixed, both given the complex ecological dynamics of ocean areas, the common challenge of overcapacity outside of protected areas, and the real-world difficulties in effectively preventing fishing activity from entering areas of higher biomass, legally protected or not (Goñi et al. 2011; Barceló et al. 2021). Despite being claimed as a universal solution, it is clear that implementing MPAs will require addressing critical issues in ecology, as well as recognizing local social contexts and goals.

4.5.2 Climate Change and Fisheries (See also Chap. *12*)

It is likely that the already pressed coastal fisheries become somehow impacted by climate change, as manifested by sea level rise, acidification, sea temperature rise, increasing storm intensity and frequency, and the interaction of these variables (Pecl et al. 2014; Hare et al. 2016). However, coastal ecosystems are complex, with large degrees of trophic redundancy and feedback relationships, and the outcomes of climate change are difficult to predict. The increase of sea surface temperature may cause poleward shifts of fish species and fisheries (Cheung et al. 2013). This could be advantageous for fish and shellfish communities in temperate waters. It is difficult to anticipate how species re-distribution would occur in the trailing (warmer) edge of the species' distribution, or what type of fish assemblages can develop in equatorial waters. Some authors (Cheung et al. 2013) suggest that the warmest coasts may become inhospitable, as was recently demonstrated for a suite of fishes in Kenya and Tanzania (Wilson et al. 2021). However, recent research indicates that life-stages of some species may nonetheless be anchored in specific areas (Ciannelli et al. 2021). Similarly, some of the world's largest fisheries (e.g., Peruvian anchoveta) are located in upwelling ecosystems. Although these stocks are resilient to change, and adapted to environmental fluctuations, forecasting the response of upwelling systems at new scales of variability is difficult (Daw et al. 2009; Bakun et al. 2015).

Coral reefs provide direct benefits to fisheries since they are a permanent habitat for many important commercial species, are vital to juvenile stages, and constitute the diet of many other species. Two-thirds of all coral reefs are in developing countries, and millions of people depend on them for food and livelihoods. Studies suggest that 50–60% of coral reefs could be lost by 2030, with serious implications for ecosystem function and dependent human communities (Govan 2017; Eddy et al. 2021). The risk of severe bleaching and mortality of corals with rising sea surface temperatures and acidification threatens local fisheries and, consequently, their communities (Barange et al. 2018). Other nearshore habitats and wetlands, like salt marshes, mangroves and seagrass beds, are extremely important since they buffer the shore from storms, often support some small-scale fisheries, and provide breeding and nursery areas for many species. In many regions of the world, these habitats are under intense harvest and degradation owing to population growth, construction and industrial utilization of the littoral zone (e.g., aquaculture, saltworks, urbanization), as well as collection of wood for fuel and construction. This impact may be intensified by sea level rise (Daw et al. 2009).

Climate change may also increase the frequency and magnitude of harmful algal blooms (HABs), which produce toxic effects on people and other marine species (Erdner et al. 2008) (see also Chap. 10). Closure of fishery during HABs causes severe socio-economic disruption to fishery-dependent communities and require good communication, cost-effective strategies, and action plans (Barange et al. 2018; Ritzman et al. 2018).

Predicting the effects of climate change at local levels is difficult or impossible, and strategies that diminish vulnerability and increase resilience are the best options. Vulnerability is defined as the susceptibility to harm of individuals, groups or systems as a result of climatic changes, and resilience is a concept related to the capacity to adapt to new states of nature (Daw et al. 2009). Fisheries have always been dependent and susceptible to the climate, but it is important to integrate adaptation strategies to climate change within any policy agenda (Barange et al. 2018). Despite the difficulty in providing precise predictions at local levels, science can help identify vulnerable species, fisheries, and human populations, and can recommend strategies to mitigate and adapt to these impacts (Miller et al. 2018).

4.5.3 The Importance of Fisheries Associations and International Cooperation

Across all scales of fishery management, it is essential to establish effective collaboration between fishers and management agencies, as well as between intra- and international governments. Perhaps the clearest example of this need is in areas beyond national jurisdiction—the "high seas"—that are accessed by all countries, but where no single party is responsible for its use or protection. There is extensive evidence of the linkages between high-seas species and coastal fisheries (Sumaila et al. 2015; Cheung et al. 2017; Vierros et al. 2020), and the lessons of high seas fisheries management are highly relevant for cooperative management within and between nations (Crespo et al. 2019). Aside from shipping routes, fisheries are the most prevalent human activity on the high seas and are often governed by Regional Fisheries Management Organizations (RFMOs). RFMO members collaborate to establish and allocate allowable catch, agree on rules regarding fishing gears and areas, and enact guidelines for monitoring catches and funding scientific research to inform their decisions. These RFMOs are non-state bodies but are officially recognized and have led some successful fisheries management initiatives. Some important critiques of RFMOs are that their membership inclusion and decisions can lack transparency (Petersson 2020), particularly regarding quota allocations. In addition, RFMOs only partially address activities within their own areas and for only a few high-value species (Ewell et al. 2020); there have been studies showing that a substantial proportion of fishing activity on the high seas—even when operating in compliance with RFMO guidelines—is unreported or misreported (Coulter et al. 2020).

It is important to critically analyze the role and current challenges in shared spaces and shared fisheries, and RFMOs specifically. For one, high seas areas are declared by UNCLOS to be the common heritage of mankind and thus the public at large has a stake in their use and conservation, not only RFMO members or those fishing on the high seas. It has indeed been proposed that it would be more equitable and perhaps financially profitable to close the high seas to fishing so that coastal states without the capacity to fish in the high seas can catch fish as they move closer to their shores (White and Costello 2014; Sala et al. 2018). Beyond the high seas themselves, as climate change affects fish species distribution around the world, there is a rapidly increasing number of transboundary fish stocks (Palacios-Abrantes et al. 2020). These are defined as stocks that are shared by two or more coastal states, and this of course requires cooperative fisheries management open to learning from past experiences.

Take-Home Messages:

- The primary concern of ecological fishery management is the avoidance of extinction or extirpation of vulnerable species, habitats and unique food-web relationships.
- Beyond first-order conservation objectives, there is a continuum of sustainable management objectives that match different social criteria (maximum profit, maximum yield, maximum employment or inclusion) for particular fisheries.

- There is a wide range of technical, effort and quota control available, and these can be used in different combinations, but all have their costs and benefits of implementation.
- Marine Protected Areas (MPAs) are primarily a tool for biodiversity and habitat conservation, but can also play a role for fisheries management in some settings.
- The most up to date local knowledge and scientific information on local effects of climate change should be considered when developing fisheries policy and mitigatory actions.
- Climate change, and counter-acting measures, may have pervasive effects along the whole value chain, from the fish and fishing, to habitats, community, markets and distribution.
- It is a right and duty of all coastal states to participate in RFMOs (Regional Fisheries Management Organizations).
- All states should be aligned or have a common understanding of fisheries management goals.
- There must be close and equitable cooperation between agencies and stakeholders across borders and boundaries to promote compliance with fisheries management.

4.6 Fisheries and the UN Sustainable Development Goals (SDG)

Coastal fisheries support food security, livelihood, revenue generation, employment, and social and economic development and are, therefore, of critical importance to several Sustainable Development Goals (SDGs). Fisheries help to fight poverty (SDG 1), contribute to zero hunger (SDG 2), are one of the best components for good health (SDG 3), and directly or indirectly employ a significant number of people (SDG 8). However, fisheries also constitute a serious issue for SDG 14—Life below Water—by overexploiting marine resources, contributing to marine pollution, damaging and/or destroying environments, and endanger biodiversity.

4.6.1 Fisheries Related Targets of SDG 14—Life Below Water

Most coastal fishery resources are heavily exploited as a consequence of the growing demand. In many cases, it is the failure of the governance systems that cope with human population growth and technological development that leads to overexploitation (Purcell et al. 2016; Hanich et al. 2018). The poor state of coastal resources is a multi-dimensional problem that the different targets of SDG 14 can address.

The first target of SDG 14 (14.1) is to reduce marine pollution of all kinds, particularly from land-based activities, including marine debris and nutrient pollution. Countries around the world are taking action to significantly reduce use of plastic by

2030, and many have already started by proposing or imposing rules on certain single-use plastics (plastic bags, straws, boxes, and other). Fisheries are a main contributor of marine plastics, mainly because of accidental loss or intentional disposal of old gear. This contributes to ingestion of macro and micro-plastics in some trophic levels and to the so-called ghost gear, which are responsible for the entrapment, entanglement and death of a significant number of animals. Educational programs directed to stakeholders and legislation need to be implemented worldwide, at national and international levels, to prevent marine plastics, as well as research on alternative materials and fishing practices.

Marine and coastal ecosystems need to be protected and restored (SDG 14.2), as well as to be conserved, based on the best available scientific information (SDG 14.5). As a complement to the large toolbox of input and output controls used in fisheries management, marine protected areas (MPAs) can be a useful tool for biodiversity conservation. According to the UNEP-WCMC and IUCN (2021) report, at the end of 2019, 17% of coastal waters under national jurisdiction (200 nautical miles from shore) were covered by protected areas, more than doubling in extent since 2010. However, many of these are probably non-operational MPAs. Some countries offer good settings for the application of MPAs, for example, Palau, a small island state in the Pacific, where about 80% of the nation's maritime territory has become a marine sanctuary. This makes it the sixth largest protected area of the world (Pew Charitable Trusts 2019). The reserve is spatially disaggregated, with an exploitable area dedicated to local fishermen and small-scale commercial fisheries.

Owing to increasing demand, the state of global fishery resources continues to decline, although at a reduced rate. Overfishing, illegal, unreported and unregulated (IUU) fishing, as well as destructive fishing practices need to end to achieve proper sustainability (SDG 14.4). The Port State Measures Agreement (PSMA) is the first binding international agreement specifically targeted to prevent, deter and eliminate IUU fishing. The Agreement entered into force in 2016, and currently it includes 66 members (FAO 2021c). However, more concerted efforts are needed (UN 2021).

Many industrial fisheries around the world are largely subsidized. Certain forms of industrial subsidies should be eliminated, if contributing to overcapacity, overfishing and to IUU fishing. However, there may be a need for special treatment for developing and least developed countries, and this mechanism should be an integral part of the World Trade Organization (WTO) fisheries subsidies negotiation (SDG 14.6). In areas where coastal fisheries are predominantly for domestic consumption, aid conditional upon access or trade must be carefully considered because artisanal fisheries aid is not covered by the WTO. Many coastal regions rely on development assistance to assist artisanal and subsistence fishers that do not have the necessary capital (Govan 2017). The Trade Ministers of the Organisation for Africa Caribbean and Pacific States (OACPS) also stressed the importance of coastal fisheries to their national economies, and the need to develop policies for their fishing capacity, under the special and differential treatment principle mandated in SDG 14.6, while preserving small-scale artisanal fishing as well as facilitating technical assistance and capacity building (Pacific Islands Forum 2021).

There is a need to increase economic benefits from the sustainable use of marine resources to small island developing states and least developed countries (SDG 14.7). The Pacific Small Island Developing States (SIDS) currently supply over 60% of the world's tuna supply, but are striving to implement measures to curb IUU fishing in their territories.

There is an urgent need to increase scientific knowledge, develop research capacity and transfer marine technology, considering the Intergovernmental Oceanographic Commission (IOC) Criteria and Guidelines on the Transfer of Marine Technology (CGTMT), to improve ocean health and to enhance the contribution of marine biodiversity to the development of developing countries, in particular the SIDS and least developed countries (SDG 14.A). The present IOC/CGTMT text states as a basic principle that the "*transfer of marine technology should be done free of charge or at a reduced rate for the benefit of the recipient state*" (IOC/ABE LOS 2005). Capacity development is particularly relevant with regard to fisheries research, oceanic aquaculture, and the exploration and exploitation of new marine compounds, as well as marketing of these.

Target SDG 14.B states the need to provide access for small-scale artisanal fishers to marine resources and markets. In Pacific Island countries, small-scale fishery resources have been under serious threat that continues to worsen, despite all the regional and national instruments. Therefore, there is a need for paradigm shift in fisheries management that recognizes the critical role of women and subsistence fishers, whose income increased by 33% between 2002 and 2008 (Narsey 2011). Of utmost importance is to implement and control effective policies that give strong rights to small-scale operations, in fishing, processing and marketing.

It is essential to enhance the conservation and sustainable use of the ocean and its resources by implementing international law as reflected in UNCLOS, which provides the legal framework needed (SDG 14.C). The contribution of sustainable marine capture fisheries remained relatively stable at the global level, with regional variations, representing the largest contribution to the GDP in Pacific SIDS and least developed countries (UNEP-WCMC and IUCN 2021). Regional cooperation has been the logical approach to address shared issues, such as COVID-19, IUU fishing, resource depletion and environment management, community-based fisheries management, innovative new methods such as aerial surveillance programs, data collection, analysis and validation for development of scientific, evidence-based economic and social impact assessments for informing management responses to fisheries.

Take-Home Messages:

- The 17 SDGs outline plans and action strategies that people at all levels of governance globally must adopt, use, and share.
- The SDGs promote the end of poverty, building of sustainable and equitable economic growth, addressing essential social needs, and protecting the environment.

- Coastal fisheries are of critical importance to several SDGs: fighting poverty (SDG 1), contributing to zero hunger (SDG 2), being one of the best components for good health (SDG 3), and ensuring work and economic growth (SDG 8).
- Coastal fisheries, however, also constitute a threat to SDG 14—Life Below Water—via overexploitation, marine pollution, environmental damage, and biodiversity threats.

4.7 Fisheries and the Governance of the Blue Economy

The ocean's sustainability is continuously threatened, considering that most of the world's marine fish stocks are now fully exploited, overexploited or depleted (FAO 2018; Pauly and Zeller 2019). Under this scenario, there is no room for the development of new coastal fisheries but, instead, we need a transformative approach that delivers infrastructure and policies to building healthy, clean and affordable communities, creating jobs, supporting businesses, producing renewable energy, and curtailing greenhouse gasses. The Blue Economy is a change agent and underpins the next big economic wave. Establishing a global Blue Economy—equitable, sustainable, and viable ocean sectors—would be transformative, but most importantly, the social equity goals at its core must fundamentally change how ocean development and management are approached and maintained (Cisneros-Montemayor et al. 2019). Furthermore, the impact of climate change on fisheries is projected to be mostly due to changes in life cycles, abundances, and distribution of marine species, that all will directly influence the availability of local seafood and income opportunities (Perry et al. 2005; Pörtner et al. 2014). For fisheries around the world, therefore, it will be crucial to be explicit about how equity under a Blue Economy looks and how it can be achieved, primarily because indicators for equity are continuously challenged, particularly in small-scale fisheries (Bennett et al. 2021a). Small-scale fisheries have an "iconic" role within the debates on international development and fisheries, as "they stand for counternarratives of social justice and ecological sustainability" (Johnson 2006).

The need to build equity-centered capacity in a Blue Economy and what it means for all sectors involved (including fisheries) is crucial to address concerns about integration, inclusion, equity, and active participation of all sectors. However, one of the most obvious obstacles is the lack of agreed-upon goals for the development of marine and aquatic resources (Voyer et al. 2018). For some, this implies the need for a paradigm shift regarding the need for growth and the transformation of ocean governance and a greater representation of small islands developing states (SIDS), civil society organizations, and indigenous peoples (Bennett et al. 2019; Decker-Sparks and Sliva 2019). This inclusion of communities and stakeholders in decision-making processes can also help redress historical injustices beyond fisheries management itself (Von der Porten et al. 2019). However, others have expressed the need to promote a Blue Economy to support and grow the maritime sector and maximize the economic benefits of marine and aquatic resources. The latter approach often lacks the notion of an economy that fosters sustainability, equity and inclusion, focusing on a neoliberal and capitalist model of resource use that can further marginalize vulnerable peoples through “ocean grabbing” (Bennett et al. 2015).

The Blue Economy concept aims at emphasizing the sustainable use of the ocean and its resources for economic, social, and environmental development (UNCTAD 2014). This requires better understanding of the ocean and how it works, the many uses and their impacts. Equity-centered capacity in a Blue Economy should provide the lens, the technology and the understanding (or context) of its complexity to develop specific strategies that support well-being for all at local and regional levels as they operate in a changing coastal and marine environment under a changing climate. Also, blue economy should build upon a vision and goals of the wide array of sectors involved to aim at sustainable practices within an equitable economy. And in its ambition, it should link to policies specifying clear goals for key enabling conditions to address systemic dis-functionalities to establish the foundation for equitable transformation and achieving sustainable development (Cisneros-Montemayor et al. 2021).

Research indicates that only fisheries that are well managed can make a long-term contribution to the blue economy, making governance reform and sound policies key components of a transition toward a blue economy (WB and UNDESA 2017). A history of mismanagement of marine activities and minimal to no engagement with relevant coastal communities and stakeholders has resulted in an estimated 60% of the world’s major marine ecosystems degraded (UNEP 2011). Bennett et al. (2021a) recognize the importance of resource protection under spatial-based and access rights management strategies together with the recognition of livelihoods and policy mechanisms to foster and ensure equitable distribution of economic benefits. This comes in handy particularly when we focus on local scales where socio-economic and environmental issues are intensifying under new scenarios of climate change and there is an urgent need to understand local people’s needs and concerns in their own socio-political context. Fisheries is one of the most established parts of the Blue Economy. A full integration with the new industries and cultures will not be easy to achieve, but it does represent a transformative way forward for future ecosystems and societies.

Take-Home Messages:

- All social sectors must have effective participation in policy planning and implementation for a Blue Economy. Policies that include minorities and disadvantaged groups tend to gain wider support and be more effective in the long term.
- Many coastal fisheries are at their maximum capacity or are overexploited, but necessary improvements to their management must address historical and current inequities to avoid further impacting vulnerable populations.
- Bulk resources and scientific knowledge alone will not automatically lead to sustainable development, and improved well-being. It is critical to support specific enabling conditions to their application.
- Ocean development and management must directly follow from the needs and goals of the people who are most directly connected to the ocean.

References

Aburto-Oropeza O, López-Sagástegui C, Moreno-Báez M et al (2018) Endangered species, ecosystem integrity, and human livelihoods. Conserv Lett 11(1):e12358

Adão AC, Breen M, Eichert M, Borges TC (2018) By-catch species susceptibilities and potential for survival in Algarve (southern Portugal) deep-water crustacean trawl fishery. Sci Mar 82S1:141–149

Alverson DL, Freeberg MH, Murawski SA et al (1994) A global assessment of fisheries bycatch and discards. FAO Fisheries Technical Paper, No. 339. Rome, FAO

Bakun A, Black BA, Bograd SJ et al (2015) Anticipated effects of climate change on coastal upwelling ecosystems. Curr Clim Change Rep 1(2):85–93

Barange M, Bahri T, Beveridge MCM et al (eds.) (2018) Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options. FAO Fisheries and Aquaculture Technical Paper No. 627. Rome, FAO

Barceló C, White JW, Botsford LW et al (2021) Projecting the timescale of initial increase in fishery yield after implementation of marine protected areas. ICES J Mar Sci 78(5):1860–1871. https://doi.org/10.1093/icesjms/fsaa233

Bell JD, Kronen M, Vunisea A et al (2009) Planning the use of fish for food security in the Pacific. Mar Policy 33:64–76

Bennett NJ, Ban NC, Schuhbauer A et al (2021a) Access rights, capacities and benefits in small-scale fisheries: insights from the Pacific Coast of Canada. Mar Policy 130:104581. https://doi.org/10.1016/j.marpol.2021.104581

Bennett NJ, Blythe J, Cisneros-Montemayor AM et al (2019) Just transformations to sustainability. Sustainability-Basel 11(14):3881. https://doi.org/10.3390/su11143881

Bennett NJ, Blythe J, White CS et al (2021b) Blue growth and blue justice: ten risks and solutions for the ocean economy. Mar Policy 125:104387. https://doi.org/10.1016/j.marpol.2020.104387

Bennett NJ, Govan H, Satterfield T (2015) Ocean grabbing. Mar Policy 57:61–68

Blaha F, Katafono K (2020) Blockchain application in seafood value chains. FAO Fisheries and Aquaculture Circular No. 1207, Rome, FAO. https://doi.org/10.4060/ca8751en

Borges TC, Erzini K, Bentes L et al (2001) By-catch and discarding practices in five Algarve (southern Portugal) métiers. J Appl Ichthyol 17:104–114

Boughattas F, Le Fur B, Karoui R (2019) Identification and quantification of tuna species in canned tunas with sunflower medium by means of a technique based on front face fluorescence spectroscopy (FFFS). Food Control 101:17–23. https://doi.org/10.1016/j.foodcont.2019.02.003

Burke WT (1994) The new international law of fisheries: UNCLOS 1982 and beyond. Clarendon Press, Oxford

Campos A, Fonseca P, Pilar-Fonseca T et al (2015) Survival of trawl-caught Norway lobster (*Nephrops norvegicus* L.) after capture and release—potential effect of codend mesh type on survival. Fish Res 172:415–422

Carvalho DC, Palhares RM, Drummond MG et al (2017) Food metagenomics: next generation sequencing identifies species mixtures and mislabelling within highly processed cod products. Food Control 80:183–186. https://doi.org/10.1016/j.foodcont.2017.04.049

Cashion T, Le Manach F, Zeller DD et al (2017) Most fish destined for fishmeal production are food-grade fish. Fish Fish 18(5):837–844

Castro M, Araújo A, Monteiro P (2005) Fate of discards from deep water crustacean trawl fishery off the south coast of Portugal. New Zeal J Mar Fresh 39:437–446

Cawthorn D-M, Baillie C, Mariani S (2018) Generic names and mislabelling conceal high species diversity in global fisheries markets. Conserv Lett 11(5):e12573. https://doi.org/10.1111/conl.12573

Cheung WW, Jones MC, Lam VW et al (2017) Transform high seas management to build climate resilience in marine seafood supply. Fish Fish 18(2):254–263

Cheung WWL, Watson R, Pauly D (2013) Signature of ocean warming in global fisheries catch. Nature 497:365–368

Ciannelli L, Neuheimer AB, Stige LC et al (2021) Ontogenetic spatial constraints of sub-arctic marine fish species. Fish Fish 23(2):342–357. https://doi.org/10.1111/faf.12619
Cisneros-Montemayor AM, Becerril-García EE, Berdeja-Zavala O et al (2020) Shark ecotourism in Mexico: scientific research, conservation, and contribution to a blue economy. Adv Mar Biol 85(1):71–92. https://doi.org/10.1016/bs.amb.2019.08.003
Cisneros-Montemayor AM, Moreno-Báez M, Reygondeau G et al (2021) Enabling conditions for an equitable and sustainable blue economy. Nature 591:396–401. https://doi.org/10.1038/s41586-021-03327-3
Cisneros-Montemayor AM, Moreno-Báez M, Voyer M et al (2019) Social equity and benefits as the nexus of a transformative blue economy: a sectoral review of implications. Mar Policy 109:103702
Cisneros-Montemayor AM, Ota Y, Bailey M et al (2020) Changing the narrative on fisheries subsidies reform: enabling transitions to achieve SDG 14.6 and beyond. Mar Policy 117:103970
Clark CW, Clark CW (2006) The worldwide crisis in fisheries: economic models and human behavior. Cambridge University Press
Costa ME, Erzini K, Borges TC (2008) Bycatch of crustacean and fish bottom trawl fisheries from southern Portugal (Algarve). Sci Mar 72(4):801–814. https://doi.org/10.3989/scimar.2008.72n4801
Coulter A, Cashion T, Cisneros-Montemayor AM et al (2020) Using harmonized historical catch data to infer the expansion of global tuna fisheries. Fish Res 221:105379
Course GP, Pierre J, Howell BK (2020) What's in the net? Using camera technology to monitor, and support mitigation of wildlife bycatch in fisheries. WWF (online). https://wwfeu.awsassets.panda.org/downloads/whatsinthenetfinal.pdf
Crespo GO, Dunn DC, Gianni M et al (2019) High-seas fish biodiversity is slipping through the governance net. Nature Ecol Evol 3(9):1273–1276. https://doi.org/10.1038/s41559-019-0981-4
Daw T, Adger WN, Brown K et al (2009) Climate change and capture fisheries: potential impacts, adaptation and mitigation. In: Cochrane K, De Young C, Soto D et al (eds) Climate change implications for fisheries and aquaculture: overview of current scientific knowledge. FAO Fisheries and Aquaculture Technical Paper. No. 530. Rome, FAO, pp 107–150
Dayton PK, Thrush SF, Agardy MT et al (1995) Environmental effects of marine fishing. Aquat Conserv 5(3):205–232. https://doi.org/10.1002/aqc.3270050305
Decker-Sparks JL, Sliva SM (2019) An intersectionality-based analysis of high seas policy making stagnation and equity in United Nations negotiations. J Community Pract 27(3–4):260–278
Duncan MI, Bates AE, James NC et al (2019) Exploitation may influence the climate resilience of fish populations through removing high performance metabolic phenotypes. Sci Rep-UK 9(1):1–10. https://doi.org/10.1038/s41598-019-47395-y
EC (2013a) Commission Regulation (EC) No. 1379/2013 of the European Parliament and of the Council of 11 December 2013, on the common organization of the markets in fishery and aquaculture products, amending Council Regulations (EC) No. 1184/2006 and (EC) No. 1224/2009 and repealing Council Regulation (EC) No. 104/2000. Official Journal of the European Union L. 354
EC (2013b) Regulation (EU) No. 1380/2013 of the European Parliament and of the Council of 11 December 2013 on the Common Fisheries Policy, amending Council Regulations (EC) No. 1954/2003 and (EC) No. 1224/2009 and repealing Council Regulations (EC) No. 2371/2002 and (EC) No. 639/2004 and Council Decision 2004/585/EC
EC (2021) The EU Blue Economy Report. 2021. Publications Office of the European Union. Luxembourg. https://data.europa.eu/doi/10.2771/5187
Eddy TD, Lam VW, Reygondeau G et al (2021) Global decline in capacity of coral reefs to provide ecosystem services. One Earth 4(9):1278–1285. https://doi.org/10.1016/j.oneear.2021.08.016
Erdner DL, Dyble J, Parsons ML et al (2008) Centers for oceans and human health: a unified approach to the challenge of harmful algal blooms. Environ Health 7(S2). https://doi.org/10.1186/1476-069X-7-S2-S2
Erzini K, Bentes L, Coelho R et al (2008) Catches in ghost-fishing octopus and fish traps in the northeastern Atlantic Ocean, Algarve, Portugal. Fish B-NOAA 106:321–327

Erzini K, Costa ME, Bentes L et al (2002) A comparative study of the species composition of discards from five fisheries from the Algarve (southern Portugal). Fisheries Manag Ecol 9:31–40
Erzini K, Monteiro CC, Ribeiro J et al (1997) An experimental study of gill net and trammel net “ghost fishing” in the Algarve (southern Portugal). Mar Ecol Prog Ser 158:257–265
Ewell C, Hocevar J, Mitchell E et al (2020) An evaluation of regional fisheries management organization at-sea compliance monitoring and observer programs. Mar Policy 115:103842
Fagan B (2017) Fishing: how the sea fed civilization. Yale University Press
FAO (1955) The state of food and agriculture. Review of a Decade and Outlook. Rome, FAO
FAO (1995) Code of conduct for responsible fisheries. FAO, Rome, 41p
FAO (2015) Voluntary guidelines for securing sustainable small-scale fisheries in the context of food security and poverty eradication. Rome, FAO. http://www.fao.org/fishery/ssf/guidelines/en
FAO (2018) The state of world fisheries and aquaculture 2018. Meeting the sustainable development goals. Rome, FAO
FAO (2020) The state of world fisheries and aquaculture 2020. Sustainability in action. Rome, FAO. https://doi.org/10.4060/ca9229en
FAO (2021a) Fishery and aquaculture statistics. Global capture production 1950–2019 (FishstatJ). In: FAO Fisheries Division (online). Rome. Updated 2021a. www.fao.org/fishery/statistics/software/fishstatj/en
FAO (2021b) Food loss and waste in fish value chains (online). Rome. http://www.fao.org/flw-in-fish-value-chains/value-chain/en/
FAO (2021c) Agreement on Port State Measures (PSMA) (online). https://www.fao.org/port-state-measures/background/history/en/
FAO/WHO (2011) Report of the Joint FAO/WHO expert consultation on the risks and benefits of fish consumption. Rome, FAO; Geneva, World Health Organization, 50p
Finley C, Oreskes N (2013) Maximum sustained yield: a policy disguised as science. ICES J Mar Sci 70(2):245–250
Fonseca P, Campos A, Larsen RB et al (2005) Using a modified Nordmøre grid for by-catch reduction in the Portuguese crustacean-trawl fishery. Fish Res 71:223–239
Gabriel O, Lange K, Dahm E et al (2005) Fish catching methods. Blackwell Publishing
Garcia SM, Zerbi A, Aliaume C et al (2003) The ecosystem approach to fisheries: issues, terminology, principles, institutional foundations, implementation and out-look. FAO Fish. Tech. Pap. No. 443, Rome
Gillett RD (2016) Fisheries in the Economies of Pacific Island Countries and Territories SPC, FFA, AUSAID (online). https://www.spc.int/sites/default/files/wordpresscontent/wp-content/uploads/2016/11/Gillett_16_Benefish-fisheries-in-economies-of-pacific-countries.pdf
Gilman E, Chopin F, Suuronen P et al (2016) Abandoned, lost and discarded gillnets and trammel nets: methods to estimate ghost fishing mortality, and the status of regional monitoring and management. FAO Fish. Tech. Pap. No. 600. Rome
Giron-Nava A, Lam VWY, Aburto-Oropeza O et al (2021) Sustainable fisheries are essential but not enough to ensure well-being for the world’s fishers. Fish Fish 22(4):812–821. https://doi.org/10.1111/faf.12552
Gonçalves JMS, Bentes L, Coelho R et al (2008) Non-commercial invertebrate discards in an experimental trammel net fishery. Fisheries Manag Ecol 15:199–210. https://doi.org/10.1111/j.1365-2400.2008.00607.x
Goñi R (1998) Ecosystem effects of marine fisheries: an overview. Ocean Coast Manage 40:37–64. https://doi.org/10.1016/S0964-5691(98)00037-4
Goñi R, Badalamenti F, Tupper MH (2011) Fisheries—effects of marine protected areas on local fisheries: evidence from empirical studies. In: Marine protected areas: A multidisciplinary approach, pp 72–98. https://doi.org/10.1017/CBO9781139049382.006
Govan H (2017) Ocean governance—our sea of Islands. In: Katafono R (ed) A sustainable future for small states: Pacific 2050 (forthcoming). Commonwealth Secretariat, London
Greenberg P, Worm P (2015) When humans declared war on fish. *The New York Times*, May 8

Griffiths AM, Sotelo CG, Mendes R et al (2014) Current methods for seafood authenticity testing in Europe: is there a need for harmonisation? Food Control 45:95–100. https://doi.org/10.1016/j.foodcont.2014.04.020

Grorud-Colvert K, Sullivan-Stack J, Roberts C et al (2021) The MPA guide: a framework to achieve global goals for the ocean. Science 373(6560):eabf0861

Haapasaari P, Kulmala S, Kuikka S (2012) Growing into interdisciplinarity: how to converge biology, economics, and social science in fisheries research? Ecol Soc 17(1):6. https://doi.org/10.5751/ES-04503-170106

Hanich Q, Wabnitz CCC, Otac Y et al (2018) Small-scale fisheries under climate change in the Pacific Islands region. Mar Policy 88:279–284

Hare JA, Morrison WE, Nelson MW et al (2016) A vulnerability assessment of fish and invertebrates to climate change on the Northeast U.S. continental shelf. PLoS One 11(2):e0146756. https://doi.org/10.1371/journal.pone.0146756

Harper S, Zeller D, Hauzer M et al (2013) Women and fisheries: contribution to food security and local economies. Mar Policy 39:56–63

Hilborn R, Akselrud CA, Peterson H et al (2021) The trade-off between biodiversity and sustainable fish harvest with area-based management. ICES J Mar Sci 78(6):2271–2279

Ho JKI, Puniamoorthy J, Srivathsan A et al (2020) MinION sequencing of seafood in Singapore reveals creatively labelled flatfishes, confused roe, pig DNA in squid balls, and phantom crustaceans. Food Control 112:107144. https://doi.org/10.1016/j.foodcont.2020.107144

Huang Y-R, Yin M-C, Hsieh Y-L et al (2014) Authentication of consumer fraud in Taiwanese fish products by molecular trace evidence and forensically informative nucleotide sequencing. Food Res Int 55:294–302. https://doi.org/10.1016/j.foodres.2013.11.027

IOC/ABE LOS (2005) IOC Criteria and Guidelines on the Transfer of Marine Technology (CGTMT). Intergovernmental Oceanographic Commission (IOC) Advisory Body of Experts on the Law of the Sea. UNESCO

Jennings S, Kaiser MJ (1998) The effects of fishing on marine ecosystems. Adv Mar Biol 34:201–352

Jennings S, Kaiser MJ, Reynolds JD (2001) Marine fisheries ecology. Blackwell Science Lda

Jentoft S, Chuenpagdee R, Barragán-Paladines MJ et al (eds) (2017) The small-scale fisheries guidelines: global implementation, vol 14. Springer, Amsterdam

Johnson DS (2006) Category, narrative, and value in the governance of small-scale fisheries. Mar Policy 30(6):747–756

Jordaan GL, Santos J, Groeneveld JC (2020) Shark discards in selective and mixed-species pelagic longline fisheries. PLoS One 15(8):e0238595

Kadagi NI, Wambiji N, Belhabib D et al (2021) Ocean safaris or food: characterizing competitive interactions between recreational and artisanal billfish fisheries on the coast of Kenya. Ocean Coast Manage 201:105432. https://doi.org/10.1016/j.ocecoaman.2020.105432

Kelleher K (2005) Discards in the world's marine fisheries: an update. FAO Fisheries Technical Paper. No. 470. Rome, FAO, 131p

Kroodsma DA, Mayorga J, Hochberg T et al (2018) Tracking the global footprint of fisheries. Science 359(6378):904–908. https://doi.org/10.1126/science.aao5646

Larkin PA (1977) An epitaph for the concept of maximum sustained yield. T Am Fish Soc 106(1):1–11

Marchetti P, Mottola A, Piredda R et al (2020) Determining the authenticity of shark meat products by DNA sequencing. Foods 9:1194. https://doi.org/10.3390/foods9091194

Marean CW, Bar-Matthews M, Bernatchez J et al (2007) Early human use of marine resources and pigment in South Africa during the Middle Pleistocene. Nature 449:905–908. http://www.nature.com/doifinder/10.1038/nature06204

Mazor T, Pitcher CR, Rochester W et al (2021) Trawl fishing impacts on the status of seabed fauna in diverse regions of the globe. Fish Fish 22:72–86. https://doi.org/10.1111/faf.12506

Miller DD, Ota Y, Sumaila UR et al (2018) Adaptation strategies to climate change in marine systems. Glob Change Biol 24(1):e1–e14

Morais P, Borges TC, Carnall V et al (2007) Trawl-induced bottom disturbances off the south coast of Portugal: direct observations of the "Delta" manned-submersible on the Submarine Canyon of Portimão. Mar Ecol-P S Z N I 28(Suppl. 1):112–122. https://doi.org/10.1111/j.1439-0485.2007.00175.x

Munguia-Vega A, Weaver AH, Domínguez-Contreras JF et al (2021) Multiple drivers behind mislabeling of fish from artisanal fisheries in La Paz, Mexico. Peerj 9:e10750

Narsey W (2011) Report on the 2008–09 household income and expenditure survey, Suva

Nguyen T (2020) Ghost fishing gear: a major source of marine plastic pollution. Hillnotes. Library of Parliament. Canada (online). https://hillnotes.ca/2020/01/30/ghost-fishing-gear-a-major-source-of-marine-plastic-pollution/

Pacific Islands Forum (2021) Pacific ministers engage on fisheries subsidies negotiations. https://www.forumsec.org/2021/06/25/pacific-ministers-engage-on-fisheries-subsidies-negotiations/

Palacios-Abrantes J, Reygondeau G, Wabnitz CC et al (2020) The transboundary nature of the world's exploited marine species. Sci Rep-UK 10(1):1–12

Palomares ML, Pauly D (2019) Coastal Fisheries: the past, present, and possible futures. In: Wolanski E, Day JW, Elliott M et al (eds) Coasts and Estuaries, pp 569–576. https://doi.org/10.1016/B978-0-12-814003-1.00032-0

Pauly D, Zeller D (2016) Toward a comprehensive estimate of global marine fisheries catches. In: Global atlas of marine fisheries: a critical appraisal of catches and ecosystem impacts, Island Press, pp 171–181

Pauly D, Zeller D (2019) Agreeing with FAO: comments on SOFIA 2018. Mar Policy 100:332–333. https://doi.org/10.1016/j.marpol.2018.12.009

Pecl GT, Ward TM, Doubleday ZA et al (2014) Rapid assessment of fisheries species sensitivity to climate change. Clim Change 127(3–4):505–520. https://doi.org/10.1007/s10584-014-1284-z

Pérez-Roda MA (ed.), Gilman E, Huntington T, Kennelly SJ et al (2019) A third assessment of global marine fisheries discards. FAO Fisheries and Aquaculture Technical Paper No. 633. Rome, FAO, 78p

Perry AL, Low PJ, Ellis JR et al (2005) Climate change and distribution shifts in marine fishes. Science 308(5730):1912–1915

Petersson MT (2020) Transparency in global fisheries governance: the role of non-governmental organizations. Mar Policy: 104128

Pew Trust (2019) Transhipment in the Western and Central Pacific. Greater understanding and transparency of carrier vessel fleet dynamics would help reform management. Report September 12, 2019 (online). https://www.pewtrusts.org/en/research-and-analysis/reports/2019/09/transshipment-in-the-western-and-central-pacific#:~:text=

Pörtner H-O, Karl DM, Boyd PW et al (2014) Ocean systems. 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. Cambridge University Press, pp 411–484

Probst WN (2019) How emerging data technologies can increase trust and transparency in fisheries. ICES J Mar Sci 77:1286–1294

Purcell SW, Ngaluafe P, Aram AT et al (2016) Trends in small-scale artisanal fishing of sea cucumbers in Oceania. Fish Res 183:99–110

Ritzman J, Brodbeck A, Brostrom S et al (2018) Economic and sociocultural impacts of fisheries closures in two fishing-dependent communities following the massive 2015 U.S. West Coast harmful algal bloom. Harmful Algae 80:35–45. https://doi.org/10.1016/j.hal.2018.09.002

Roser M, Ritchie H, Ortiz-Ospina E (2013) World population growth. Published online at OurWorldInData.org. https://ourworldindata.org/world-population-growth

Rousseau Y, Watson RA, Blanchard JL et al (2019) Evolution of global marine fishing fleets and the response of fished resources. P Natl Acad Sci USA 116(25):12238–12243. https://doi.org/10.1073/pnas.1820344116

Royce WF (1996) Introduction to the practice of fishery science. Academic Press

Saila SB (1983) Importance and assessment of discards in commercial fisheries. FAO Fish Circ, 765
Sala E, Mayorga J, Costello C et al (2018) The economics of fishing the high seas. Sci Adv 4(6):eaat2504
Santos J, Groeneveld JC, MacKay F et al (in press) Seasonal and decadal change in socio-ecological systems of Western Indian Ocean estuaries: A regional assessment. Afr J Mar Sci
Schuhbauer A, Chuenpagdee R, Cheung WW et al (2017) How subsidies affect the economic viability of small-scale fisheries. Mar Policy 82:114–121
Schwinghamer P, Gordon DC, Rowell TW et al (1998) Effects of experimental otter trawling on surficial sediment properties of a sandy-bottom ecosystem on the Grand Banks of Newfoundland. Conserv Biol 12:1215–1222
Short R, Gurung R, Rowcliffe M et al (2018) The use of mosquito nets in fisheries: a global perspective. PLoS One 13(1):e0191519. https://doi.org/10.1371/journal.pone.0191519
Smith CJ, Rumohr H, Karakassis I et al (2003) Analyzing the impact of bottom trawls on sedimentary seabeds with sediment profile imagery. J Exp Mar Biol Ecol 285–286:479–496. https://doi.org/10.1016/50022-0981(02)00545-2
Smith PJ (1994) Genetic diversity of marine fisheries resources: possible impacts of fishing. FAO Fisheries Technical Paper, 344. Rome, FAO
Smylie M (2015) The perilous catch: a history of commercial fishing. TJ International, Lda
SPC (2008) Fish and Food security, Policy Brief 1/2008. Secretariat of the Pacific Community. Nouméa, New Caledonia
Sumaila UR, Lam VW, Miller DD et al (2015) Winners and losers in a world where the high seas is closed to fishing. Sci Rep 5(1):1–6
Sumaila UR, Skerritt DJ, Schuhbauer A et al (2021) WTO must ban harmful fisheries subsidies. Science 374(6567):544–544. https://doi.org/10.1126/science.abm1680
UN (1982) United Nations Convention on the Law of the Sea (UNCLOS). Third United Nations Conference on the Law of the Sea. Division for the Ocean Affairs and the Law of the Sea. https://www.un.org/Depts/los/convention_agreements/texts/unclos/unclos_e.pdf
UN (2016) Atlas of the oceans: human settlements on the coast. 2002–2016 (online). http://www.oceansatlas.org/subtopic/en/c/114/#jfmulticontent_c321051-3
UN (2021) The sustainable development goals report. United Nations, Department of Economic and Social Affairs
UNCTAD (2014) Sustainable development first: delivering results. United Nations Conference on Trade and Development—UNCTAD—Annual Report
UNEP (2011) Taking steps toward marine and coastal ecosystem-based management—an introductory guide. UNEP Regional Seas Reports and Studies No. 189
UNEP-WCMC and IUCN (2021) Protected Planet Report 2020. UNEP-WCMC and IUCN: Cambridge UK; Gland, Switzerland. https://livereport.protectedplanet.net/
Veneza I, Silva R, Freitas L et al (2018) Molecular authentication of Pargo fillets *Lutjanus purpureus* (Perciformes: Lutjanidae) by DNA barcoding reveals commercial fraud. Neotrop Ichthyol 16(1):e170068. https://doi.org/10.1590/1982-0224-20170068
Vierros MK, Harrison AL, Sloat MR et al (2020) Considering indigenous peoples and local communities in governance of the global ocean commons. Mar Policy 119:104039. https://doi.org/10.1016/j.marpol.2020.104039
von der Porten S, Ota Y, Cisneros-Montemayor A et al (2019) The role of indigenous resurgence in marine conservation. Coast Manage 47(6):527–547
Voyer M, Quirk G, McIlgorm A et al (2018) Shades of blue: what do competing interpretations of the Blue Economy mean for oceans governance? J Environ Pol Plan 20(5):595–616. https://doi.org/10.1080/1523908X.2018.1473153
Wainwright BJ, Ip YCA, Neo ML et al (2018) DNA barcoding of traded shark fins, meat and mobulid gill plates in Singapore uncovers numerous threatened species. Conserv Genet 19(6):1393–1399. https://doi.org/10.1007/s10592-018-1108-1

Walters CJ, Martell SJ (2020) Fisheries ecology and management. Princeton University Press, Princeton

Watson R (2017) A database of global marine commercial, small-scale, illegal and unreported fisheries catch 1950–2014. Sci Data 4:170039. https://doi.org/10.1038/sdata.2017.39

WB, UNDESA (2017) The potential of the blue economy: increasing long-term benefits of the sustainable use of marine resources for Small Island developing states and coastal least developed countries. World Bank—WB, and United Nations Department of Economic and Social Affairs—UNDESA. World Bank, Washington, DC

Weber CT, Borit M, Aschan M (2019) An interdisciplinary insight into the human dimension in fisheries models: a systematic literature review in a European Union context. Front Mar Sci 6:369. https://doi.org/10.3389/fmars.2019.00369

White C, Costello C (2014) Close the high seas to fishing? Plos Biol 12(3):e1001826

Wilson RJ, Sailley SF, Jacobs ZL et al (2021) Large projected reductions in marine fish biomass for Kenya and Tanzania in the absence of climate mitigation. Ocean Coast Manage 215:105921. https://doi.org/10.1016/j.ocecoaman.2021.105921

WOR (2013) WOR 2 the future of fish—the fisheries of the future. World Ocean Review. Living with the oceans. Maribus gGmbH Publisher, Hamburg

Zeller D, Cashion T, Palomares MLD et al (2018) Global marine fisheries discards: a synthesis of reconstructed data. Fish Fish 19(1):30–39

Zeller D, Pauly D (2019) Viewpoint: back to the future for fisheries, where will we choose to go? Global Sustainability 2(e11):1–8. https://doi.org/10.1017/sus.2019.8

Chapter 5
Effects of Groundwater Extraction and River Regulation on Coastal Freshwater Resources

Guangquan Chen, Bochau Xu, Butsawan Bidorn, and William C. Burnett

Abstract With increasing coastal development based on the so-called "blue economy", freshwater resources in nearshore areas have come under increased pressure. Improved coastal zone management is needed to sustain coastal ecosystems and resource use, as well as support for industries and infrastructure related to blue economic development. We present and synthesize here case studies of how groundwater extraction and river regulation schemes (including dam construction) have affected natural coastal environments. This includes consideration of some unanticipated consequences of these activities. Dams, even when located hundreds of kilometers upstream, can still result in significant environmental changes to estuaries, deltas, and adjacent seas. Modifications and engineering of rivers has resulted in changing volumes and compositions of river flow and submarine groundwater discharge. Groundwater and/or hydrocarbon extraction in deltaic settings often leads to subsidence, which results in flooding and coastal erosion. The examples in this chapter, drawn mostly from Asia, illustrate issues that are developing worldwide. We show how application of the most up-to-date scientific approaches, such as natural geochemical tracers (e.g., radium isotopes), can provide useful information

---

G. Chen (✉)
Key Laboratory of Coastal Science and Integrated Management, First Institute of Oceanography, Ministry of Natural Resources, Qingdao 266061, China
e-mail: chenguangquan@fio.org.cn

B. Xu
Frontiers Science Center for Deep Ocean Multispheres and Earth System, and Key Laboratory of Marine Chemistry Theory and Technology, Ministry of Education, Ocean University of China, Qingdao 266100, China
e-mail: xubc@ouc.edu.cn

B. Bidorn
Department of Water Resources Engineering, and WISE Research Unit, Chulalongkorn University, Bangkok 10330, Thailand
e-mail: butsawan.b@gmail.com

W. C. Burnett
Department of Earth, Ocean and Atmospheric Science, Florida State University, Tallahassee, FL 32306, USA
e-mail: wburnett@fsu.edu

E. R. Urban Jr. and V. Ittekkot (eds.), *Blue Economy*,
https://doi.org/10.1007/978-981-19-5065-0_5

in support of sustainable management actions. These issues are presented to call for more science-based and ecosystem-inclusive management plans to achieve “blue economy” goals.

Keywords Coastal freshwater use · Ground water extraction · Coastal subsidence · River regulation · Isotope geochemistry

5.1 Introduction

Coastal zones are at the interface between land and sea and are influenced by both marine and terrestrial processes that are highly dynamic and continually change over time. Globally, nearly 40% of the world’s population lives within 100 km of a coastline, an area that accounts for only 22% of the world’s land area (Rosen 2000). The population in coastal zones continues to rise, and natural ecosystems are under increasingly greater pressure. For example, China has approximately 40% of its population and 56% of its total GDP located within coastal provinces (National Bureau of Statistics of China 2019).

There has been a dramatic increase in human activities in coastal zones around the world, as more and more nations base their national development on the so-called “blue economy”, that is, “the sustainable use of ocean resources for economic growth, improved livelihoods, and jobs while preserving the health of ocean ecosystems”[1] In this context, the management of coastal freshwater resources becomes critical not just as a resource for the day-to-day needs of the local coastal population, but also for the sustenance of coastal ecosystems and resources as well as the support of industries and infrastructure related to blue economic development.

Groundwater, the largest reservoir of unfrozen freshwater on Earth, is a critical resource. In the United States, groundwater supplies drinking water for more than 50% of the total population and about 99% of the rural population.[2] The largest use of groundwater, by far, is for irrigation. Perhaps because groundwater is out of sight, there are relatively few regulations protecting this valuable resource. In a recent paper, Jasechko and Perrone (2021) point out that more than half of the world’s major aquifers are being depleted, some of them at an alarming pace. Literally millions of wells are in danger of being pumped dry. Based on a data set of about 39 million wells they estimated that up to 20% of wells from 40 countries are at risk of running dry. This danger results from either long-term groundwater decline by over pumping, seasonal variation in water levels, or both. Long-term trends of large-scale water storage in the North China Plain and elsewhere—as shown by satellite GRACE (Gravity Recovery and Climate Experiment)—are clearly moving in a downward direction, as shown recently by Famiglietti and Ferguson (2021). This information shows that we need to rethink how groundwater resources are managed, especially those located in the coastal zone.

---

[1] www.worldbank.org/oceans.

[2] https://www.groundwater.org/get-informed/basics/groundwater.html.

Exploiting groundwater near the coast raises the additional problems of seawater intrusion and land subsidence. As we continually pump groundwater out of coastal wells, the recovered water eventually turns brackish and then saline. In some situations, the solution has been to implement desalinization procedures, usually by reverse osmosis. This is being done, for example, in the Tampa Bay, Florida area, where the largest desalinization plant in North America is located (Tampa Bay Water 2010). This seems like a somewhat surprising situation for a subtropical area with above-average rainfall. Sustainable approaches to freshwater supply, particularly in coastal areas of the developing world, must be implemented.

We consider in this chapter how groundwater extraction and river regulation schemes in the coastal zone affect the natural environment, including the unanticipated consequences of these activities. We also consider how the engineering of waterways via dam construction and other approaches influences the coastal environment. Dams, even if located hundreds of kilometers inland, can still result in significant environmental effects in the coastal zone and further offshore. Groundwater extraction in deltaic settings can lead to subsidence with resulting flooding and erosion of the shoreline. The examples in this chapter, mostly from Asia, illustrate issues that are developing worldwide. We present these issues in a call for more science-based and ecosystem-inclusive management plans, to achieve blue economy goals. Inadequate management of freshwater resources can hinder the establishment of blue economies by creating environmental problems that diminish the availability of blue economy resources.

5.2 Coastal Freshwater Resources

5.2.1 Climate Control of Groundwater Resources

Climatic factors are the main driving force of variability in the hydrologic cycle on multiple spatial and temporal scales (Sheffield and Wood 2008; Rasanen and Kummu 2013). Hydrologic processes can be impacted by variations in precipitation, drought frequency and intensity, snowmelt runoff, and streamflow (Vicente-Serrano et al. 2011). The links between groundwater levels and specific climatic indexes have been investigated in several locations, including Spain (Luque-Espinar et al. 2008), Argentina (Tanco and Kruze 2001), the United Kingdom (Jones and Banner 2003; Holman et al. 2009) and in different parts of the United States (Velasco et al. 2016). The four-leading atmospheric–ocean circulation systems that affect coastal interannual to multidecadal climate variability include the El Niño-Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), Pacific Decadal Oscillation (PDO), and the Atlantic Multidecadal Oscillation (AMO) (Ghil 2002; McCabe et al. 2004). High-frequency (synoptic to seasonal) climate variability creates short-term hydrologic responses, but groundwater levels and recharge are partially controlled by complex interactions of low-frequency (interannual to multidecadal) climate variability (Perez-Valdivia et al. 2012), and are not solely a function of temporal patterns in groundwater pumping. Different climate modes affect different areas of the world. For example, ENSO and PDO have a greater control than NAO and AMO on variability in groundwater levels across the United States (Kuss and Gurdak 2014). An improved understanding of the long-term fluctuations in groundwater availability that is influenced by low-frequency climate variability is essential for best informed management and policy decisions. This is particularly true within the context of the increasing use of groundwater for human consumption and irrigation (Wada et al. 2010). There is also a need to narrow the uncertainty of the effects of climate change and related impacts on groundwater quantity and quality (Hanson et al. 2006; Gurdak et al. 2012).

One promising scientific approach for understanding the effects of climate on groundwater resources involves analysis of the wavelet coherence between mean monthly groundwater levels in selected wells and monthly precipitation and tide levels at the nearest ocean station. The use of wavelet coherence can provide important insights in how the strength of groundwater teleconnections varies through time. The method of wavelet coherence analysis is detailed by Torrence and Compo (1998) and Grinsted et al. (2004). In an example from Shandong Province, the periodicity of groundwater levels was best described by precipitation (Chen 2013). The coherence between groundwater levels and precipitation appears throughout the spectra with the highest coherence found at 6-to-12-month periods. The groundwater level-precipitation lag is also about 1 year, with groundwater levels decreasing as precipitation decreases. The data from Shandong Province show that the wavelet coherence between groundwater and tidal levels show a continuously significant relationship on a 1-year scale and intermittent significance on scales of 1–6 months in the coastal zone. These results support the view that links do exist between groundwater levels and climate indices.

5.2.2 Coastal Groundwater Resources in China

The situation in China can serve as a case study for freshwater issues in many parts of the world. Several national hydrogeological surveys have been conducted in China since the 1950s, with the most recent being the National Groundwater Monitoring Project in 2019. It has been reported that the annual flux of groundwater recharge (replenishment) reaches 8.2×10^{11} m^3, of which 1.8×10^{11} m^3 is exploitable. The use of groundwater for irrigation, industrial, and domestic purposes has been steadily increasing in coastal regions. However, the distribution of groundwater is quite different between the northern and southern regions of China, which are separated by a geographical boundary called the Qin Mountains–Huai River Line. The available water resources per capita for the northern coastal provinces, such as Hebei and Shandong, are very low, comparable to several Middle Eastern countries.

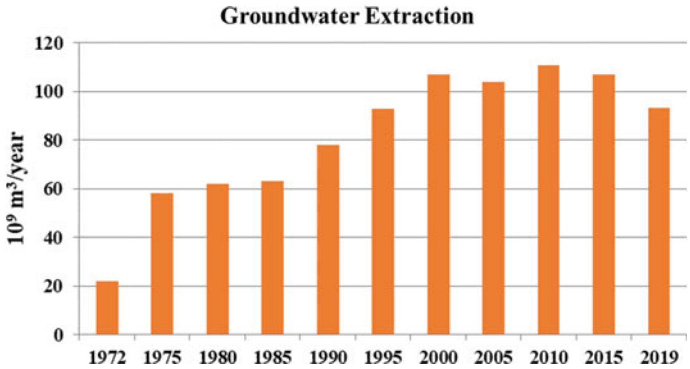


Fig. 5.1 Historical development of groundwater extraction in China 1972–2019 (Ministry of Water Resources of China 2020)

The percentage of potential groundwater resources that can be extracted in the coastal areas of the Northern provinces is much higher than in the southern provinces (Zhang and Li 2004). Excessive groundwater pumping has caused a dramatic drawdown of groundwater levels in the North China Plain, generating a regional cone of depression in an area of over 2,000 km^2 in the coastal Hebei Province alone (Jiao and Wen 2004) and 40,000 km^2 along all coastal areas (Figs. 5.1 and 5.2). Excessive pumping is a common phenomenon in the northern coastal provinces and has led to severe seawater intrusion. The annual volume of groundwater extracted in this region increased from 6.2×10^{10} m^3 in 1980 to 9.3×10^{10} m^3 in 2019 (Ministry of Water Resources of China 2020). Groundwater demand has increased in both the northern and southern areas, but the groundwater scarcity is much more serious in the coastal areas of the North China Plain.

5.3 Problems Encountered and the Science and Technology for Their Monitoring and Mitigation

5.3.1 Environmental Issues Relating to Groundwater Extraction

The main environmental issues relating to groundwater extraction all relate to seawater intrusion, which results in groundwater unsuitable for drinking, irrigation, and industrial production. Additionally, seawater intrusion can induce water–rock interactions, and the release of naturally occurring trace elements, including radium (Ra) and fluorine (F), that have health and scientific significance. Some examples of environmental issues caused by groundwater extraction in Northern China follow.

Fig. 5.2 Groundwater drawdown areas and saline groundwater distribution

5.3.1.1 Laizhou Bay

The main environmental issues in Laizhou Bay relate to groundwater and associated problems (Zhang et al. 2017). Groundwater in this area became salinized due to saltwater intrusion (paleo-seawater) that resulted in the deterioration of groundwater quality and the reduction in availability of water resources. Groundwater salinization led to a series of environmental problems (e.g., soil salinization, vegetation degradation, ecological deterioration) and social problems (e.g., abandonment of wells, decline in the quality of industrial and agricultural products, and poor residents' health).

In the 1980s, Laizhou Bay experienced a dry climate, while the freshwater demands for industry and agriculture increased dramatically. Surface sources could not meet this water demand, so groundwater began to be exploited (Feng et al. 2006; Han et al. 2011). Over-exploitation of groundwater resulted in a decrease of groundwater levels. Small groundwater cones of depression gradually merged into a larger scale depletion zone. In some areas, both fresh groundwater and brines are utilized, thus expanding the distribution of degraded groundwater (e.g., Changyi and Weifang-Hanting depletion zone in freshwater areas), that also occurred in the saltwater distribution areas (e.g., Changbei and Yangzi depletion zone). The location of the depletion zone is shown by Zhang et al. (2017).

Because of the decline of groundwater levels, saltwater can easily intrude into freshwater aquifers throughout the area. In the north area of the Changyi district, saltwater intrusion progressively deteriorated a zone 2.9 km southward at a rate of 145 m/y from the 1980s to 2000s. This rate accelerated to 533 m/y from 2000 to 2005 (TJR 2006). In 2007, the salty-fresh groundwater interface[3] was 25.4 km inland from the coastline. The highly saline groundwater in the area supports a large industry along the south coast of Laizhou Bay. These brines have been exploited for several years to recover useful minerals such as magnesium (Chen et al. 1997). This resulted in the formation of a large groundwater cone of depression parallel to the coastline since the 1990s. At present, the width of this groundwater depression varies from 2.9 km in the east to 7.1 km in the west.

5.3.1.2 Tianjin

Since the beginning of large-scale exploitation in the 1970s, groundwater exploitation has continuously increased in Tianjin. The rate of exploitation area reached 11×10^8 m^3/y in 1981, with more than 80% originating from deep confined aquifers. This exploitation eventually resulted in land subsidence in the exploited area. Various degrees of land subsidence occurred from 1959 to 2003, especially in the southern area. The subsidence area of Tianjin, for example, had a maximum accumulated land subsidence of 2.89 m.

Additionally, over-exploitation of groundwater influenced the occurrence of continuous and substantial drops in groundwater levels, thus forming groundwater level depletion zones in urban and suburban areas of Tanggu, Hangu, Dagang, Jinghai, and Wuqing. In coastal areas, the developing groundwater cone of depression has caused saltwater intrusion and a series of related environmental problems (e.g., groundwater pollution, soil salinization, ecological degradation), and a decline in the quality of industrial and agricultural products. Both types of seawater intrusion

[3] TDS = 1 g/L is defined as a threshold that separates freshwater from saltwater.

are recognized in Tianjin: modern seawater intrusion, mainly in the coastal area, and paleo-saltwater (brine) intrusion that is mainly present between the urban area and the modern seawater intrusion area (Guo 2016; Zhao et al. 2019).

5.3.1.3 Qinhuangdao

Seawater intrusion and associated problems are the main environmental issues in the coastal area of Qinhuangdao. In the early 1970s, groundwater in domestic wells near the coast became salty, showing the effects of the seawater intrusion. Since the 1980s, the seawater intrusion area has expanded from 22.0 km^2 in 1986 to 87.8 km^2 in 1993. Seawater intrusion increased the mineralization of the aquifer, resulting in chloride and sulfide levels in the groundwater exceeding drinking water standards. This resulted in numerous supply wells being abandoned and associated industrial and agricultural activities were seriously affected (Zang et al. 2012).

5.3.1.4 Liaodong Bay

In Liaodong Bay, the issue of seawater intrusion was first raised in Dalian in 1976. Since then, the situation has greatly deteriorated. In the 1980s, industrial and agricultural water consumption increased sharply, resulting in over-exploitation of groundwater and an increase in the intensity of seawater intrusion in the region's coastal cities. Groundwater in many areas became salty and numerous supply wells were abandoned. Furthermore, groundwater salinization caused large difficulties for industrial and agricultural production. Residents suffered from low-quality drinking water, which could potentially increase the incidence of certain diseases.

5.3.2 Saltwater Intrusion, Engineering Measures and Downstream Impacts

Generally, seawater intrusion includes modern seawater intrusion (water currently entering a coastal aquifer from the ocean) and paleo-saltwater intrusion (seawater that entered coastal sediments in the distant past) (Xue et al. 1997; Han et al. 2014). Note that we use the term "saltwater intrusion" when the source of the brackish to saline waters includes brines or ancient salt deposits not currently linked to the ocean. Seawater intrusion is caused by long-term changes (e.g., climate change and/or sea-level fluctuations) or intense episodic changes (e.g., pumping, land-use change) in coastal groundwater levels. Even a small volumetric contamination of less than 1% of seawater (~250 mg/L chloride) results in water unfit for drinking. Heavily exploited coastal aquifers may also be impacted by a mixture of seawater and other natural saline waters, such as brines, agricultural effluents, and high-nitrate wastewaters.

Seawater intrudes into freshwater aquifers because of hydraulic gradient and density differences. This type of intrusion occurs mainly in the coastal groundwater system (Werner et al. 2013). In contrast, the occurrence of paleo-saltwater intrusion consists of seawater formed since the late Pleistocene. The Bohai Rim of China is an area that is mainly affected by groundwater over-exploitation. Such intrusion can result in more ecological degradation because of the higher salinity and wider area of intrusion (Vinson et al. 2013; S. Liu et al. 2017).

Based on data from 2,180 groundwater observation wells funded by the National Key Research and Development Program of China in 2018, the areal extent of saline groundwater within the coastal area of China is over 86,000 km^2 (Fig. 5.2), of which about 11,000 km^2 was caused by seawater intrusion due to groundwater over-extraction. The remaining 75,000 km^2 corresponds to the area's paleoclimate evolution, a result of alternate sea and river sedimentary facies over three periods of sea-level fluctuation and high sea levels covering coastal areas of China since the late Pleistocene (Fig. 5.2).

Construction of subsurface physical barriers is one example of an effective engineering procedure to control seawater intrusion and store freshwater resources in coastal aquifers. However, the approach is still new, and research is needed to assess the effectiveness and environmental effects. For example, we need to produce the information needed for management of coastal groundwater resources when these structures are in place. Generally, subsurface physical barriers include underground dams and cutoff walls. Such dams consist of an impermeable wall placed at the bottom of an aquifer to slow or block seawater intrusion, while the upper percolation section allows for discharge of inland underground fresh water to the ocean. A cutoff wall, on the other hand, is an impermeable wall placed at the top of an aquifer with a percolation section at the bottom, again allowing the discharge of fresh groundwater to the ocean. At present, underground dams are more widely used. For example, to prevent further seawater intrusion, eight underground dams were constructed in the Bohai Sea area from 1995 to 2004. The barriers, usually built to about 3 m below the surface and consistent with the thickness of the aquifer, were constructed by underground injection of cement under high pressure to create impermeable walls resting on an impermeable geological layer (Ishida et al. 2011). The dams not only serve as a barrier for preventing seawater intrusion, but also create an underground reservoir for freshwater storage collected mainly during heavy monsoon precipitation (Fig. 5.3). Infiltration wells, trenches and ditches have also been built upstream of the dams to increase groundwater recharge.

In the case of the Wang River underground reservoir near Laizhou, where an underground dam was completed in 2004, the average groundwater level rose 3.3 m, and the size of the area affected by seawater intrusion was reduced by 68% (Wang et al. 2012). The underground reservoir here can store more than 32 million m^3 of water, and this has considerably enhanced regional water security and increased the sustainability of several economic and agricultural activities in the province. The construction of underground groundwater reservoirs and seawater barriers requires systematic hydrogeological knowledge and should be followed up with frequent monitoring of the effectiveness and any unintended consequences of these structures.

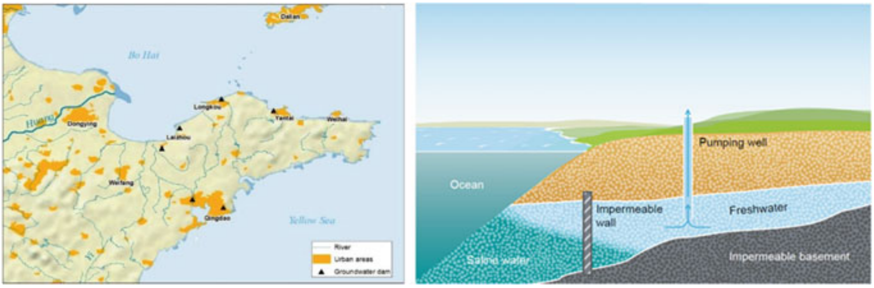


Fig. 5.3 Location map Shandong, China, and location of groundwater dams (Wang et al. 2012) and a cross section of an underground dam (Adapted from Ishida et al. 2011)

Furthermore, reliable data and projections of water availability and water demand are crucial for adequate design and operation. Certain conditions may require special attention or preclude the application of this technology. For example, underground barriers may increase spring discharge or flood cave systems in karst aquifers. Also, water quality implications should be assessed (Ishida et al. 2011).

5.3.3 Human Impacts on Water Resources in the Coastal Zone

5.3.3.1 Effects of Dam Construction

Humans have been engineering natural waterways and river basins for thousands of years. Early agriculture, canal development, and other activities resulted in increased sediment loads in many rivers, as for example the Huanghe (Yellow) River in China. After a long period of increasing sediment flux extending into the Twentieth Century, the situation reversed for many rivers as dams became more commonplace. Globally, there are now more than 48,000 large dams (>15 m high) with thousands more under construction (Syvitski and Kettner 2011). Dams provide several benefits, including power production, flood control, flow regulation (storing water in the wet season and releasing water in the dry season), water diversion for irrigation and other activities, and recreational opportunities. Unfortunately, there are human and environmental side effects to be considered as well. The displacement of large numbers of residents to construct large dams has drawn considerable attention, as for example the construction of the Three Gorges Dam that spans the Yangtze River in Yichang, Hubei province, central China.[4]

Most dams were built since the 1940s, and by the 1950s many rivers displayed reduced sediment loads relative to their pristine condition. Large reservoirs are known

[4] https://en.wikipedia.org/wiki/Three_Gorges_Dam.

to be efficient sediment scavengers, typically trapping about 80% of a river's particulate flux (Syvitski and Milliman 2007). As a result of the proliferation of dams, the flux of sediment from rivers to the coastal ocean has decreased globally, depleting downstream beaches and deltas of sediment. Examples include the many rivers and large deltas in Asia that originate from the Himalayan and Tibetan Plateau regions (e.g., Huanghe, Yangtze, Pearl, Mekong, etc.). The future sustainability of these deltas is in question due to the anthropogenic changes of these riverine sediment fluxes (Kuehl et al. 2020).

As a consequence of damming rivers around the world, there are patterns emerging of riverine sediment fluxes changing from muddy to clear, and in some cases pristine to muddy and then back to clear. The Huanghe River shows this evolutionary cycle particularly well. Thousands of years ago, early farmers caused erosion rates, and thus sediment yields, to increase dramatically by clearing forests on the Tibetan Plateau to plant crops. Such impacts continue today, for example in the Amazon Basin, as deforestation and urbanization are causing some rivers to transition from clear to muddy. It has been estimated that dam construction in the 20th Century has resulted in global sediment loads being about 15% lower than during the pre-Anthropocene (Syvitski and Kettner 2011).

Deltas that historically advanced into the sea because of sedimentation are now displaying shoreline retreat because of sediment starvation. Many Asian deltas, including the Chao Phraya, Ganges, Mekong, Irrawaddy, and others, have experienced chronic flooding over the last several years. Even the Huanghe Delta, once the largest in the world, with a historical formation rate of 20–25 km^2/y, is now shrinking due to sediment trapping by dams (Saito et al. 2007). Most deltas that suffer from flooding do not receive enough sediment because of upstream damming (Syvitski et al. 2009). However, reduced sediment loads are not the only factor causing flooding and shoreline erosion.

An important issue in many deltas around the world concerns the extraction of groundwater. Pumping of groundwater, and hydrocarbons in some cases, often leads to "accelerated subsidence", or increased relative sea level rise. This, in turn, often leads to severe flooding, erosion and shoreline retreat. A recent study by Minderhoud et al. (2017) found that subsidence related to groundwater extraction on the Mekong Delta has gradually increased over the past several decades, with the highest sinking rates occurring at present. Their models suggest current average subsidence rates due to groundwater extraction amount to 1.1 cm/y, with some areas subsiding at rates over 2.5 cm/y, outpacing global sea level rise almost by an order of magnitude. Subsidence has become an issue in many parts of the world, such as the Mississippi Delta in coastal Louisiana. Below we summarize how groundwater and/or hydrocarbon extraction has seriously affected two Asian deltas, the Huanghe (China) and Chao Phraya (Thailand).

5.3.3.2 The Huanghe Delta

The Huanghe originates on the Tibetan or Loess Plateau and flows about 5,460 km, the 2nd longest in China, to the Bohai Sea. Before about 1,000 years ago, the sediment discharge was estimated at about 1×10^8 mt/y. This is only about one tenth of the sediment load it would carry after human activity, especially deforestation and agriculture, began on the Loess Plateau (Saito 2001; Saito et al. 2007). Due to dam construction in the 20th Century, the sediment flux was drastically reduced, leading to the present-day erosion of the delta (Fig. 5.4). The decreasing water and sediment discharge have led to seawater intrusion as well as erosion of the coastal zone.

The modern Huanghe Delta dates from 1855, when the mouth of the Huanghe River shifted north from the Yellow Sea to the Bohai Sea. Beginning in the 1960s, dams were built upstream, reducing the water flux from 43 km^3/y to 4.9 km^3/y (Fan and Huang, 2008). Sediment discharge to the river mouth decreased dramatically from more than 1 Gt/y in the 1960s to 0.15 Gt/y in the 21st Century (Wang et al. 2011). Fish farms and factories to extract minerals from hypersaline groundwaters were built along the entire coastline between 1970 and 2000. By 2001, groundwater extraction in the delta had reached 1×10^6 m^3/y (Fan et al. 2006). Oil production from depths of 3 to 5.5 km in the delta also continued throughout the Twentieth Century (Guo et al. 2010).

Although many studies have examined erosion of the Huanghe Delta, no consensus has been reached as to the primary cause of coastal erosion. Clearly,

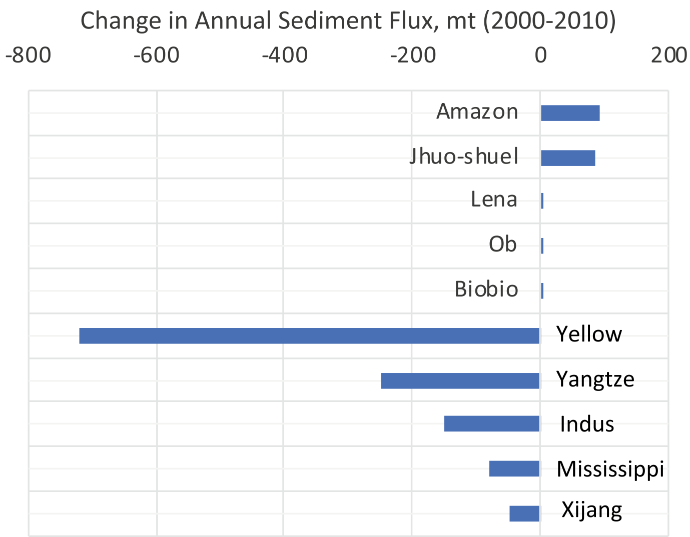


Fig. 5.4 Recent changes in riverine sediment flux. Deforestation and farming increased the sediment loads in some large rivers from 2000 to 2010, particularly in South America. But dams have cut sediment loads elsewhere, especially in Asia. Figure modified from Malakoff (2020). Reprinted with permission from AAAS. The original data are from L. Li et al. (2020)

the reduced sediment load is one factor, but land subsidence also appears to play an important role. Higgins et al. (2013) used satellite-based Synthetic Aperture Radar to show that subsidence rates as high as 250 mm/y occur at aquaculture facilities in the area. These rates, induced by groundwater extraction for use in fish farms, as well as hydrocarbon pumping in the basin, must be a main contributor to the erosion occurring in the delta today.

Asia produces 89% of the world's farmed fish, and much of this production occurs in river deltas. Fish and shrimp ponds have expanded tremendously and have effectively become the boundary between land and sea in the Huanghe Delta, as well as deltas of the Pearl, Mekong, Chao Phraya, and others. While impacts of global sea level rise on aquaculture is often mentioned, little has been said about relative sea level rise produced by the industry itself because of groundwater mining (FAO 2012). The largest threat to coastal stability in deltas may not be global sea level rise, but the effective change in sea level due to land subsidence from groundwater extraction.

5.3.3.3 The Chao Phraya Delta

The Chao Phraya River, the "River of Kings," is the largest and most important river in Thailand. It is formed by the coalescing of four rivers, the Ping, Wang, Yom, and Nan in the uplands of northern Thailand. The river hosts the largest city, Bangkok, and the main port of the country. The drainage basin is about 160×10^3 km^2 and the river has a length of 1,200 km (Saito 2001). The Chao Phraya has an average discharge of 15.2 km^3/y (70-year average) with typical monsoonal variations with dry season flows around 1.6 km^3/y and high-season discharges of about 75.7 km^3/y.

Geologically, the Chao Phraya Delta advanced into the Gulf of Thailand at a rate of about 1.5 km^2/y (Tanabe et al. 2003). However, the situation has been very different over the past few decades. The deltaic shoreline has been retreating landward at rates of up to 20 m/y on both sides of the river mouth (Bidorn et al. 2021). These shoreline erosion rates are among the highest in the world. In a review of world deltas, Syvitski et al. (2009) placed the Chao Phraya Delta in the category of "…in greatest peril." This represents a dramatic reversal from a constantly expanding delta to one that is eroding so quickly that some villages near the shoreline have had to relocate several times since the 1950s (Bidorn et al. 2018). What caused this situation to develop?

Many investigators have proposed that sediment trapping behind two large storage dams, constructed in the mid-1960s and early 1970s, is likely the main factor affecting the high shoreline retreat of the delta (Nutalaya 1996; JICA 2000; Uehara et al. 2010; Gupta et al. 2012; Milliman and Farnsworth 2013). However, a recent study showed that the rate of sediment accumulation in the delta, determined via ^{210}Pb dating, has increased over the last few decades (Bidorn et al. 2021). While these dams do trap sediment, their location at several hundred kilometers upstream may not directly influence sedimentation in the delta (Namsai et al. 2021). Increased sedimentation downstream in the delta is apparently due to land use changes related to more aquaculture and urban development activities around the lower reaches of the

Chao Phraya (Bidorn et al. 2021). Aquaculture activities can lead to accumulation of food and waste materials and increased settling of suspended sediments. Furthermore, activities such as destruction of shrimp pond dikes can remobilize soils, resulting in enhanced shoreline retreat and increased sedimentation offshore (Bidorn et al. 2017, 2021; Namsai et al. 2021).

Local sea level change, destruction of mangrove forests, sand mining, and reduction of sediment supply may all play a role in causing the extremely high rates of shoreline erosion in the Chao Phraya Delta (JICA 2000; Winterwerp et al. 2005; Saito et al. 2007; Syvitski et al. 2009; Siripong 2010). However, land subsidence coupled to global sea level rise are likely the most important components of shoreline retreat in the region (Bidorn et al. 2021). The total land subsidence in the delta over the past 60 years has varied between 65 and 96 cm, with the greatest subsidence near the Chao Phraya River mouth (DMCR 2011; RTSD 2015). The magnitude of land subsidence is related to the amount of groundwater extraction, which accelerated during the expansion of the city of Bangkok from the 1970s (Nutalaya 1996). The very high “accelerated compaction” or subsidence, ranges from 50–150 mm/y, the highest rate of human-induced subsidence of the world’s major deltas (Syvitski et al. 2009). The subsidence is largely due to intensive groundwater pumping (Fig. 5.5).

Intensive groundwater use began in Thailand in 1953 and became widely used in Bangkok from about 1980 (Lorphensri et al. 2011). The initial groundwater levels in Bangkok were close to ground surface and some wells were artesian. Because of high subsidence rates, the Thai government instituted regulations that led to a large decline in groundwater pumping during the late 1980s to the early 1990s (Buapeng et al. 2006). However, groundwater use increased again in newly developed areas in the suburbs of Bangkok since 1993 because of rapid economic growth (Das Gupta and Babel 2005). We caution that the groundwater use figures shown here are estimates, as

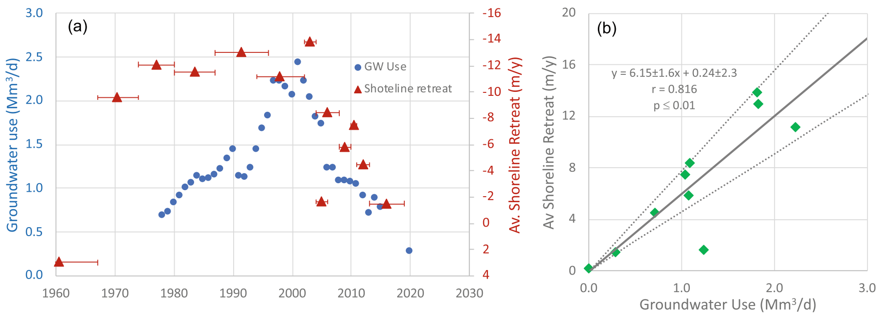


Fig. 5.5 **a** Temporal trends of groundwater pumping (blue circles, millions of cubic meters per day, left scale) in the Bangkok area that includes the Chao Phraya Delta together with average rates of shoreline erosion (red triangles, meters lost per year, right scale) on the western side of the Chao Phraya Delta. **b** Scatter plot of average shoreline retreat rates (m/y) versus groundwater use during the period 1992–2019. The dotted lines represent 1σ uncertainty zone of the regression. The groundwater extraction data are from Lorphensri et al. (2011) and the Thailand Bureau of Groundwater Conservation and Restoration (pers. comm.). The shoreline retreat estimates are from Bidorn et al. (2021)

private unlicensed use may represent an important fraction of the total use. Lorphensri et al. (2011) estimated that unlicensed use may account for an additional 35% of the values reported by the Thai Department of Groundwater Resources.

Comparison of estimated groundwater pumping rates (m^3/day) from 1980 to present together with shoreline retreat rates (m/y) shows that erosion increased during the long period of increasing groundwater withdrawals (~1980–2000), while shoreline retreat decreased after government regulations required groundwater pumping to decrease after about 2003 (Fig. 5.5a). Historical aerial photos were used to estimate the extent of shoreline erosion over time (Bidorn et al. 2021). Since total shoreline retreat can only be estimated between aerial surveys, the shoreline loss is reported as an average rate since we cannot determine precisely when the major losses occurred. The horizontal bars on the shoreline loss data points represent the time interval before and after the mid-point between two aerial flights (Fig. 5.5a). Note that the change in slope for both groundwater pumping and shoreline erosion occurred at about the same time in the early 2000s. It is thus inferred that increased groundwater withdrawals resulted in increased subsidence in the delta and that, in turn, led to increased shoreline erosion. While the trends from the early 1990s to present match well, it is not clear why shoreline erosion was already high in the 1970s before groundwater extraction accelerated in the 1980s. The shoreline retreat at that time may be related to an unusually busy period of tropical cyclones with 5 tropical storms and a typhoon impacting the Gulf of Thailand between 1960 and 1970.

When we plot the average shoreline retreat rates against groundwater withdrawals during the period from 1992 to 2016 in a scatter plot, we find a significant relationship exists between these two parameters ($r = 0.816$, $p \leq 0.01$; Fig. 5.5b). While the earlier data do not follow the same trend, this plot is exceptionally strong over almost three decades. Such relationships can be valuable for coastal zone management. Our example would imply to a manager that one could expect to lose about 6 m of shoreline around the Chao Phraya Delta for every million cubic meters of groundwater pumped out of the ground. Fortunately, recent trends in the Chao Phraya area indicate lower groundwater pumping rates and shoreline erosion appears to be responding favorably. In fact, the most recent studies indicate some minor accretion over the last few years (Bidorn et al. 2021).

5.3.4 Human Regulation Impacts on River-Estuary-Aquifer Biogeochemistry

5.3.4.1 Sediment and Nutrient Retention Effects

Human activities have extensively altered river-estuary and river-dam systems through impoundments and regulations out of concern for water, energy, and transportation needs, as well as ecological protection. Damming a river for water storage in reservoirs decreases water velocity, which leads to an increase in suspended sediments deposition (Milliman 1997; Nilsson et al. 2005; Syvitski et al. 2009; Sojka et al. 2018), modifications in nutrient dynamics, as well as vegetation and animal habitats (Bosch and Allan 2008). Due to the loss of energy in the reduced flow, downstream fluvial and estuarine hydrodynamics are also significantly weakened. From a biogeochemical perspective, nutrient transformation processes are more effective and thoroughly developed within such aquatic domains. Therefore, river reservoirs and estuaries consequently tend to act as a sediment filter and/or a biogeochemical reactor (Bouwman et al. 2013; Xu et al. 2016, 2018).

As we discussed earlier (Sect. 5.3.3), numerous dams and reservoirs have been built in China and elsewhere over the last several decades as the most effective facilities for irrigation, flood control, water supply, and power generation (Wang et al. 2006; Kong et al. 2015). Since the 1950s, more than 3,000 and 50,000 dams and reservoirs were constructed in the basins of the Huanghe River (Zhang et al. 2001) and Changjiang River (Yang et al. 2011), respectively. Both rivers are now both highly fragmented and regulated by human activities. The Three Gorges Reservoir (TGR) in the Changjiang River basin is the world's largest water conservancy project. Concerns about the effects of the TGR has been focused on sediment-related topics, such as sediment trapping in reservoirs, downstream channel erosion and sediment starvation in the delta (Sun et al. 2021). Since the TGR began operating in 2003, sediment load has notably decreased (Yang et al. 2011, 2018). For example, the sediment loads immediately below the Three Gorges Dam decreased by 92% during the period 2003–2015 compared to 1950–1985 (Guo et al. 2018). In terms of dissolved nutrients, the TGR behaves as a converter and only a small fraction of inflow loads is trapped due to internal transformation of reactive nutrients (Ran et al. 2015, 2019). Sediment-associated nutrients, however, are removed. The TGR behaves as a filter for particulate phosphorus, especially in the coarse sediment fraction, which results in the retention of 98% of suspended particulate matter (SPM), 72% of biogenic silica (BSi) and 70% of the non-bioavailable particulate phosphorus (Ran et al. 2013, 2015). Nutrient stoichiometry changes in water flowing through the Changjiang River to the East China Sea clearly shows that the TGR is likely to induce increasing phosphorus limitation in phytoplankton over time. Harmful algal blooms of both non-siliceous and siliceous algae are occurring and may be related to a combination of high N levels, high N:P ratios, and/or declining dissolved Si (DSi) levels, depending on the species (Li et al. 2009; Ran et al. 2019).

In the Huanghe River basin, the Xiaolangdi Reservoir is the most downstream large reservoir, which controls more than 90% of the Huanghe River basin area and almost all its sediment (Wang et al. 2016). Upon the impoundment of Xiaolangdi, the sediment discharge to the sea sharply decreased from 0.2–0.4 Gt/y to approximately 0.02–0.05 Gt/y, due to sediment trapping effects (Bi et al. 2014). Controlling factors for SPM also significantly affects DSi and BSi abundance and composition of the Huanghe River (Ran et al. 2015). Due to the reduction in discharge of the Huanghe River and dam construction, a rapid decrease of atomic Si/N ratios in the Bohai Sea have been observed (Liu et al. 2018). This has resulted in a shift of the phytoplankton community from a system dominated by the diatom (*Chaetoceros* sp.) to one dominated by diatoms (*Navicula* sp.) and dinoflagellates (*Ceratium* sp.). These ecological changes may be related to the increased frequency of harmful algal blooms (HABs), mainly by *Ceratium furca* and *Phaeocystis globos*e species (SOA 2017), that have occurred in the Bohai Sea during recent decades (Liu et al. 2018). This may result in long-term effects on zooplankton and fish.

5.3.4.2 Retention Effects by Reservoirs and Estuaries Assessed by Natural Tracers

Traditional methods for assessing the retention of water in reservoirs and estuaries and flow to the ocean require stream flow meters and gauging stations, but these methods miss the portion of freshwater flow through sediments and released to the ocean as submarine groundwater discharge. In recent decades, radiotracers have proven to integrate water inflows from different sources because the natural radioactive decay of radiotracers makes it possible to add a time component to these measurements. Under the impact of government regulations, retention effects of sediment and nutrients in river reservoirs and estuaries are more difficult to evaluate, because these systems are stochastically variable. Natural isotopes, specifically, radium isotopes, have been shown to act as robust tracers to quantitatively assess the retention effects of suspended particles and nutrients in river reservoir-estuary systems (Xu et al. 2016, 2018). Based on the apparent radium age model pioneered by Moore (2000), one can easily calculate "water ages" in river reservoirs as well as estuaries. These ages can then be used as an independent parameter to quantify nutrient removal rates and characterize zonation inside aquatic domains. Using this approach, the nearshore area of the Huanghe River estuary with water ages of 10 days was found to be the major estuarine filtration region, where nutrient removal rate constants ranged from 0.11–0.19/day before reaching oceanic background levels (Xu et al. 2016). In this nutrient-enriched region with low water ages, microplankton (20–200 μm) and nanoplankton (2–20 μm) are the major primary producers, accounting for 40 and 45% of primary production, respectively. As water is flushed offshore, nutrients are rapidly consumed and the minor amounts remaining are only sufficient for small species to grow. Therefore, picoplankton (0.2–2 μm) becomes more dominant in the older aged (2 weeks) water bodies, contributing 57% of the total chlorophyll a on average (Xu et al. 2013).

River-reservoir systems may be more suitable than estuaries for the application of this approach because model assumptions are more easily satisfied. Xu et al. (2018) expanded the use of this approach to the Xiaolangdi Reservoir, a typical fluvial-to-lentic continuum. The system was sectioned into the riverine, transition, and lentic reaches inside the reservoir based on the water mass ages calculated via the activity ratios of ^{224}Ra/^{226}Ra and ^{223}Ra/^{226}Ra (Fig. 5.6).

Based on the relationship between water ages and material concentrations, suspended sediment was calculated to be removed at a rate of 1.4 ± 0.6 g/m^3/day,

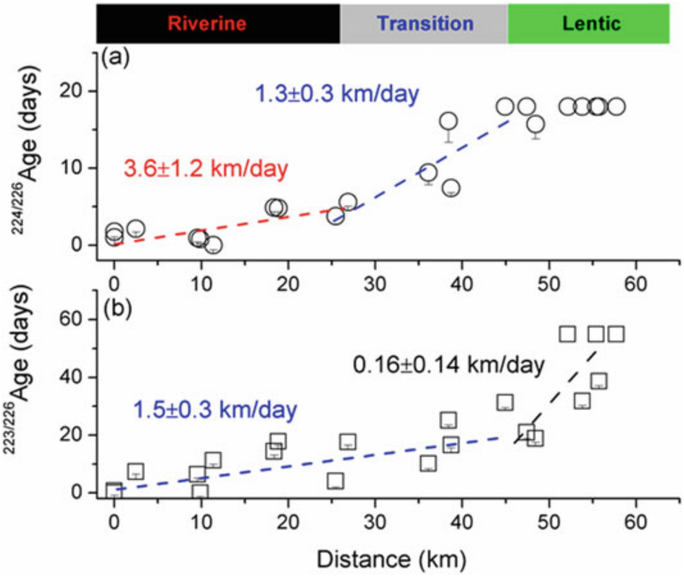


Fig. 5.6 Apparent radium water ages in the Xiaolangdi Reservoir river-reservoir system during June 2017, based on **a** $^{224}Ra/^{226}Ra$ ratios and **b** $^{223}Ra/^{226}Ra$ ratios. The upper (0–25 km), middle (25–45 km), and lower (45–60 km) sections of the Xiaolangdi Reservoir are now classified as riverine, transition, and lentic zones, respectively (Xu et al. 2018). Permission to reuse figure granted from John Wiley & Sons

mainly in the riverine zone. Nutrient dynamics were more complicated, with addition or removal at different rates within the three zones. This Ra tracing technique is relatively easy to conduct at low cost with the right equipment and trained personnel. For example, results like those shown here can be obtained with a 1- to 2-day sampling scheme followed by a few days of radium measurements. These types of measurements allow one to assess retention effects of SPM and nutrients in river-reservoir-estuary systems.

5.3.4.3 Water–Sediment Regulations and Coastal Groundwater–Seawater Interactions

Water–sediment regulations for dammed rivers drastically alters the natural seasonal discharge patterns of water, sediment and associated terrestrial materials. Elevation or lowering of the river-estuarine water level could subsequently alter the groundwater seawater interactions in the subterranean estuary, leading to an even more complicated ecological responses in estuaries and coastal seas.

The “Water Sediment Regulation Scheme” (WSRS) in the Huanghe River

Since the middle of the 20th Century, the annual water and sediment load of the Huanghe River was dramatically decreased under the influence of both natural processes and human activities (Wang et al. 2007). The Huanghe River Conservancy Commission implemented a joint reservoir operation on three reservoirs (Wanjiazhai, the Sanmenxia, and the Xiaolangdi reservoirs), the so-called “Water Sediment Regulation Scheme” (WSRS) to ensure an adequate flow of water and to maintain the channeling capacity of the main course of the river (Miao et al. 2016). Since 2002, the WSRS has been performed annually, except for 2016 and 2017 (Chen et al. 2019). A controlled release of a huge amount of water from these reservoirs on the mainstream and tributaries was used to scour the lower river reaches over a 10–20-day period (Wang et al. 2010; Kong et al. 2015). Instantaneous discharge rates reached up to 4000 m^3/s, which is over ten-fold higher than during typical non-WSRS periods (discharge about 300 m^3/s). Because of these efforts over the past two decades, annual river discharge during 2002–2018 significantly increased compared with the period of 1996–2001 (Xu et al. 2013; L. Li et al. 2020). The WSRS drastically altered the original seasonal variations in the water and sediment discharges and sediment properties, such as an increase of median grain size of suspended particles and riverbed sediments (Chu and Zhai 2006; Wang et al. 2010; Bi et al. 2014). A larger quantity of coarser sediments was transported to the sea during shorter time intervals. These sediments were deposited rapidly and formed a series of river mouth sand bars, triggered a rapid shift in the pathway of the river plume (Wang et al. 2005), and caused most of the observed changes in the erosion–accretion patterns and topographic variations in the active delta (Bi et al. 2014; Hou et al. 2021).

Hydrodynamic and sediment transport processes in the Huanghe River estuary have been fundamentally altered by the WSRS (Wang et al. 2010; Hou et al. 2021). In addition, profound ecological effects were also observed in the estuarine ecosystem (Guo et al. 2017). A large amount of material enters the ocean in a very short time, which can dramatically influence the river and estuary systems as well as the associated coastal ecosystems (Wu et al. 2017). Metal fluxes during the WSRS accounted for 42–54% for the entire year and the transported metals were dominated by particulates (Liu et al. 2019). About 50% of the annual nutrient load, 1/3 of the annual suspended organic carbon and 50% of the annual particulate organic carbon flux is transported to the coast during a WSRS (Yao et al. 2009; Hou et al. 2021). It has been reported that the WSRS not only shifted the seasonal patterns of nutrient delivery to the estuary (Liu 2015; X. Li et al. 2017), with high concentrations moved from autumn to June and July, but also promoted the extent of nutrient spreading to the south-central part of the Bohai Sea (Wang et al. 2017). Estuarine nutrient concentrations and the magnitude of terrestrial input areas were both elevated 2–4 times during a WSRS. Nutrient loadings during a WSRS reduced absolute P limitation in the estuary and south-central Bohai Sea, but the stoichiometric P limitation situation was even more severe (Xu et al. 2016). Furthermore, the environment in the lower reaches of the Huanghe River and estuary were shown to be affected (Li et al. 2017).

For example, zooplankton abundance and biomass increased rapidly during the inter-stage of WSRS, leading to significant increase of fishery resources, but there was a decline of phytoplankton abundances and biodiversity (Zhang et al. 2021).

WSRS Increases Seawater-Groundwater Mixing

Submarine groundwater discharge (SGD), which includes recycled seawater as well as terrestrial freshwater, has been drawing increased attention from the scientific community (Moore 1996, 2010; Burnett et al. 2003, 2006; Kwon et al. 2014). A recent estimate shows that even conservatively calculated SGD-derived nutrient fluxes are on the same order as river contributions to the global ocean (Cho et al. 2018; Santos et al. 2021). Some research has suggested that SGD could alter the biogeochemical makeup of the ocean's benthic boundary layer, including parameters such as dissolved oxygen (DO) and pH. For example, Santos and Eyre (2011) reported that water pH is inversely related to groundwater inputs because of acidic groundwater. Peterson et al. (2016) and Guo et al. (2020) found that saline, cold, anoxic groundwater generated an undersaturated DO bottom water mass that appears to be related to coastal hypoxia events. Therefore, SGD should be considered for both element/compound budgets and ecosystem management strategies in the global coastal oceans.

The Huanghe River estuary (HRE) is one of the most important river estuaries in China. SGD in the HRE has been found to be an important material source which has to be considered in estuarine biogeochemical studies. SGD fluxes in the HRE have been estimated via seepage meters to be in the range 4 ~ 130 cm/day, which is several-fold higher than the Huanghe River surface discharge during the same period (Taniguchi et al. 2008). Studies using radium/radon isotopes as tracers confirmed these high rates (Peterson et al. 2008; Xu et al. 2013, 2014; X. Wang et al. 2015, 2016; Xia et al. 2016). During the annual WSRS, groundwater tables along the riverbanks are significantly elevated, especially on the south bank (Fan et al. 2009). Increased river discharge and the elevated river water level during WSRS leads to a higher hydraulic head, enhancing groundwater discharge in the estuary. Xia et al. (2016) reported that the SGD flow rates increased from 2 to 20 cm/day to 67–122 cm/day during an WSRS event. The freshwater component (FSGD) also increased from less than 10% (Wang et al. 2015; Xia et al. 2016; Zhang et al. 2016, 2018) to more than 20% of the total SGD, especially near the river mouth, where the FSGD component was up to 40% (Xia et al. 2016). This relatively fresh benthic discharge was apparently strong enough to disturb benthic hyperpycnal flows, leading to very abrupt variations in bottom water profiles of dissolved oxygen and turbidity (Xu et al. 2014).

SGD has now been recognized as an important source term for nutrients in the HRE. During a non-WSRS period, SGD nitrate fluxes were 2–3 times higher than that delivered by the river, which may help to understand the increasing DIN levels in the central Bohai Sea over the past few decades (Peterson et al. 2008). Xu et al. (2013) reported more recently that SGD was the dominant delivery factor of all estuarine nutrients, contributing 83, 69 and 83% of the total estuarine DIN, DIP and DSi, respectively. During WSRS events, the increased SGD significantly enhances nutrient inputs (Xu et al. 2014). However, these nutrient fluxes were calculated by simply multiplying the dissolved nutrient concentrations in the groundwater endmember by the SGD flux. It is now well known that care must be taken in interpreting such fluxes, as geochemical reactions often alter the nutrient composition within the subterranean estuary and in the benthic water–sediment boundary layer before discharge (Kroeger and Charette 2008; Young 2013). For example, a recent laboratory study found enhanced P desorption from sediment associated with elevated levels of inorganic silicon, implying a possible unknown process of P release to the coastal oceans via SGD (Cho et al. 2019).

5.3.5 Submarine Groundwater Discharge Fuels HABs

SGD has been recognized as a potential trigger of harmful algal blooms (HABs; see also Chap. 10). Red tides were the most reported cases, such as studies in the Gulf of Mexico (Hu et al. 2006) and Little Lagoon (Su et al. 2014) in the United States, the south coast of Korea (Lee and Kim 2007; Lee et al. 2009), and Kinvara Bay off the west coast of Ireland (Gregory et al. 2020). Blooms of green macroalgae are also occurring worldwide, posing a significant threat to the health of marine ecosystems, and leading to serious economic losses. Since 2007, the world's largest green tide, consisting of *Ulva prolifera*, has been observed every summer in the South Yellow Sea off the Jiangsu and Shandong coasts of China. High nutrient loading via rivers was suggested to be one of the dominant factors controlling the large macroalgae blooms that occurred there (Li et al. 2017). However, the extremely low annual river runoff in the area suggests that SGD could be the dominant pathway for nutrients to these coastal waters. Based on a ^{228}Ra mass balance model, the SGD-derived biogenic elemental loading of dissolved inorganic nitrogen (DIN), phosphorus (DIP) and dissolved silica (DSi) were estimated as 18 times, 7 times and 13 times the riverine inputs from both mainland China and Korea (S. Liu et al. 2017). FSGD has been suggested to play an important role in nutrient sources to the Yellow Sea, as such inputs not only affect nutrient budgets and ratios, but also enhances primary productivity (Liu et al. 2021). A recent study focused on the Subei Shoal coast, an area less than 5% of the entire South Yellow Sea (Zhao et al. 2021). They showed that despite the small areal extent, the calculated SGD flux was about 3 times larger than previously documented for the entire South Yellow Sea. Based on these findings, it was recommended that specific attention should be paid to the ecological significance of SGD hotspots, especially for coastal systems that are shallow, intensively mixed, anthropogenically polluted, sandy, or muddy with heavy bio-irrigation (Zhao et al. 2021). SGD may serve as a functional conveyor belt to (1) continuously transfer organic matter into the subterranean estuary, where it is further mineralized to inorganic nutrients (Cai et al. 2020); and (2) discharge labile forms of nutrients back into the coastal ocean, leading to eutrophication and nutrient imbalances (Zhang et al. 2020). Therefore, areas with similar characteristics may have a higher risk of suffering harmful ecological problems, even with limited river input. Improved management strategies should be developed, with consideration of the potential impacts of groundwater discharge.

5.4 Conclusions and Recommendations

Since increasing regulations are being launched to protect rivers and coastal aquifers, special care needs to be focused on multi-discipline observations of these aquatic systems. On-going hydrological and biogeochemical observations in river basins and estuaries should be maintained, especially in the zone between the last hydrologic observation station and the estuary. It is now recognized that this gap area might be a very important source and sink area for nutrient and micronutrient elements. For example, SGD in these areas may be more intense than offshore because the water table contours tend to focus flow along the axes of river valleys. Further downstream along the coast, low relief favors tidal pumping, and enhanced interactions between water and sediment may release more porewater with associated materials. However, additional observational data are needed in these gap areas because difficult logistics have hindered progress in these zones. We therefore strongly suggest more attention should be paid to these “missing geological zones” in the future.

During past decades, investigators realized that naturally occurring radioactive geochemical isotopes are powerful tracers to study natural geophysical processes. More recently, research has shown that isotopes can assess hydrodynamics in estuaries and subterranean estuaries and quantify associated terrestrial material fluxes from land to sea. But similar studies in river basins are still rare. Studies using radium isotopic approaches in rivers are far less numerous than those within coastal seas. Researchers still lack some fundamental understanding concerning radium behavior in rivers. We thus suggest that isotopic tracing techniques should be initiated in river environments, especially in the “missing zones” mentioned above.[5]

Coastal regions host a disproportionately large share of the world’s population and economic activity and require a reliable water supply for future development. Groundwater plays a major role in coastal settings but is at risk of salinization by seawater intrusion. The primary driver is aquifer over-exploitation, which also causes land subsidence, thus adding not only to salinization risk but flooding and related shoreline erosion. Flooding of low-lying coastal zones, often caused by subsidence, is another cause of seawater intrusion and may increase in the future with sea level rise.

[5] As explained earlier, radiotracer methods provide information not readily available through other approaches and are relatively easy to use with proper training. The International Atomic Energy Agency (IAEA; https://www.iaea.org) can assist developing countries with locating relevant information on isotopic techniques and with training.

The principal management aim relating to coastal water resources should always be to keep the demand for water as low as possible, collectively decided by all stakeholders (Post et al. 2018). Because population and food demand are still growing in most regions of the world, a reduction of water use per capita and per unit area is essential. Fundamental steps towards efficient water use include systematic monitoring of water extraction, metering of water consumption, and realistic pricing. Economic incentives like subsidies for water-efficient technologies used for irrigation, industrial production, and domestic applications can be effective instruments for promoting water conservation. At the same time, strict enforcement of water allocation limits should be part of a successful management plan.

Factors that affect coastal aquifers are both dynamic and diverse. To maintain the sustainability of these freshwater resources, managers should apply scientific approaches, as outlined throughout this chapter, to address threats to the resource. The limited capacity of groundwater systems to meet water demands necessitates a re-thinking of our concept of water supply. Assessments of the status of coastal river and groundwater systems should be based on innovative approaches (e.g., natural radioisotopic tracers). Managers, to the extent possible, should include a diversification of water sources. Coastal aquifers, as shown in the many examples highlighted in this chapter, are more sensitive to threats than their inland counterparts because of possible seawater intrusion. Future freshwater availability should be a prime guiding principle before initiating additional economic development and planning. The focus should not only be on direct human needs, but also on ecosystem health and services. Such a balancing act will be a delicate one in many coastal regions, but necessary to meet the challenges expected for the remainder of the 21st Century.

Wise management of freshwater resources in coastal areas is critical for achieving blue economy goals by sustaining coastal and marine resources and avoiding some problems that can plague the coastal ocean environment. Freshwater flows of adequate volume and quality are necessary to maintain sediment loads, salinity, and nutrients within levels known to support coastal ecosystems that deliver goods and services as a basis for blue economic development. Coral reefs may be damaged if incoming freshwater contains too many nutrients or pesticides (see Chap. 2). Maintenance of coastal mangrove and seagrass zones depends on adequate sediment supplies to prevent erosion of supporting sediments (see Chap. 3). Harmful algal blooms (HABs) can be stimulated when SGD inputs contribute to elevated nutrient concentrations (see Chap. 10). HABs can have negative impacts on other blue economy resources, such as fisheries (see Chap. 4) and tourism (see Chap. 6).

Frequent observations of freshwater systems are of primary importance, including observations of the quantity and quality of freshwater entering the ocean from surface flow and SGD, as well as groundwater levels that determine the direction of flow of freshwater and dissolved materials at the land–ocean interface. Such observations are especially important in river systems when new dams are installed, or river flow is otherwise changed dramatically. Continuous observations are needed in areas of special relevance to blue economy that receive major freshwater inflows, such as important habitats (mangrove forests, seagrass beds, and coral reef areas), eco-tourism areas, important fishery zones, etc. These represent prime locations for enhanced ocean, river, estuary observations and research related to impacts of freshwater extraction and river regulation practices on blue economy resources.

References

Bi N, Wang H, Yang Z (2014) Recent changes in the erosion-accretion patterns of the active Huanghe (Yellow River) delta lobe caused by human activities. Cont Shelf Res 90:70–78

Bidorn B, Buser M, Phanomphongphaisarn N et al (2018) Effects of coastal disaster on coastal community living along the Upper Gulf of Thailand. In: Proceedings of the 6th RCND, Yogyakarta, Indonesia, pp 1–6

Bidorn B, Kish S, Donoghue J et al (2017) Variability of the total sediment supply of the Chao Phraya River, Thailand, In: Proceedings river sedimentation, proceedings of the 13th international symposium on river sedimentation (Stuttgart, Germany, 19–22 September 2016), CRC Press, pp 23–30

Bidorn B, Sok K, Bidorn K et al (2021) An analysis of the factors responsible for the shoreline retreat of the Chao Phraya Delta (Thailand). Sci Total Environ 769:145253

Bosch NS, Allan JD (2008) The influence of impoundments on nutrient budgets in two catchments of Southeastern Michigan. Biogeochemistry 87:325–338

Bouwman AF, Bierkens MFP, Griffioen J et al (2013) Nutrient dynamics, transfer and retention along the aquatic continuum from land to ocean: Towards integration of ecological and biogeochemical models. Biogeosciences 10:1–22

Buapeng S, Lorphensri O, Ladawadee A (2006) Groundwater situation and land subsidence mitigation in Bangkok and its vicinity. In: Proceedings of the 3rd international conference on hydrology and water resources in Asia Pacific Region (APHW 2006)

Burnett WC, Aggarwal PK, Aureli A et al (2006) Quantifying submarine groundwater discharge in the coastal zone via multiple methods. Sci Total Environ 367:498–543

Burnett WC, Bokuniewicz H, Huettel M et al (2003) Groundwater and porewater inputs to the coastal zone. Biogeochemistry 66:3–33

Cai P, Wei L, Geibert W et al (2020) Carbon and nutrient export from intertidal sand systems elucidated by ^{224}Ra/^{228}Th disequilibria. Geochim Cosmochim Ac 274:302–316

Chen G (2013) Mechanisms underlying of seawater intrusion and evaluation of early warning systems in the Laizhou Bay area. East China Normal University, Shanghai, China (in Chinese)

Chen H, Zhang Y, Wang X et al (1997) Salt-water intrusion in the lower reaches of the Weihe River, Shandong Province, China. Hydrogeol J 5:82–88

Chen J, Fan Y, Wu W et al (2019) Evolution characteristics of the Yellow River Estuary after interruption of the Yellow River Water and Sediment Regulation in 2016–2017. Yellow River 41:6–10

Cho H, Kim G, Kwon E et al (2018) Radium tracing nutrient inputs through submarine groundwater discharge in the global ocean. Sci Rep-UK 8:1–7

Cho H, Kim J, Kim G (2019) Desorption of phosphate on sandy sediments by silicate in groundwater. Geochim Cosmochim Ac 257:184–190

Chu Z, Zhai S (2006) Effects of Three Gorges Reservoir (TGR) water storage in June 2003 on Yangtze River sediment entering the estuary. Hydrol Earth Syst Sc Disc 3:1553–1567

Das Gupta A, Babel MS (2005) Challenge for sustainable management of groundwater use in Bangkok, Thailand. Int J Water Resour Dev 21:453–464

DMCR (2011) Master and action plans for shoreline erosion management in the Upper Gulf of Thailand: Final report, Department of Marine Coastal Resources (DMCR). Ministry of National Resources and Environment, Govt of Thailand, Bangkok

Famiglietti JS, Ferguson G (2021) The hidden crisis beneath our feet. Science 372:344–345

Fan H, Huang H (2008) Response of coastal marine eco-environment to river fluxes into the sea: A case study of the Huanghe (Yellow) River mouth and adjacent waters. Mar Environ Res 65:378–387

Fan H, Huang H, Zeng T (2006) Impacts of anthropogenic activity on the recent evolution of the Huanghe (Yellow) River delta. J Coastal Res 22:919–929

Fan X, Liu G, Shu L et al (2009) Influence of a regulated discharge regime of the Yellow River to dynamic condition of groundwater of estuary region. Yellow River 31:34–35 (in Chinese)

FAO (2012) The state of world fisheries and aquaculture 2012, Tech. Rep., Fisheries and Aquaculture Department, Food and Agriculture Organization (FAO) of the United Nations, Rome. https://doi.org/10.1596/978-0-8213-7137-4

Feng A, Gu D, Xia D (2006) Developments and causes of seawater intrusion in the south coast area of the Laizhou Bay. Coast Eng 25:7–13 (in Chinese)

Ghil M (2002) Natural climate variability. Munn, T. (Eds), Encyclopedia of global environmental change (pp. 544–549). Chichester, John

Gregory C, Cave RR, Raine R et al (2020) The interaction of retention areas and submarine ground water (SGD) in small bays: Implications for phytoplankton growth. Estuar Coast Shelf S 238:106681

Grinsted A, Moore JC, Jevrejeva S (2004) Application of the cross wavelet transform and wavelet coherence to geophysical time series. Nonlinear Proc Geoph 11:561–566

Guo K, Zou T, Jiang D et al (2017) Variability of Yellow River turbid plume detected with satellite remote sensing during water-sediment regulation. Cont Shelf Res 135:74–85

Guo L, Su N, Zhu C et al (2018) How have the river discharges and sediment loads changed in the Changjiang River basin downstream of the Three Gorges Dam? J Hydrol 560:259–274

Guo SY (2016) Study on the relationship among exploitation of deep confined groundwater-the groundwater level-the land subsidence in Tianjin Plain. China University of Geosciences (Beijing), 98p (in Chinese with English abstract)

Guo X, He S, Liu K et al (2010) Oil generation as the dominant overpressure mechanism in the Cenozoic Dongying depression, Bohai Bay Basin, China. AAPG Bull 94:1859–1881

Guo X, Xu B, Burnett WC et al (2020) Does submarine groundwater discharge contribute to summer hypoxia in the Changjiang (Yangtze) River Estuary? Sci Total Environ 719:137450

Gupta H, Kao S, Dai M (2012) The role of mega dams in reducing sediment fluxes: A case study of large Asian rivers. J Hydrol 464:447–458

Gurdak JJ, McMahon PB, Bruce BW (2012) Vulnerability of groundwater quality to human activity and climate change and variability, High Plains aquifer, USA. Climate change effects on groundwater resources: A global synthesis of findings and recommendations: International Association of Hydrogeologists (IAH)-International Contributions to Hydrogeology, Taylor & Francis publishing, company ISBN: 978-0415689366

Han DM, Kohfahl C, Song X et al (2011) Geochemical and isotopic evidence for Palaeo-Seawater intrusion into the south coast aquifer of Laizhou Bay, China. Geochemistry 26:863–883

Han DM, Song X, Currell MJ et al (2014) Chemical and isotopic constraints on evolution of groundwater salinization in the coastal plain aquifer of Laizhou Bay, China. J Hydrol 508:12–27

Hanson RT, Dettinger MD, Newhouse MW (2006) Relations between climatic variability and hydrologic time series from four alluvial basins across the southwestern United States. Hydrogeol J 14:1122–1146

Higgins S, Overeem I, Tanaka A et al (2013) Land subsidence at aquaculture facilities in the Yellow River delta, China. Geophys Res Lett 40:3898–3902

Holman IP, Rivas-Casado M, Howden NJK et al (2009) Linking North Atlantic ocean-atmosphere teleconnection patterns and hydrogeological responses in temperate groundwater systems. Hydrol Process 23:3123–3126

Hou C, Yi Y, Song J et al (2021) Effect of water-sediment regulation operation on sediment grain size and nutrient content in the lower Yellow River. J Clean Prod 279:123533

Hu C, Muller-Karger FE, Swarzenski PW (2006) Hurricanes, submarine groundwater discharge, and Florida's red tides. Geophys Res Lett 33(11). https://doi.org/10.1029/2005GL025449

Ishida S, Tsuchihara T, Yoshimoto S et al (2011) Sustainable use of groundwater with underground dams. JARQ-Jpn Agr Res Q 45:51–61

Jasechko S, Perrone D (2021) Global groundwater wells at risk of running dry. Science 372:418–421

Jiao J, Wen D (2004) Perspectives on Chinese ground water resources. Groundwater 42:488–490

JICA (2000) The feasibility study on mangrove revival and extension project in the Kingdom of Thailand. Draft Final Report (Japan International Co-operation Agency (JICA), Ministry of Agriculture, Thailand

Jones IC, Banner JL (2003) Estimating recharge thresholds in tropical karst island aquifers: Barbados, Puerto Rico and Guam. J Hydrol 278:131–143

Kong D, Miao C, Borthwick AGL et al (2015) Evolution of the Yellow River Delta and its relationship with runoff and sediment load from 1983 to 2011. J Hydrol 520:157–167

Kroeger KD, Charette MA (2008) Nitrogen biogeochemistry of submarine groundwater discharge. Limnol Oceanogr 53:1025–1039

Kuehl SA, Yang S, Yu F et al (2020) Asia's mega rivers: common source. Diverse Fates. Eos. https://doi.org/10.1029/2020EO143936

Kuss AJM, Gurdak JJ (2014) Groundwater level response in US principal aquifers to ENSO, NAO, PDO, and AMO. J Hydrol 519:1939–1952

Kwon EY, Kim G, Primeau F et al (2014) Global estimate of submarine groundwater discharge based on an observationally constrained radium isotope model. Geophys Res Lett 41:8438–8444

Lee YW, Hwang DW, Kim G et al (2009) Nutrient inputs from submarine groundwater discharge (SGD) in Masan Bay, an embayment surrounded by heavily industrialized cities, Korea. Sci Total Environ 407:3181–3188

Lee YW, Kim G (2007) Linking groundwater-borne nutrients and dinoflagellate red-tide outbreaks in the southern sea of Korea using a Ra tracer. Estuar Coast Shelf S 71:309–317

Li H, Huang C, Zhang C et al (2020) Coastal erosion and sediment dynamics of the Yellow River Delta and their responses to the runoff-sediment flux since 1976. Resources Science 42:486–498

Li H, Zhang Y, Tang H et al (2017) Spatiotemporal variations of inorganic nutrients along the Jiangsu coast, China, and the occurrence of macroalgal blooms (green tides) in the southern Yellow Sea. Harmful Algae 63:164

Li L, Jinren N, Fang C et al (2020) Global trends in water and sediment fluxes of the world's large rivers. Sci Bull 65:62–69. https://doi.org/10.1016/j.scib.2019.09.012

Li X, Chen H, Jiang X et al (2017) Impacts of human activities on nutrient transport in the Yellow River: The role of the water-sediment regulation scheme. Sci Total Environ 592:161–170

Li Y, He R, McGillicuddy DJ Jr et al (2009) Investigation of the 2006 *Alexandrium fundyense* bloom in the Gulf of Maine: In-situ observations and numerical modeling. Cont Shelf Res 29:2069–2082

Liu J, Du J, Yu X (2021) Submarine groundwater discharge enhances primary productivity in the Yellow Sea, china: insight from the separation of fresh and recirculated components. Geosci Front 12(6):101204. https://doi.org/10.1016/j.gsf.2021.101204

Liu J, Su N, Wang X et al (2017) Submarine groundwater discharge and associated nutrient fluxes into the Southern Yellow Sea: A case study for semi-enclosed and oligotrophic seas-implication for green tide bloom. J Geophys Res-Oceans 122:139–152

Liu J, Zang J, Hao W et al (2018) Changes in the distribution and preservation of silica in the Bohai Sea due to changing terrestrial inputs. CONT SHELF RES 166:1–9

Liu M, Fan D, Bi N et al (2019) Impact of water-sediment regulation on the transport of heavy metals from the Yellow River to the sea in 2015. Sci Total Environ 658:268–279

Liu S (2015) Response of nutrient transports to water–sediment regulation events in the Huanghe Basin and its impact on the biogeochemistry of the Bohai. J Marine Syst 141:59–70

Liu S, Tang Z, Gao M et al (2017) Evolutionary process of saline-water intrusion in Holocene and Late Pleistocene groundwater in southern Laizhou Bay. Sci Total Environ 607:586–599

Lorphensri O, Ladawadee A, Dhammasarn S (2011) Review of groundwater management and land subsidence in Bangkok, Thailand. In: Tanaguchi M (ed) Groundwater and Subsurface Environments: Human Impacts in Asian Coastal Cities. Springer, Tokyo, pp 127–142

Luque-Espinar JA, Chica-Olmo M, Pardo-Igúzquiza E et al (2008) Influence of climatological cycles on hydraulic heads across a Spanish aquifer. J Hydrol 354:33–52
Malakoff D (2020) Mud on the move. Science 369:896–897
McCabe GJ, Palecki MA, Betancourt JL (2004) Pacific and Atlantic Ocean influences on multidecadal drought frequency in the United States. P Natl Acad Sci USA 101:4136–4141
Miao C, Kong D, Wu J et al (2016) Functional degradation of the water–sediment regulation scheme in the lower Yellow River: spatial and temporal analyses. Sci Total Environ 551:16–22
Milliman J (1997) Blessed dams or damned dams? Nature 386:325–327
Milliman JD, Farnsworth KL (2013) River discharge to the coastal ocean: A global synthesis. Cambridge University Press, Cambridge
Minderhoud PSJ, Erkens G, Pham VH et al (2017) Impacts of 25 years of groundwater extraction on subsidence in the Mekong Delta. Vietnam. Environ Res Lett 12:064006. https://doi.org/10.1088/1748-9326/aa7146
Ministry of Water Resources of China 1980–2020 (2020) China Water Resources Bulletin
Moore WS (1996) Large groundwater inputs to coastal waters revealed by ^{226}Ra enrichments. Nature 380:612–614
Moore WS (2000) Ages of continental shelf waters determined from ^{223}Ra and ^{224}Ra. J Geophys Res 105:22117–22122
Moore WS (2010) The effect of submarine groundwater discharge on the ocean. Annu Rev Mar Sci 2:59–88
Namsai M, Charoenlerkthawin W, Sirapojanakul S et al (2021) Did the construction of the Bhumibol Dam cause a dramatic reduction in sediment supply to the Chao Phraya River? Water 13:386
Nilsson C, Reidy CA, Dynesius M et al (2005) Fragmentation and flow regulation of the world's large river systems. Science 308:405–408
National Bureau of Statistics of China (2019) China Statistical Yearbook
Nutalaya P (1996) Coastal erosion in the Gulf of Thailand. GeoJournal 38:283–300
Perez-Valdivia C, Sauchyn D, Vanstone J (2012) Groundwater levels and teleconnection patterns in the Canadian Prairies. Water Resour Res 48: WO7516. https://doi.org/10.1029/2011WR010930
Peterson RN, Burnett WC, Taniguchi M et al (2008) Determination of transport rates in the Yellow River-Bohai Sea mixing zone via natural geochemical tracers. Cont Shelf Res 19:2700–2707
Peterson RN, Moore WS, Chappel SL et al (2016) A new perspective on coastal hypoxia: The role of saline groundwater. Mar Chem 179:1–11
Post VEA, Eichholz M, Brentführer R (2018) Groundwater management in coastal zones. Bundesanstalt für Geowissenschaften und Rohstoffe (BGR). Hannover, Germany, p 107
Ran X, Bouwman AF, Yu Z et al (2019) Implications of eutrophication for biogeochemical processes in the Three Gorges Reservoir, China. Reg Environ Change 19:55–63
Ran X, Chen H, Wei J et al (2015) Phosphorus speciation, transformation and retention in the Three Gorges Reservoir, China. Mar Freshwater Res 67:173–186
Ran X, Yu Z, Chen H et al (2013) Silicon and sediment transport of the Changjiang River (Yangtze River): Could the Three Gorges Reservoir be a filter? Environ Earth Sci 70:1881–1893
Rasanen TA, Kummu M (2013) Spatiotemporal influences of ENSO on precipitation and flood pulse in the Mekong River Basin. J Hydrol 476:154–168
Rosen C (2000) World Resources 2000–2001: People and ecosystems: The fraying web of life. Elsevier, Amsterdam
RTSD (2015) Land subsidence monitoring in Bangkok and vicinity during the past three decades. Royal Thai Survey Department (RTSD), Ministry of Defense, Govt of Thailand, Bangkok
Saito Y (2001) Deltas in Southeast and East Asia: their evolution and current problems. In Mimura N, Yokoki H (eds) Global Change and Asia Pacific coasts: proceedings of APN/SURVAS/LOICZ Joint Conference on Coastal Impacts of Climate Change and Adaptation in the Asia-Pacific Region, Kobe, Japan, pp 185–191
Saito Y, Chaimanee N, Jarupongsakul T et al (2007) (2007) Shrinking megadeltas in Asia: Sea-level rise and sediment reduction impacts from case study of the Chao Phraya Delta. Inprint Newsletter of the IGBP/IHDP Land Ocean Interaction in the Coastal Zone 2:3–9

Santos IR, Chen X, Lecher AL et al (2021) Submarine groundwater discharge impacts on coastal nutrient biogeochemistry. Nat Rev Earth Environ 2:307–323

Santos IR, Eyre BD (2011) Radon tracing of groundwater discharge into an Australian estuary surrounded by coastal acid sulphate soils. J Hydrol 396:246–257

Sheffield J, Wood EF (2008) Global trends and variability in soil moisture and drought characteristics, 1950–2000, from observation-driven simulations of the terrestrial hydrologic cycle. J Climate 21:432–458

Siripong A (2010) Detect the coastline changes in Thailand by remote sensing. Int Arch Photogrammetry Remote Sens Spat Inform Sci 38:992–996

SOA (State Oceanic Administration) (2017) China marine disaster bulletin. Available from: http://www.soa.gov.cn/ (in Chinese)

Sojka M, Siepak M, Jaskuła J et al (2018) Heavy metal transport in a river-reservoir system: a case study from Central Poland. Pol J Environ Stud 27:1725–1734

Su N, Burnett WC, Macintyre HL et al (2014) Natural radon and radium isotopes for assessing groundwater discharge into Little Lagoon, AL: implications for harmful algal blooms. Estuar Coast 37:893–910

Sun J, Xiao Z, Lin B, Yuan B, Zhang X (2021) Longitudinal transport timescales in a large dammed river—The Changjiang River. Sci Total Environ 771:144886

Syvitski JPM, Kettner A (2011) Sediment flux and the Anthropocene. Philos T Roy Soc A 369:957–975

Syvitski JPM, Kettner AJ, Overeem I et al (2009) Sinking deltas due to human activities. Nat Geosci 2:681–686

Syvitski JPM, Milliman JD (2007) Geology, geography, and humans battle for dominance over the delivery of fluvial sediment to the coastal ocean. J Geol 115:1–19

Tampa Bay Water (2010) Tampa Bay seawater desalination plant—fact sheet. 7 p. https://www.tampabaywater.org/documents/fact-sheets/desal-fact-sheet.pdf

Tanabe S, Saito Y, Sato Y et al (2003) Stratigraphy and Holocene evolution of the mud-dominated Chao Phraya delta. Thailand. Quaternary Sci Rev 22:789–807

Tanco R, Kruse E (2001) Prediction of seasonal water-table fluctuations in La Pampa and Buenos Aires, Argentina. Hydrogeol J 9:339–347

Taniguchi M, Ishitobi T, Chen J et al (2008) Submarine groundwater discharge from the Yellow River delta to the Bohai Sea, China. J Geophys Res-Atmos 113(C6). https://doi.org/10.1029/2007JC004498

TJR (2006) Report of "Study of real-time monitoring and warning on sea-salt water intrusion in Laizhou Bay—a case study of Changyi-Liutuan Profile". Tianjin Institute of Geology and Mineral Resources 37–38 (unpublished in Chinese)

Torrence C, Compo GP (1998) A practical guide to wavelet analysis. B Am Meteorol Soc 79:61–78

Uehara K, Sojisuporn P, Saito Y et al (2010) Erosion and accretion processes in a muddy dissipative coast, the Chao Phraya River delta, Thailand. Earth Surf Proc Land 35:1701–1711

Velasco EM, Gurdak JJ, Dickinson JE et al (2016) Interannual to multidecadal climate forcings on groundwater resources of the U.S. west coast. J Hydrol Regional Stud 11(C):250–265

Vicente-Serrano SM, López-Moreno JI, Gimeno L et al (2011) A multiscalar global evaluation of the impact of ENSO on droughts. J Geophys Res-Atmos 116(D20). https://doi.org/ https://doi.org/10.1029/2011JD016039

Vinson DS, Tagma T, Bouchaou L et al (2013) Occurrence and mobilization of radium in fresh to saline coastal groundwater inferred from geochemical and isotopic tracers (Sr, S, O, H, Ra, Rn). Appl Geochem 38:161–175

Wada Y, van Beek LPH, van Kempen CM et al (2010) Global depletion of groundwater resources. Geophys Res Lett 37(20). https://doi.org/10.1029/2010GL044571

Wang H, Bi N, Saito Y et al (2010) Recent changes in sediment delivery by the Huanghe (Yellow River) to the sea: Causes and environmental implications in its estuary. J Hydrol 391:302–313

Wang H, Saito Y, Zhang Y et al (2011) Recent changes of sediment flux to the western Pacific Ocean from major rivers in East and Southeast Asia. Earth-Sci Rev 108:80–100

Wang H, Yang Z, Bi N et al (2005) Rapid shifts of the river plume pathway off the Huanghe (yellow) river mouth in response to water-sediment regulation scheme in 2005. Chinese Sci Bull 50:2878–2884
Wang H, Yang Z, Saito Y et al (2006) Interannual and seasonal variation of the Huanghe (Yellow River) water discharge over the past 50 years: connections to impacts from ENSO events and dams. Global Planet Change 50:212–225
Wang H, Yang Z, Saito Y et al (2007) Stepwise decreases of the Huanghe (Yellow River) sediment load (1950–2005): Impacts of climate change and human activities. Global Planet Change 57:331–354
Wang K, Li B, Yu Q et al (2012) The construction of underground reservoir and its beneficial effect on resource and environment in Shandong Province Peninsula. In: China geological survey—achievements. http://en.cgs.gov.cn/achievements/201601/t20160112_35475.html
Wang S, Fu B, Piao S et al (2015) Reduced sediment transport in the Yellow River due to anthropogenic changes. Nat Geosci 9:38–41
Wang X, Li H, Jiao J et al (2015) Submarine fresh groundwater discharge into Laizhou bay comparable to the Yellow River flux. Sci Rep-UK 5:8814
Wang Y, Liu D, Lee K et al (2017) Impact of water-sediment regulation scheme on seasonal and spatial variations of biogeochemical factors in the Yellow River estuary. Estuar Coast Shelf S 198:92–105
Wang Z, Xia J, Li T et al (2016) An integrated model coupling open-channel flow, turbidity current and flow exchanges between main river and tributaries in Xiaolangdi Reservoir, China. J Hydrol 543:548–561
Werner AD, Bakker M, Post VEA et al (2013) Seawater intrusion processes, investigation and management: Recent advances and future challenges. Adv Water Resour 51:3–26
Winterwerp JC, Borst WG, De Vries MB (2005) Pilot study on the erosion and rehabilitation of a mangrove mud coast. J Coastal Res 21:223–230
Wu X, Bi N, Xu J et al (2017) Stepwise morphological evolution of the active Yellow River (Huanghe) delta lobe (1976–2013): Dominant roles of riverine discharge and sediment grain size. Geomorphology 292:115–127
Xia D, Yu Z, Xu B et al (2016) Variations of hydrodynamics and submarine groundwater discharge in the Yellow River estuary under the influence of the water-sediment regulation scheme. Estuar Coast 39:333–343
Xu B, Burnett W, Dimova N et al (2013) Hydrodynamics in the Yellow River estuary via radium isotopes: Ecological perspectives. Cont Shelf Res 66:19–28
Xu B, Xia D, Burnett WC et al (2014) Natural ^{222}Rn and ^{220}Rn indicate the impact of the water–sediment regulation scheme (WSRS) on submarine groundwater discharge in the Yellow River estuary, China. Appl Geochem 51:79–85
Xu B, Yang D, Burnett WC et al (2016) Artificial water sediment regulation scheme influences morphology, hydrodynamics and nutrient behavior in the Yellow River estuary. J Hydrol 539:102–112
Xu B, Yang D, Yao P et al (2018) A new perspective for assessing water transport and associated retention effects in a large reservoir. Geophys Res Lett 45:9642–9650
Xue Y, Wu J, Xie C et al (1997) Sea water intrusion and salt water intrusion in the coastal area of Laizhou Bay. Chinese Sci Bull 42:2360–2368
Yang H, Yang S, Xu K et al (2018) Human impacts on sediment in the Yangtze River: A review and new perspectives. Global Planet Change 162:8–17
Yang S, Milliman J, Li P et al (2011) 50,000 dams later: Erosion of the Yangtze River and its delta. Global Planet Change 75:14–20
Yao Q, Yu Z, Wang T et al (2009) Effect of the first water-sediment regulation on the variations of dissolved inorganic nutrients' concentrations and fluxes in the lower main channel of the Yellow River. Environm Sci 30:3534 (in Chinese)
Young C (2013) Fate of nitrogen during submarine groundwater discharge into long island north shore embayments. (Doctoral Dissertation). Stony Brook University, USA

Zang W, Zhang X, Gong C et al (2012) An overview of the geo-environment in the Qinhuangdao region. J Geol Hazards Environ Preserv 23(32–35):43 (In Chinese)
Zhang J, Li F, Lv Q et al (2021) Impact of the Water-Sediment Regulation Scheme on the phytoplankton community in the Yellow River estuary. J Clean Prod 294(7120):126291
Zhang L, Dawes W, Walker G (2001) Response of mean annual evapotranspiration to vegetation changes at catchment scale. Water Resour Res 37:701–708
Zhang X, Miao J, Hu B et al (2017) Hydrogeochemical characterization and groundwater quality assessment in intruded coastal brine aquifers (Laizhou Bay, China). Environ Sci Pollut R 24:21073–21090
Zhang Y, Li H, Wang X et al (2016) Estimation of submarine groundwater discharge and associated nutrient fluxes in eastern Laizhou Bay, China using Rn-222. J Hydrol 533:103–113
Zhang Y, Li W, Sun G et al (2018) Understanding coastal wetland hydrology with a new regional-scale, process-based hydrological model. Hydrol Process 32:3158–3173
Zhang Y, Santos IR, Li H (2020) Submarine groundwater discharge drives coastal water quality and nutrient budgets at small and large scales. Geochim Cosmochim Ac 290:201–215
Zhang Z, Li L (eds) (2004) Groundwater resources of China. China Atlas publishing company (In Chinese), Beijing
Zhao S, Xu B, Yao Q et al (2021) Nutrient-rich submarine groundwater discharge fuels the largest green tide in the world. Sci Total Environ 770:144845. https://doi.org/10.1016/j.scitotenv.2020.144845
Zhao W, Liang H, Gong SJ (2019) Hydrochemical characteristics and oxygen isotope tracing study of shallow groundwater seawater-intrusion in Tianjin. J Capital Normal University (natural Science Edition) 40:66–69

Chapter 6
Marine Tourism and the Blue Economy: Perspectives from the Mascarene and Pacific Islands

Mridula Srinivasan, Deepeeka Kaullysing, Ranjeet Bhagooli, and Stephen Pratt

Abstract The blue economy is built on the principle that socio-economic progress can occur in tandem with environmental protection and sustainable resource extraction. Nations with coastal and ocean-based economies have struggled to realize the promise of the blue economy without taking conciliatory measures. Island nations are especially affected due to their overwhelming reliance on marine tourism and related activities and disproportionate susceptibility to climate change and fluctuating touristic demands. Not all island nations are the same and national ocean economies can be vastly different, dictated by complex geopolitics, cultural models, and social value systems. We explore these facets further through two contrasting case studies from two remarkably different corners of the world—the island of Mauritius in the western Indian Ocean and Pacific Island Countries and Territories. We recommend that marine tourism, the largest component of the Islands' blue economy, must be handled as an anthropogenic stressor subject to environmental assessments, regulatory enforcement, and adaptive mitigation measures. Further, tourism fees levied by different island nations should proportionally allocate funds towards periodic monitoring and restoration evaluation studies. Findings from such studies could facilitate

M. Srinivasan (✉)
Marine Mammal and Turtle Division, Southeast Fisheries Science Center, National Marine Fisheries Service, 75 Virginia Beach Drive, FL Key Biscayne, USA
e-mail: mridula.srinivasan@noaa.gov

D. Kaullysing · R. Bhagooli
Faculty of Science and Pole of Research Excellence in Sustainable Marine Biodiversity, Department of Biosciences and Ocean Studies, University of Mauritius, Réduit 80837, Republic of Mauritius
e-mail: de.kaullysing@uom.ac.mu

R. Bhagooli
e-mail: r.bhagooli@uom.ac.mu

The Biodiversity and Environment Institute, Réduit, Republic of Mauritius

S. Pratt
Department of Tourism, Events and Attractions, Rosen College of Hospitality Management, University of Central Florida, FL Orlando, USA
e-mail: stephen.pratt@ucf.edu

E. R. Urban Jr. and V. Ittekkot (eds.), *Blue Economy*,
https://doi.org/10.1007/978-981-19-5065-0_6

participatory decision-making processes and build marine environment and tourism resilience against global disruptions, climate change, and severe habitat loss.

Keywords Marine tourism · Climate change · Marine biodiversity · Small islands

6.1 Introduction—Tourism and the Blue Economy

The coastal and marine tourism industry is a flourishing sector of the blue economy. The "blue economy" encompasses a variety of marine resource exploitation and infrastructure development activities for societal gain as defined by the World Bank and United Nations Department of Economic and Social Affairs (2017). The blue economy concept is built on the principle that socio-economic progress can occur in tandem with environmental protection and sustainable resource extraction. There is debate over the precise definition of the blue economy and the variable application and societal consequences in different regions; however, this has been discussed elsewhere (Voyer et al. 2018; Mallin and Barbesgaard 2020; Chap. 1 of this book) and is not covered here further.

Within the blue economy construct, some dominant activities include maritime activities, such as fisheries, aquaculture, offshore renewable energy development, transport, and tourism. Also, subsumed within the blue economy are non-market value components that include carbon sequestration and biodiversity preservation (World Bank and United Nations Department of Economic and Social Affairs 2017). Undoubtedly, marine tourism is one of the largest revenue sectors in many countries, with a significant impact on coastal community livelihoods, but vulnerable to climate change effects and fluctuating touristic demands (Orams 1999; Hoyt 2001; Moreno and Amelung 2009). In 2006, the estimated global revenue from marine tourism exceeded the combined global revenue from fisheries and aquaculture (Higham et al. 2016 and references therein). The U.S. Economics—National Ocean Watch data indicated that (https://coast.noaa.gov/digitalcoast/data/enow.html) marine tourism and recreation contribute \$143 billion to the U.S. gross domestic product (GDP) and employed nearly 2.5 million people in this sector in 2018. Similarly, in the first Marine Economy Satellite Account statistics released by the U.S. Bureau of Economic Analysis, in 2019, the U.S. marine economy accounted for \$397 billion or 1.9% of current-dollar U.S. gross domestic product (GDP). Moreover, tourism represented approximately 35% of the marine economy's gross output (https://www.bea.gov/data/special-topics/marine-economy). In Europe, per the 2021 European Union (EU) Blue Economy Report (https://blueindicators.ec.europa.eu/published-reports_en), the gross value added from coastal tourism (the largest sector of the EU blue economy) increased by about 20% in 2018 from 2009, and supported nearly 2.8 million employees. For small islands, the contributions of tourism to national economies can be much more significant, based on tourism receipts.

Globally, big and small coastal nations—especially islands with vast coastlines and natural biodiversity—attract millions of tourists seeking ocean-based activities and experiences. Conceptually, a blue economy offers the perfect balance between supporting the local economy and maintaining critical habitats and populations. In practice, blue economy concepts like ecosystem-based management and marine spatial planning are variously interpreted by decision-making entities and, thus, implementation can fall far short of promoted ideals (Silver et al. 2015; Voyer et al. 2018). In many situations, revenue and economic sustainability predominate concerns over indigenous and livelihood issues, animal welfare, environmental protection, and unmitigated resource exploitation. Brockington and Stefano (2015) emphasized similar concerns on the redistribution of resources, external investors dictating green sector management through disproportionate influence on governments and marginalizing local voices, and overemphasis on green economy jobs at the expense of limiting land access to existing local populations in the Global South. In profit-based marine tourism-based economies, there is little incentive to sustain resources when there is high and continuous demand, non-existent regulations and limited to no enforcement of existing regulations, and a passive government (Constantine 2014; Higham et al. 2016; Barbesgaard 2018). The result is a moving scale of acceptable trade-offs (Sala et al. 2021). Moreover, climate change is expected to have a disproportionate effect on small island developing state economies due to a combination of storm surges, sea leave rise, and coastal erosion (Pathak et al. 2021).

While trade-offs are inevitable, we argue that a scientific decision-making framework can allow societies and countries to evaluate these trade-offs in terms of costs and benefits, assess and mitigate risk proactively, and decide if any changes can or should be made to existing blue economy or blue growth models. However, analytical frameworks and scientific understanding can only highlight potential cause and effect or ecosystem repercussions. To realize blue economy aspirations, governing entities must have the training and knowledge to trust the data, and the authority to enforce regulations that can secure the livelihoods of tourism-dependent communities and propagate resilience against the inevitable onslaught of climate change, pandemics (e.g., COVID-19), and other global cataclysms. Small island nations are especially vulnerable to the vagaries of economic and climate change due to their overwhelming reliance on marine or coastal tourism, and tradeoffs with other blue economy activities. Not all island nations are the same and national ocean economies can be vastly different, dictated by complex geopolitics, cultural models, and social value systems. In this chapter, we explore these facets further through two contrasting case studies from two remarkably different corners of the world—the island of Mauritius in the western Indian Ocean and Pacific Island Countries and Territories. The assessment and assertions made here can be readily extended or adapted to other nations with developed or developing coastal or marine tourism-based economies.

6.2 Mauritius

Mauritius is a small island of 1,865 km^2 situated on the Mascarene Plateau in the western Indian Ocean, with a population of 1,261,663 in 2019 (Fig. 6.1). It has a lagoon area of 243 km^2 surrounded by 300 km^2 of coral reef (fringing and barrier). The scenic coastline of Mauritius Island extends over 322 km. It is characterized by various types of shores—sandy, rocky, muddy, cliffs, mixed, reclaimed, and wetlands (Bhagooli and Kaullysing 2019; Bhagooli et al. 2021a).

Mauritian waters are home to about 1,656 species in 290 families of marine organisms, including 160 coral species (Moothien-Pillay et al. 2002; Bhagooli et al. 2017; Fig. 6.2), two mangrove species—*Rhizophora mucronata* and *Bruguiera gymnorrhiza* (Appadoo et al. 2017), 435 seaweed species (Bolton et al. 2012), five seagrass species (Paupiah et al. 2000; Ramah et al. 2014), 340 fish species (6th National Report for the Convention on Biological Diversity) and two sea turtle species—*Eretmochelys imbricata* and *Chelonia mydas* (Ramah et al. 2019). Seventeen species of marine mammals are also known to visit Mauritian waters. Corbett (1994) reports the presence of 13 cetacean species both inshore and offshore Mauritius, with sperm whale *Physeter macrocephalus* (offshore) and the spinner dolphin *Stenella longirostris* (inshore) being the most common and abundant species encountered. Webster et al. (2020) documented several other cetacean species in Mauritian waters from 2008 to 2014. Although studies on marine species' rarity and/or endemism are scarce in Mauritian waters (McClanahan et al. 2021).

Fig. 6.1 Moka Range seen from Le Pouce mountain, Mauritius (Photo by Ranjeet Bhagooli)

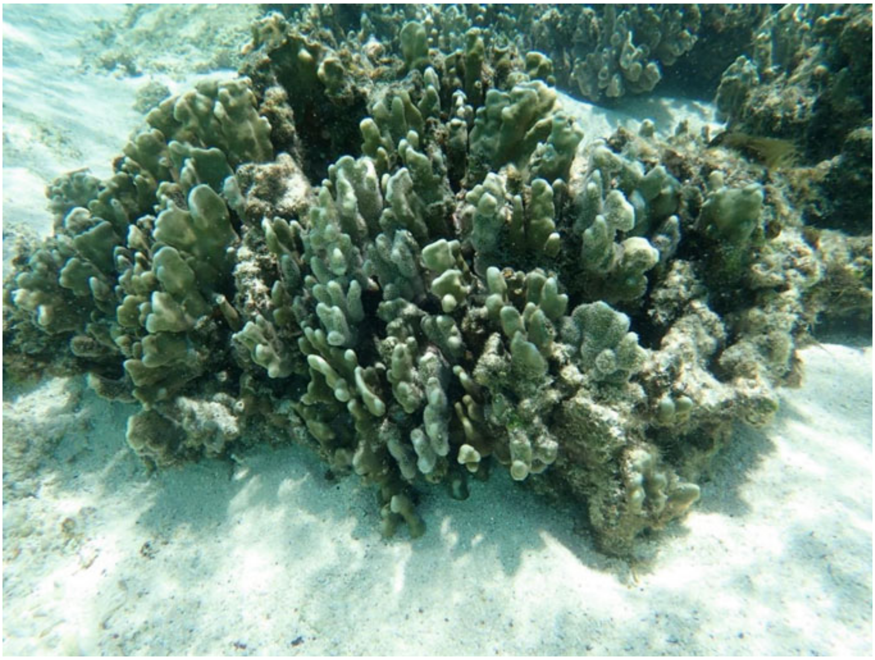


Fig. 6.2 Blue corals, Flat Island, Mauritius (Photo by Ranjeet Bhagooli)

6.2.1 Tourism Revenue

Tourism in Mauritius is one of the leading economic pillars and is predominantly coastal-based and dependent on the level of conservation and preservation of the local marine biodiversity. Tourist arrivals have been increasing from 72,915 in 1974 to 1,383,488 in 2019, a more than 18-fold increase (Fig. 6.3). The principal tourist markets were France (21.8%), United Kingdom (10.2%), and Reunion Island (9.9%) in 2019. Tourism receipts for 2019 are estimated at MUR 63,107 million (~USD 1,469 million; EUR 1,244 million), with a contribution of 8.1% (in 2019) to the Gross Domestic Product (GDP) of Mauritius, compared to MUR 503 million (~USD 12 million) in 1983. Direct employment in hotels, restaurants, and travel and tourism establishments employing 10 persons or more was 31,827 in 2019 compared to 4,360 in 1983. Employment in these establishments increased by 1.2% in 2019 as compared to 31,455 for 2018. The average length of stay for a tourist is estimated at 10.6 nights (Handbook of Statistical Data on Tourism 2019). In Mauritius, around 1,500 skippers have licenses to operate sea activities. Of these, 60 skippers and 40 operators (including tour operators, canvassers, and agencies) manage dolphin-watching activities year-round in the region of Tamarin and nearby (Gowreesunkar and Rycha 2015).

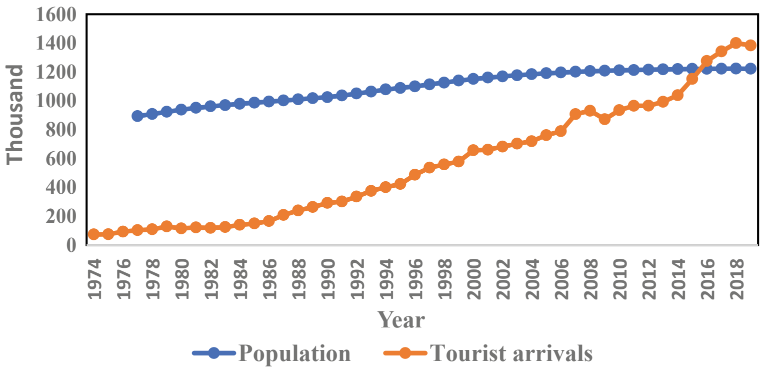


Fig. 6.3 Human population (blue: 1977–2019) and tourist arrivals (orange: 1974–2019) trends in Mauritius Island (Handbook of Statistical Data on Tourism 2019)

An increase in tourist arrivals over the past decades has led to the rapid expansion of the marine tourism industry. The main contributors of tourism to the GDP of Mauritius include freeport activities (competitive logistics and distribution center for international trade, hotels and restaurants, leisure boat activities, and ship store and bunkering) (Freeport Act 2004; Cervigni and Scandizzo 2017).

Coastal areas of Mauritius have recently witnessed uncontrolled and non-strategic development, and increased construction of buildings. The number of licensed tourism activities along the coastal zone and in the marine environment has also increased dramatically. A total of 559 new licenses were issued during the financial year 2018–2019, which include 102 Tourist Enterprises licenses, 106 Pleasure Craft licenses, 267 Skipper Licenses and 84 Tourist Accommodation Certificates (Ministry of Tourism Annual Report 2019). The Central Statistical Office/Bureau gathers information mostly on tourist arrivals. The peak tourist season is generally during the Southern Hemisphere summer season from October to January.

In Mauritius, the Marine Conservation Division of the Ministry of Blue Economy, Marine Resources, Fisheries and Shipping is responsible for the long-term protection and conservation of marine biodiversity and habitats for sustainable use while maximizing socio-economic benefits. The ministry aims to achieve these goals through the management of the eight Marine Protected Areas (MPAs); assessment of coastal development and tourism-related projects; and regulation of permissible activities through the issue of permits for the Blue Bay Marine Park and interference permits for the other MPAs; among others. MPA managers can limit and/or prohibit damaging touristic activities, control the number of visitors, educate visitors, and assess visitor use impacts (Laffoley et al. 2019). In addition, to foster the engagement of local NGOs, coastal communities, and fishers in the protection and conservation of coastal areas and marine areas and resources, Mauritius has also adopted the concept of designating coastal areas as Voluntary Marine Conservation Areas (VMCAs). The VMCAs are local NGO- and community-driven, and do not fall under any legal entity for enforcement. VMCAs consist of important biodiversity areas worth protecting and ecotourism is encouraged through controlled visits and awareness campaigns. In Mauritius, currently, there are VMCAs in the lagoons of Pointe d'Esny (managed by the NGO Eco-Sud); Roches Noires and Anse La Raie (managed by the NGO Reef Conservation); and St. Felix (managed by the NGO Coral Garden Conservation). The effectiveness of these VMCAs is highly variable and questions about equity, social justice, and connectivity across VMCAs are concerns. Also, Eco-Sud and Reef Conservation provide marine eco-guide or naturalist training to skippers, coastal inhabitants, graduated students, and fishermen to help them seek alternate livelihoods in the tourism sector. The Ministry of Tourism, in consultation with relevant stakeholders and the assistance of the Mauritius Standards Bureau, has developed an eco-label for tourism operators to promote sustainable tourism. The idea is that the eco-label will attract environmentally conscious consumers and tourists. The grant scheme provides a centralized framework and is anticipated to improve environmental performance and maximize the efficient use of resources, among other objectives (Ministry of Tourism and Leisure Eco Label Grant Scheme).[1]

6.2.2 Regulatory Frameworks

The Mauritian Ministry of Tourism regulates and permits, or prohibits, most of the sea-based activities in the country, while the Tourism Authority and the National Coast Guard (NCG) enforce these regulations. The Ministry of Blue Economy, Marine Resources, Fisheries and Shipping is concerned with the area where the activity is being carried out. This ministry provides guidelines regarding minimizing impacts on fishing activities, fishermen/Fish Aggregating Devices/conservation zones/aquaculture sites, and the marine environment in general, and demarcates operation zones for various marine structures (e.g., jetty, pier, marina) as defined by the Fisheries and Marine Resources Act (2007). The government also emphasizes the development of environmental impact assessments for all businesses operating in the tourism sector.

The Tourism Authority (Dolphin and Whale Watching) Regulations (2012) of the Tourism Authority Act provide guidelines for dolphin and whale watching activity in Mauritius, primarily prohibiting physical contact, feeding, and any kind of noise pollution near marine mammals. A no-approach zone of 50 m radius from the closest dolphin and 100 m from the closest whale is also prescribed to avoid causing any form of harassment or disturbance to the mammals. All the activities are assessed and reviewed at the level of the National Coordination Committee for sea-based tourism activities of the Ministry of Tourism. The guidelines to regulate dolphin watching activity and the conduct codes have been developed with the help of a non-governmental organization (NGO), the Mauritius Marine Conservation Society,

[1] http://www.tourismauthority.mu/userfiles/file/tourismauthority/eco-label/Ministry_of_Tourism_A5_Brochure.pdf.

plus the Global Environment Facility (GEF) and the United Nations Development Programme (UNDP) (Gowreesunkar and Rycha 2015).

Regulated tourism activities in Mauritius that are considered as contributing to the blue economy include sea walking (equipment-aided walking on the seafloor), parasailing, kite surfing, water-skiing, SCUBA diving, kayaking, big game fishing, speed boating, catamaran trips, and glass bottom boat visits to shallow ecosystems. Jet skiing has been banned since 2016 in Mauritius (Tourism Authority [Prohibition of Jet Ski] Regulations 2016), as it is considered as a hazardous and unsustainable practice that may cause considerable damage to coastal and marine ecosystems, especially coral reefs (L'Express 2016). Dolphin watching is performed by local tour operators in boats, catamarans, and speed boats. This activity, has existed since 1998, was initiated by the biologist Delphine Legay for research purposes and was continued as a business by tour operators after her death. Dolphin tours occur mostly on the west coast of the island, primarily from the public beaches of Tamarin and Black River, and from hotels off Flic en Flac and Le Morne.

The Ministry of Tourism has declared non-motorized zones in the north of the island at Mont Choisy and Pereybere, designated specific swimming zones in public beaches, and has also well-demarcated embarkation points to ensure public safety. Tourist-related activities are further regulated in marine parks of the island—Blue Bay and Balaclava Marine Parks. Both were proclaimed national parks in October 1997 under the "Wildlife and National Parks Act 1993" and declared as Marine Park and Marine Protected Areas (MPAs) in June 2000 under the "Fisheries and Marine Resources Act 1998", amended in 2007.

Situated in the southeast of Mauritius, the Blue Bay Marine Park (BBMP) extends over 3.53 km^2 and is mostly visited by tourists for its pristine and ancient coral beds. It is enclosed by coral reefs protecting it from oceanic waves. The site was classified as a Ramsar Convention Wetlands of International Importance in 2008. The BBMP is divided into several zones depending on the various activities allowed. The MPA provides a wide variety of services to communities in addition to its direct conservation function—coastal protection zone, fish spawning, tourism/recreation, conservation, species protection, scientific research, and education areas. In 2011, 422 permits for authorized activities were issued for operation in BBMP (146 for boats/vessels, 67 for commercial activities, 99 for line fishing, 83 for recreational activities, 8 for temporary interference and 19 for basket traps). Activities such as swimming, snorkeling, diving, skiing, fishing, and -glass-bottom and non-motorized boating at the Marine Park are regulated by the Ministry of Blue Economy, Marine Resources, Fisheries and Shipping.

6.2.3 Tourism Impacts and Mitigation

Construction of hotels, resorts, coastal tourism residences and second homes along the coastal zones of Mauritius has considerably contributed to coastal erosion and degradation of intertidal and coastal habitats (Baird 2003; Bhagooli and Kaullysing

2019). Following the increase in the number of tourist arrivals, the country witnessed a boost in tourist accommodation construction along the coastal zones (Bhagooli et al. 2021b).

The Albion Fisheries Research Centre (AFRC), under the aegis of the present Ministry of the Blue Economy, Marine Resources, Fisheries, and Shipping, monitored five stations at BBMP for live coral cover. At one station, total live coral cover increased from 12% in 2010 to 32.15% in 2011, while at two other stations it decreased from 61.9 to 50.95% and from 38.1 to 36.4%. Other stations had an overall coral cover of less than 0.1% during both years (Ministry of Fisheries and Rodrigues Annual Report 2011). Bacha Gian et al. (2017) reported a gradual increase in overall live coral cover in the BBMP after the 2009 coral bleaching event, although from 2002 to 2010 a decline in coral cover was noted on Mauritian coral reefs. Conversely, McClanahan and Muthiga (2021) reported a decline in coral cover in BBMP wherein the percentage coral cover decreased at two sites from 57.5 and 29.8% in 2004 to 27.3 and 24.1% in 2019, respectively. Twenty-two out of the 24 coral taxa reported in 2004 were lost by 2019.

Furthermore, Bhagooli et al. (2021a) compared coral site data from 2005 and 2010 with 2002 data and noted declines in coral cover as drastic as 90–100% at some sites, with significant phase-shifts from coral to algal-dominated reef sites. Even in uninhabited islets like Gabriel there is a decrease of about 50% in coral cover between 1998 and 2018 (Bhagooli et al. 2021b). Also, *Stegastes* fish associated with the bleaching-susceptible branching coral *Acropora* provide indirect protection from predation to bleaching-resistant massive *Porites* and the loss of such *Acropora* coral cover due to ocean warming events may jeopardize the health of bleaching survivors like *Porites* (Tiddy et al. 2021). In terms of rare and/or endemic coral reef fish, only three (Mauritian Gregory, Mauritian anemonefish, and Blacklip damselfish) out of 10 such targeted species were found in Grand Port district, which includes BBMP (McClanahan et al. 2021).

The Balaclava Marine Park (BMP) is in the northwest part of the island and extends over 4.85 km^2. The marine park is divided into different zones, although management of the zones has not been fully implemented (Bhagooli and Kaullysing 2019). In BMP, 23 artisanal fishing boats, 6 glass-bottom boats, 17 speedboats, 6 security/rescue boats, 9 diving/snorkeling boats, 2 parasails, 22 pedalos or variously shaped pedal boats, 46 kayaks, 22 sailboats, 23 windsurfing boards/sails, and 124 snorkeling sets operated in 2011. Monitoring of live coral cover at seven stations at BMP revealed a decrease in percentage coral cover from 2010 to 2011 at four stations (51.8–10.5%, 49.3–33.1%, 63.6–56.4%, and 32.6–30.3%), and an increase at the remaining three stations during the same period (42.7–55.3%, 7.2–9.2%, and 24.9–26.4%) (Ministry of Fisheries and Rodrigues Annual Report 2011).

Monitoring surveys have been recurring since Blue Bay and Balaclava were proclaimed marine parks, but no in-depth scientific evaluation of the effectiveness of the regulations at the marine parks has been published. This makes it difficult to gauge the effectiveness of these measures in conserving the biodiversity and tourism-related uses of the protected marine parks. Landscape changes during construction activities in the coastal region of Balaclava (in the vicinity of the BMP) between 2006 and 2021 are shown in Fig. 6.4. Most of the hotels in this region were constructed or underwent major renovation prior to 2003. Additionally, the only airport of Mauritius that is located near the BBMP was expanded in the early 2010s and a new runway was also constructed (Fig. 6.4d–f). A new resort also was built in 2019 in this region (Fig. 6.4d–f). These developments may have caused an impact on the resources and habitats in the nearby marine protected areas. In addition to the influence of warming-induced mass coral bleaching/mortality, localized changes in the landscape over the years due to human activities might have led to changes in seascapes and coastal habitats. Coastal developments that lack consideration of their short- and long-term local impacts on coastal and marine ecosystems and habitats are prevalent. Illegal sand mining from beaches, dunes, and reef flats was carried out without appropriate authorization to nourish or reprofile beach areas in front of hotels (Duvat 2009).

Some mitigation measures of damaged reefs through coral "restoration programs" are in place with the support of the local concerned Ministry, UNDP (https://www.adaptation-undp.org/projects/Mauritius-Seychelles-Marine-AF), local NGOs, and hotels in Mauritius. So far, the focus is on establishing coral nurseries. However, the effectiveness of coral gardening/farming concepts and practices have yet to be thoroughly and independently assessed in Mauritius. Published scientific studies on coral transplantation/rehabilitation are rare from Mauritius. Pilot studies suggest that *ex-situ* coral culture may be a useful tool for coral conservation initiatives (Moothien Pillay et al. 2011). Bhagooli et al. (2021c) reported fragment-size dependency for coral nubbin mounted on concrete blocks for *Acropora muricata*, one of the thermally susceptible coral species. Further scientific investigations are required to support coral restoration activities with the engagement of tourists and the tourism industry in Mauritius.

Gowreesunkar and Rycha (2015) assessed the impacts of dolphin watching activities in Mauritius, as documented by a sample of 37 out of 40 tour operators, and 53 out of 60 local skippers operating along the west coast. Positive impacts included economic prosperity and employment generation and a willingness to protect marine life. Unfortunately, Gowreesunkar and Rycha (2015) found that compliance with guidelines was poor. For example, the 50 m no-approach zone was not observed, single animals were chased and exit routes blocked, and the skippers or tourists whistled or tapped in the water to attract the animals and often approached the animals at high speeds (Fig. 6.5).

Other activities, such as trampling while snorkeling and SCUBA diving, walking on shallow intertidal habitats or coral reef flats, extreme sports creating acoustic disturbance, crabbing, and gleaning have been reported to have serious impacts on coastal and marine environments (Beeharry et al. 2020). Still, there remains uncertainty about the direct impacts of these activities in Mauritius due to lack of research and reliable published data. Along with this gap in research, there is also ambiguity on the number of actual tourism operators (Duvat 2009), which makes it challenging to estimate, project, quantify and manage the damage caused to the coastal and marine environment. Nevertheless, unabated human trampling and mechanical fracturing of coral reefs during aquatic activities can have lethal and sub-lethal effects on certain coral species, as discovered in other regions (Rodgers et al. 2003).

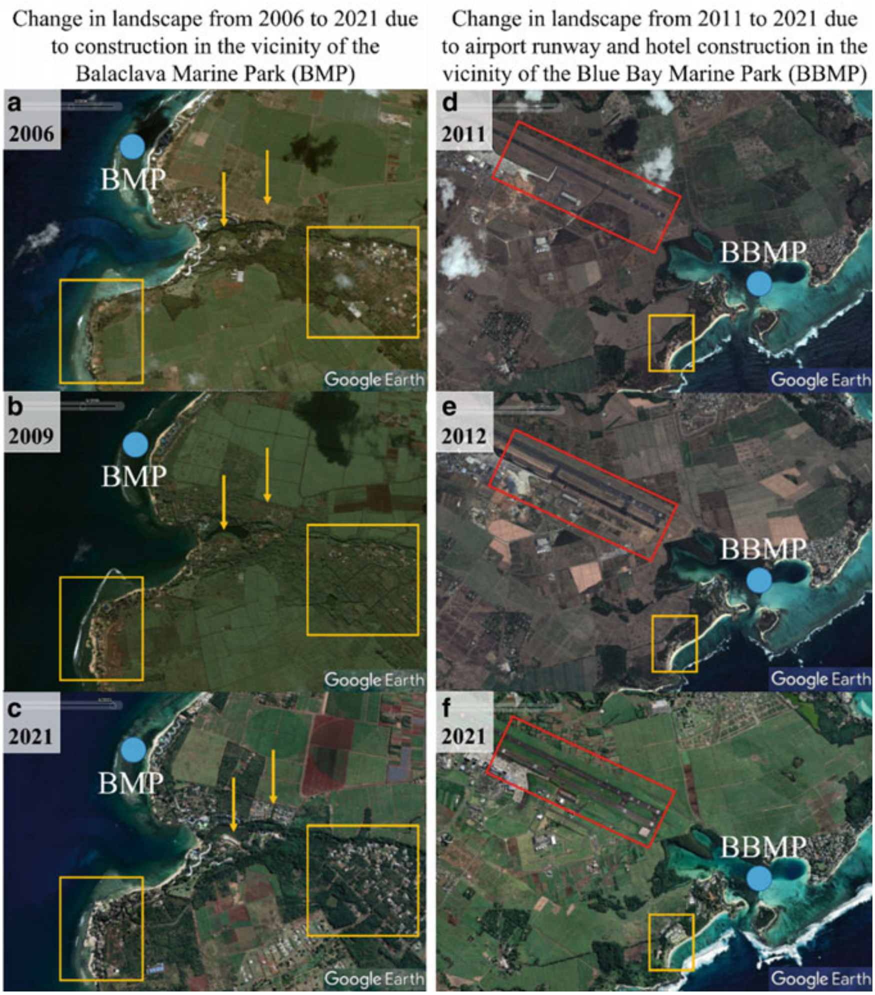


Fig. 6.4 **a–c** Resort/hotel construction along the coastal zones of Balaclava in the vicinity of the Balaclava Marine Park (BMP) showing a change in landscape from 2006 to 2021 (yellow boxes); **d–f** Change in landscape shown from 2011 to 2021 due to airport runway (red box) and resort construction (yellow box) in the vicinity of the Blue Bay Marine Park (BBMP). Image source: Google Earth.

Limited research has been carried out on the impacts of tourism activities on the marine environment and associated resources in Mauritius. A large gap exists between tourism and science in Mauritius and therefore, less investment in building resilience against the onslaught of climate change and tourism pressures. The country is data-deficient in terms of studying, understanding, and mitigating impacts resulting from the individual as well as combined marine tourism activities. Stakeholder interviews to gauge environmental impacts of tourism such as those conducted by

Fig. 6.5 (Top) Multiple tour boats lining up to search and follow dolphins. (Bottom) Swimmers in the water around a bottlenose dolphin near Tamarin, Mauritius during a dolphin sighting trip. Photos by Mridula Srinivasan

Gowreesunkar and Rycha (2015), Beeharry et al. (2020), and Gutleea et al. (2021), are useful but do not accurately capture the ecological ramifications in coastal and marine habitats from relentless and unregulated tourism. Reasons for the dissociation of tourism from science could be due to a lack of awareness about research benefits, perception that tourism is a benign activity, or that accepting or supporting scientific conclusions could jeopardize economic aspirations.

Mauritius witnessed a shift from the "Ocean Economy" concept in 2013 to "Blue Economy" in 2019. While terrestrial ecotourism (e.g., eco-tours/visits at Ile aux Aigrettes Nature Reserve) is common, being an island nation marine ecotourism has caught on, providing a source of alternate income, especially for fishing communities. For instance, when the Blue Bay Marine Park (BBMP) was established in 1997 to conserve biodiversity and control touristic and fishing activities, the fishers operating in that region were given the choice of modifying their fishing permits/registration and shifting their fishing activities to other regions of the island. Certain fishermen opted for shifting to other regions, while some became tour operators and glass-bottom boat skippers in the BBMP, with limited instruction on guidelines and regulatory practices.

Some hotel chains in Mauritius are owned by global companies. A study conducted by Fauzel et al. (2016) to analyze the impact of tourism Foreign Direct Investment (FDI) on the economic growth of Mauritius revealed a positive relationship between tourism development and economic growth of the island. The authors highlight that through the adoption of measures aimed at opening the economy, foreign investment was allowed by the government to develop key tourism assets such as restaurants, yachts, and travel agencies, among others. These policies have served to attract more FDI in the sector, attracted capital for further investment, and led to a large increase in direct and indirect employment. The downside of relying on foreign investments is that their levels can fluctuate, influenced by global market and consumer trends. Moreover, an increased presence of foreign investors can reduce the role of local communities in managing their ocean resources and potentially influence government entities to embrace a solely profit-based tourism culture.

On 6 August 2020, an oil spill emanated from the MV *Wakashio* that ran aground on the pristine reef/lagoon of Pointe d'Esny on the southeast coast of Mauritius. Over 1,000 tons of oil is estimated to have leaked into surrounding waters (Lewis 2020). The grounding of the MV *Wakashio* impacted coral reefs adjacent to the incident site, leading to excessive and recurring sedimentation plumes in the lagoon and potentially, smothering corals and other photosynthetic marine organisms (Fig. 6.6). The oil spill rapidly spread in the lagoon and towards the southeast and east coasts, adversely impacting the marine flora and fauna, especially mangroves—threatening the intricate connection among coral reefs, mangroves, and seagrass beds. This event led authorities to temporarily ban all tourism and fishing activities in the region. Consequently, several tour operators lost their jobs and faced hardship in trying to secure an alternate source of income. The highly frequented Blue Bay Marine Park and Ile aux Aigrettes nature reserve were declared off limits (Seveso et al. 2021). The oil spill was considered particularly serious because of the location of the spill—near a Ramsar site—rather than the quantity of oil released into the water. Like the 1989 oil spill from the *Exxon Valdez* and the 2010 *Deepwater Horizon* oil spill in the United States, the effects of the spill are likely to last for decades and require careful and rigorous environmental monitoring and habitat restoration.

In addition to acute impacts from events like the MV *Wakashio* spill, global climate change is occurring at an accelerated pace, compounding the negative impacts on marine ecosystem from other stressors. The Intergovernmental Panel on Climate Change (IPCC) report predicts that small island nations will be particularly susceptible to projected increases in sea level rise, cyclone activity, changing rainfall patterns, and warmer water and air temperatures (Nurse et al. 2014). The rate and intensity of climate change effects are especially evident in coral reef habitats experiencing frequent bleaching events and inhospitable environments. The rate of recovery and restoration of these systems are misaligned with the onslaught of environmental change and other synergistic human activities. Thus, tourism activities built on exploiting specific resources or habitats may cease to exist if the resource is depleted either due to unsustainable tourism practices, climate change impacts, or a combination of both.

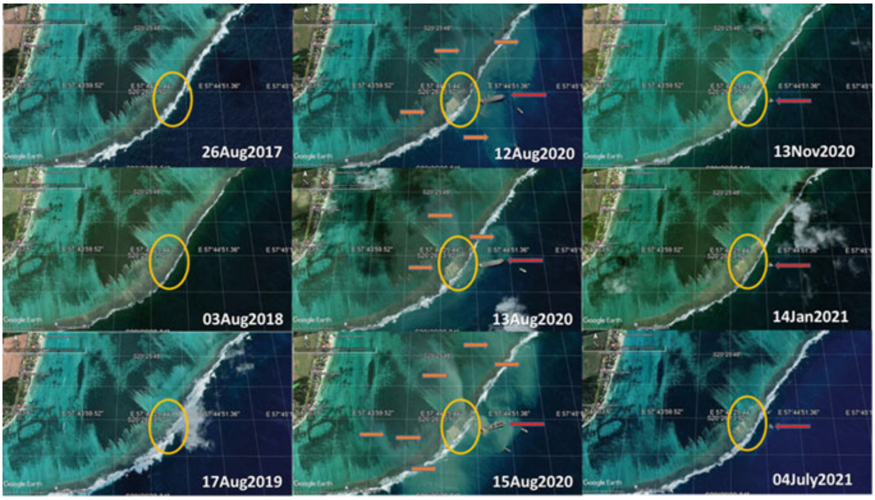


Fig. 6.6 Google Earth images captured on 26 August 2017; 3 August 2018; 17 August 2019; 12, 13, and 15 August 2020; 13 November 2020; 14 January 2021; and 4 July 2021. The red arrow, orange arrow and yellow circles indicate the position of MV *Wakashio* and/or its remnants, potential sediment plumes, and areas with and without excessive and recurring sedimentation, respectively

6.3 Pacific Islands Countries and Territories

Most tourism in the Pacific Ocean region could be classified as the Blue Tourism Economy. Despite a common depiction of many Pacific Island Countries and Territories (PICTs) as homogenous, there is much diversity among these locations. The impression of these tourist destinations from colonial times has been reinforced and perpetuated for centuries as tropical paradises with warm weather, crystal blue waters, white sandy beaches, and friendly welcoming locals (Fig. 6.7, Harrison 2001). But there are notable differences among these PICTs in terms of geography, culture, and history, and these all have a bearing on the number of tourists and the characteristics of tourism and its development.

The Pacific Ocean is the world's largest ocean basin, covering an area of 165,200,000 km^2. More than 10,000 islands are in this ocean, with a population of just over 13 million people. Even this statistic is somewhat misleading since the population of Papua New Guinea makes up two-thirds (8.7 million) of that total. A common, although blunt, categorization of PICTs (comprised of about 22 countries and territories) is to differentiate among Melanesia, Polynesia, and Micronesia based on physical geography—with Polynesia having an abundance of coral atolls, Melanesia more likely to have volcanic islands, and Micronesia having a mix (Harrison and Pratt 2013). Culturally, the Polynesian PICTs tend to be more ethnically homogeneous,

Fig. 6.7 Monuriki, Fiji (Photo by Stephen Pratt)

and Melanesian countries such as the Solomon Islands and Vanuatu are characterized by numerous people groups with different dialects and customs within their borders. Due to its colonial past, Fiji has a strong ethnic divide, which has resulted in political unrest from the late 1980s.

Often referred to as Small Islands Developing States, in the Pacific many scholars and Pacific Islanders are now seeing themselves as the Big Ocean States, emphasizing the large ocean resources they have, rather than their small land areas. This attitude has developed due to the large distances between individual countries and even within the same country. For example, in Kiribati, Kiritimati (Christmas Island) in the east is more than 3,000 km from Tarawa, the capital, with no direct air link. The large ocean resources of PICTs have driven much of the tourism in the Pacific. Encompassing a range of marine ecosystems from fringing and offshore coral reefs, mangroves and littoral forests, seamounts to seagrass habitats, the PICTs boast more rare, endangered, and protected species per capita than any other region in the world. The PICTs are unrivaled in marine species diversity and include a variety of whales and dolphins, seabirds, sea turtles, sharks, reef fishes, dugongs, and are home to the largest tuna fisheries (*Source* Secretariat of the Pacific Regional Environmental Programme http://archive.iwlearn.net/sprep.org/topic/NatRes.htm, Jupiter et al. 2014).

6.3.1 Tourism Revenue

Up until 2020 and the onset of the COVID-19 pandemic, tourism in PICTs grew steadily. Table 6.1 shows several measures of tourism size and impact for 17 PICTs.

Collectively, these 17 PICTs hosted 2,259,357 international tourists in 2019. But, there is a wide variation in the degree of tourism in each destination. Fiji (Fig. 6.8) hosted almost 900,000 tourists in 2019, roughly the same number as its population. At the other extreme, only 3,611 international tourists visited Tuvalu, one of the least visited countries in the world. Tourists spent just over USD 4 billion in the region in 2019, an average of USD 2,188.02 per capita population, again with substantial variation. With a population of 15,212, the Cook Islands has extremely high receipts per capita population, at USD16,053, while at the other end of the spectrum, visitors to Papua New Guinea and Kiribati spent an average of USD 40 and USD 79 per capita, respectively, reflecting their small-sized tourism sectors, but large populations. Tourism receipts per tourist averaged USD 1,648.68 across the 17 PICTs; the length of stay for tourists averages 10.7 days. French Polynesia, Solomon Islands, and Federated States of Micronesia (FSM) rank in the top three in tourism receipts per arrival, reflecting the more expensive nature of their destinations

Table 6.2 shows a different set of tourism indicators. Tourism earnings as a percentage of GDP averaged 17.3% across the 17 PICTs. Nevertheless, there is much variability. The Cook Islands are highly tourism-dependent, with tourism earnings being 66.1% of GDP. Fiji, Palau, Samoa, and Niue are also heavily reliant on tourism. Across the 17 PICTs, an estimated 90,821 people are employed directly in the tourism sector. The number of accommodation places and the number of rooms is another

Table 6.1 PICTs Tourism Arrivals and Receipts in the PICTs with the top 3 island nations shown in bold

PICTs	International arrivals (2019)	International Receipts (2019) ($US millions)	Receipts per capita ($US)	Receipts per arrival ($US)
American Samoa	19,237	$21.2	$374	$1,102
Cook Islands	171,606	$244.2	$16,053	$1,423
Fiji	894,389	$1,396.0	$1,566	$1,561
French Polynesia	236,642	$744.0	$2,677	$3,144
Kiribati	7,906	$9.2	$79	$1,164
Marshall Islands	10,771	$21.1	$386	$1,959
Federated States of Micronesia	19,712	$44.4	$422	$2,252
New Caledonia	130,458	$291.4	$1,070	$2,234
Niue	10,210	$7.8	$4,924	$764
Palau	94,030	$123.0	$6,873	$1,308
Papua New Guinea	158,390	$352.2	$40	$2,224
Samoa	173,920	$201.0	$1,018	$1,156
Solomon Islands	28,930	$78.2	$112	$2,703
Timor-Leste	111,400	$222.8	$172	$2,000
Tonga	67,517	$55.0	$550	$815
Tuvalu	3,611	$2.4	$229	$665
Vanuatu	120,628	$187.6	$651	$1,555

Source SPTO (2020)

measure of the size of the tourism sector from the supply side, but also indicates the size of each accommodation place. Fiji has a higher number of large resorts and hotels, including numerous internationally branded hotels, so the average number of rooms per accommodation place averages 30.5. Many of the other PICTs average 10–15 rooms per accommodation place, emphasizing the Micro Small Medium-Sized Enterprises (MSME) nature of this subsector of the tourism industry.

Table 6.3 shows the main source markets for the different PICTs. The main source markets for each PICT tend to follow geographic proximity and political/colonial ties (Harrison and Pratt 2015). The Melanesian PICTs' (Fiji, Vanuatu, Solomon Islands, PNG) main source markets are Australia. The Polynesian PICTs' (Tonga, Samoa, Cook Islands, Niue) main source market is New Zealand, while Micronesian PICTs' main source market is Asian countries. However, Europe and particularly France is the main source market for the French Overseas Territories of New Caledonia and French Polynesia. The United States, by having political ties with the Marshall Islands and American Samoa has higher representation in those PICTs.

PICTs also vary in terms of the primary motivations that tourists travel to the Pacific. While most PICTs are leisure destinations, countries such as Kiribati,

Fig. 6.8 Coral coast, Fiji (Photo by Spencer Pratt)

Marshall Islands, Papua New Guinea, Solomon Islands, and Tuvalu have a relatively high proportion of business visitors, which are classified for statistical purposes as tourists. These tourists tend to be consultants and experts who visit to work on development issues and have a relatively long length of stay. Several PICTS also have a large proportion of international tourists visiting friends and relatives. These destinations include American Samoa, Samoa, and Tonga, where a large segment of diaspora return to reconnect with their extended families.

Throughout the Pacific, there is a range of ecotourism operations related to the blue economy. These include scuba diving, snorkeling, surfing, kite surfing, dolphin and whale watching, yachting, and sailing. However, some Pacific destinations are better known for some of these activities and have developed their tourism products sustainably with a good reputation.

For example, on the island of Aitutaki in the Cook Islands, the annual Manureva Aquafest Kitesurfing Competition is held every August (Becken and Hay 2007). The week-long festival includes kitesurfing freestyle and race competitions, stand-up paddleboarding (SUP), outrigger canoeing, and a host of social activities. Scuba diving is particularly popular in the Solomon Islands, where fierce fighting in World War II led to the sinking of numerous ships and aircraft from both sides. These wrecks are now major attractions for scuba divers to explore (Panakera 2007). Fiji also has several unique scuba diving experiences where tourists can swim with manta rays (Murphy et al. 2018) or hand-feed sharks (Ward-Paige et al. 2020). Humpback whales

Table 6.2 PICTs and Mauritius Island Tourism Indicators and Supply

PICT	Tourism earnings as a % of GDP	No. Tourism Employees	Total No. of Accommodations	Total No. Rooms	Average length of stay (days)
American Samoa	3.3	1,709	20	263	8.1
Cook Islands	66.1	2,386	805	3,300	8.4
Fiji	25.8	15,094	423	12,888	9.6
French Polynesia	12.8	11,842	382	4,281	14.9
Kiribati	5.1	449	52	525	8.4
Marshall Islands	9.5	605	12	281	18.5
FSM	17.7	794	29	NA	9.0
New Caledonia	3.1	5,241	191	3,360	16.8
Niue	28.1	291	39	197	10.7
Palau	38.0	2,690	118	2,409	5.2
Papua New Guinea	1.5	25,000	501	6,195	10.2
Samoa	24.5	2,852	150	2,747	8.5
Solomon Islands	5.1	1,118	181	1,991	15.1
Timor-Leste	14.2	2,586	64	NA	10.0
Tonga	11.1	3,000	156	1,300	13
Tuvalu	5.6	87	10	NA	7.6
Vanuatu	22.6	15,000	867	1,722	8.1
Mauritius	**8.1**	**31,827**	**112**	**13,489**	**10.6 (nights)**

Source SPTO (2020), Digest of International Travel & Tourism (2019), Handbook of Statistical Data on Tourism (2019)

(*Megaptera novaeangliae*) visit Tonga and Niue from June until mid-October (IFAW, 2009). Becken and Hay (2007) estimated that the benefits from whale watching in Tonga grew from USD 500,000 per year in 1999 to USD 5 million per year by 2009.

6.3.2 Economic Value of Marine Tourism in PICTs

Several studies have been conducted estimating components of marine-based tourism in the Pacific. For example, Pascal et al. (2015) in their study of Vanuatu, report that, in 2013, a total of approximately 47,000 dives were undertaken, which equates to

Table 6.3 Source markets for tourists

PICTs	Australia (%)	New Zealand (%)	North America (%)	Europe/UK (%)	Asia (%)	Pacific Islands (%)	Other (%)
American Samoa	3.9	15.0	24.1	2.5	4.7	49.0	0.6
Cook Islands	16.1	66.7	7.1	7.2	1.3	1.1	0.6
Fiji	43.4	21.9	11.1	6.1	10.6	6.4	0.6
French Polynesia	5.0	4.7	37.5	34.5	11.0	2.9	4.3
Kiribati	19.4	8.7	23.3	7.8	11.2	26.5	3.3
Marshall Islands	3.9	2.2	26.7	2.7	26.1	34.0	4.5
FSM	N/A						
New Caledonia	19.6	8.5	1.1	36.0	20.4	12.7	1.8
Niue	9.7	79.1	2.4	5.0	1.6	2.0	0.1
Palau	0.5	0.1	6.1	0.4	91.3	0.7	0.8
Papua New Guinea	49.0	5.1	5.1	6.3	29.1	4.0	1.3
Samoa	20.9	45.5	6.7	2.8	4.4	18.3	1.4
Solomon Islands	39.5	6.6	7.0	5.5	19.9	19.7	1.7
Timor Leste	12.8	0.9	2.2	11.1	71.2	0.1	1.7
Tonga	20.7	45.2	14.5	6.7	6.9	5.3	0.8
Tuvalu	12.6	8.5	6.4	9.7	20.4	35.6	6.7
Vanuatu	52.6	10.6	2.8	6.2	4.3	21.1	2.4

Source SPTO (2017); N/A = Not Available

about 9,000 divers. Almost two-thirds of the dives took place in Efate, Vanuatu. In addition, 9,000 snorkel trips were recorded. The corresponding value-added of the dive shops is estimated at approximately USD 1,600,000 in 2013 (USD 1,100,000 in Efate and USD 500,000 in Santo, Vanuatu) (Pascal et al. 2015). In total, the annual economic value of marine and coastal ecosystem services in Vanuatu in 2013 on tourism and recreation was estimated to be USD 9.59 million.

Rouatu et al. (2017) sought to estimate the economic value of tourism from marine and coastal ecosystem services in Kiribati. In 2015, they estimate the value to be USD 3.9 million, which should be sustainable if pollution and damage from tourists are controlled. Within the same Marine and Coastal Biodiversity Management in Pacific Island Countries (MACBIO) project, the economic value of tourism from marine and coastal ecosystem services in Tonga is estimated to be between USD 2.0 and 4.9 million, which will be sustainable if pollution and damage from tourism development and tourist activities are monitored and controlled (Salcone et al. 2017). In the Solomon Islands, the tourism component of the economic value of tourism marine and coastal ecosystem services was estimated to be USD 15.8 million (Arena et al. 2015).

In Palau, Vianna et al. (2010) compare the value of shark tourism with the fisheries value of sharks. The shark-diving industry attracts 8,600 divers each year or approximately 21% of the divers visiting Palau. The value of sharks, in terms of tourism, to the Palauan economy was estimated to be USD 18 million per year, which is approximately 8% of Palau's GDP. An individual reef shark in Palau was estimated to have an annual value of USD 179,000, extrapolated up to a lifetime value of USD 1.9 million to the tourism industry. The annual income in salaries paid by the shark-diving industry to the local community was estimated to be USD 1.2 million. A fishery targeting the same 100 sharks that are interacting with the tourism industry in Palau would obtain a maximum of USD 10,800, or 0.00006% of the lifetime value of these animals as a non-consumptive resource (Vianna et al. 2010).

6.3.3 Regulatory Frameworks

In recent years, PICTs have started to enact or strengthen legislation surrounding marine and coastal resources. Nevertheless, there is also a need at the regional level, under the United Nations Law of the Sea Convention (UNCLOS), for PICTs to have integrated management plans, while still respecting sovereign rights, to increase the benefits for Pacific Islanders. Some Pacific regional initiatives have been adopted. For example, the Cleaner Pacific 2025—Pacific Regional Waste and Pollution Management Strategy 2016–2025 is a comprehensive regional framework for sustainable waste management and pollution prevention in the Pacific region (Parkinson 2020). The Secretariat of the Pacific Regional Environment Program (SPREP) also produced the Pacific Marine Action Plan: Marine Litter 2018–2025, as part of the Regional Seas Programme and the Global Partnership on Marine Litter (SPREP 2018). This Plan sets out the policy context and key actions and activities to minimize marine litter across the PICTs, including terrestrial-based marine litter point sources. Other international legislation and regulatory frameworks that apply to the blue economy and indirectly to tourism include the Convention on International Trade in Endangered Species of Wild Fauna and Flora, the IUCN Red List of Threatened Species, and the Convention on the Conservation of Migratory Species of Wild Animals.

In May 2020, Fiji provided a working draft of its first National Ocean Policy and enshrined it in law in 2021. The vision of the National Ocean Policy is to provide for "a healthy ocean that sustains the livelihoods and aspirations of current and future generations of Fiji" while the mission of the Policy is "to secure and sustainably manage all of Fiji's ocean and marine resources" (Republic of Fiji 2021). The policy recognizes that Fiji has large areas of ocean and marine resources that it has both rights to use, but also responsibility to manage (Sloan et al. 2020). These ocean areas accommodate numerous and sometimes competing uses and may be adversely impacted by a range of development activities that are regulated by different government ministries or departments. One of the goals of the National Ocean Policy is to create the foundation for Fiji's blue economy by outlining how its resources will directly benefit its citizens in terms of both direct and indirect economic benefits, support other industries including tourism and safeguard or provide for cultural knowledge, food security, border security and how it will deal with and adapt to threats like climate change (Sloan et al. 2020).

For some time, Fiji citizens have made a voluntary pledge not to eat Grouper and Coral Trout during peak breeding season. In 2018, Fiji's Ministry of Fisheries made this a legal ban in this breeding season. However, with the onset of COVID-19, this ban was removed due to concerns about residents having access to food during the pandemic. Nevertheless, seasonal bans and species restrictions remain an important management tool from a fisheries management perspective to enable the recovery of stocks of certain fish. This management tool has been used globally to manage both fish and game species and ideally should be based on knowledge of the breeding patterns of the species that are being managed (Sloan and Samuela 2020).

Environmental lawyers have urged Tuvalu to develop a national ocean policy along the lines of the Fiji version which aims to implement a shared vision for its ocean areas and resources. Given the importance of the ocean and its resources for Tuvalu, there is a need to protect and sustainably manage this natural resource in an integrated way (Pelesala et al. 2020). While the landmass of Tuvalu is just 26 km^2, its ocean resources (EEZ) are 717.8 km^2. A good ocean policy provides a framework for sustainable development, management, and conservation of oceans resources and their habitats. Developing a national ocean policy would need buy-in from a wide range of stakeholders. The policy would also need to link with existing laws and governance frameworks, such as the Marine Resources Act (2006), Fisheries (VMS) Regulations (2000), Conservation and Management Measures Regulations (2009), and the Maritime Zone Act (2012), among others. Further, a national ocean policy would also need to recognize the different responsibilities of different government ministries. For example, the Ministry of Fisheries and Trade looks after fisheries, maritime boundaries, and ocean areas; the Ministry of Foreign Affairs is responsible for the marine environment, climate change, sea patrols, and international ocean forums, while the Ministry of Transport, Energy, and Tourism is responsible for shipping, ports and marine cables (Pelesala et al. 2020).

In 2021 the South Pacific Tourism Organisation finalized its Pacific 2030 Sustainable Tourism Policy Framework, which sets out the vision, policies, and actions needed to transform tourism to make it more sustainable and provide greater benefits to the communities of the Pacific (SPTO 2021). The framework aims to support prosperous and resilient economies, empower communities, amplify and promote culture, accelerate climate action, protect ecosystems, and build resilience.

Several PICTs have produced National Tourism Development plans. The focus of many of these plans is on increasing the economic benefits of tourism to PICTs. The emphasis tends to be on increasing international tourist arrivals, destination awareness, and tourism product development. For example, the Solomon Islands National Tourism Development Strategy 2015–2019 emphasizes five areas: (1) marketing and research; (2) transport and infrastructure; (3) product development and investment; (4) human resource development; and (5) cruise shipping and yachting (Solomon Islands Government, 2015). The Vanuatu Tourism Action Plan 2014–2018 acts as a guideline to facilitate development in the tourism industry by "Doing the Basics Better". The five key priorities areas of this plan are (1) deliver tourism benefits to the outer islands; (2) focus all key marketing efforts on core markets; (3) invest in planning and building infrastructure that will benefit tourism; (4) address the expectations of the tourism markets; and (5) work effectively and with clarity on who does what for Vanuatu tourism (Vanuatu Ministry for Tourism Industry and Commerce & Ni-Vanuatu Business 2013).

Fiji has had a long tradition of producing tourism development plans. The earlier plans almost predominantly focused on marketing, such as the Fiji Visitors Bureau Strategic Plan 1989–1991 to the Fiji Tourism Development Plan 1998–2001, Fiji Tourism Development Plan 2007–2016, and the most recent Fiji Tourism Development Plan 2021 (Fiji Ministry for Industry Trade and Tourism 2019). These national tourism development plans tend to mention sustainability throughout the document, yet the key performance indicators all relate to economic growth, improved business success, and destination marketing. The SPTO Pacific 2030 Sustainable Tourism Policy Framework differs in this regard in that there is a better balance between economic viability and the environment and society and culture.

At a micro-level, for the most part, it is left up to tourism operators to self-regulate. For example, Pratt and Suntikul (2016) note that one dolphin-watching operator in Fiji follows the precautionary principle. Following the guidelines of SPREP (2008), this operator insisted that tourists should not feed the dolphins and the captains do not allow any swimming with the dolphins. The captains of the dolphin-watching vessels have been instructed not to make sudden or repeated changes in the direction or speed of the boat; not to chase, encircle or block the path of the dolphins or separate a group of dolphins.

Often, there is legislation in place to protect the environment, but Pacific Island governments have few resources available for effective monitoring and evaluation. Yet, the Pacific Islands are starting to get serious about corporations that damage the environment through tourism development. In a landmark case starting in 2019, after the New Zealand media and then Australian media highlighted environmental damage created by a foreign resort developer on Malolo Island, Fiji, the Fiji Government took the developer to court. Freesoul Real Estate Development Limited was found guilty of two counts of undertaking unauthorized developments in Malolo (Fiji Village 2021). The developers started construction on a 350-room resort without the required permits, destroying the local fishing grounds and mangroves, which will cost millions of dollars to restore (Newsroom 2019). At the time of writing, sentencing is yet to take place, but under the Environment Management Act 2005, the company and its directors face fines of up to FJ$ 750,000 (approximately US$ 360,000) a term of imprisonment of up to 10 years, or both (Fiji Village 2021).

The Pacific is particularly vulnerable to the impacts of climate change (Becken and Hay 2007). While out of the control of Pacific Island governments, they can try to reduce their vulnerability and adapt to climate change. Klint et al. (2015) discuss the interactions that effects of climate change—such as sea level rises, beach erosion, and increases in the intensity and frequency of extreme weather events—have on tourism in the Pacific. Using Kiribati, Samoa, and Vanuatu as examples, Klint et al. (2015) recommended possible adaption measures such as protection of coastal areas, desalination plants, and rainwater tanks; relocation of tourism infrastructure; adoption of stricter building standards; and diversifying tourism markets to a broad range of tourism products. In the aftermath of the 2009 tsunami in Samoa, Jiang et al. (2015) documented a community perspective to understand the resilience of those involved in the Samoan tourism industry in light of its vulnerability to climate change. With a spotlight on Vanuatu, McNamara et al. (2020) highlight several adaptive initiatives taken by the local communities who are dependent on tourism, fishing, and agriculture to combat the effects of climate change. Examples of these adaptation projects include construction of a sea wall along the coastline to adapt to the climate change risks of storm surges, erosion, cyclones, and drought and protection of coral ecosystems through training and the creation of incentives around crown-of-thorns starfish control.

6.3.4 Tourism Impacts and Mitigation

While much of the academic literature on the impacts of tourism has been quite broad and focused more on both the economic impacts and socio-cultural impacts, several studies have explored the nexus between tourism and the environment. Sykes and Reddy (2009) demonstrated that over 10 years from 1998, a small indigenous community in Fiji established a community-managed Marine Protected Area. Biological surveys and socioeconomic assessments were implemented annually. The results showed increased fish populations within the MPA after three years and increased invertebrate populations after five years. Despite some poaching still occurring inside the MPA, it did not significantly impact the overall populations, suggesting ecosystem resilience. A small coral restoration project is thriving inside the MPA. The MPA had economic and social importance to the local community and due to conservation of the MPA, healthy coral and fish stocks enabled the community to generate income through ecotourism activities.

Recognizing that the marine environment is vital for Fiji's tourism sector, Mangubhai et al. (2020) explore the extent and scale to which "Marine Conservation Agreements" (MCAs) between tourism operators and indigenous, resource owning communities are used in Fiji, and their contribution to biodiversity conservation and fisheries management. Collecting data from March to October 2017, Mangubhai et al. (2020) found that 56 of the 81 (69.1%) tourism operators surveyed had been involved, were involved, or were becoming involved in some form of MCA. All operators were using MCAs as a tool to establish some type of MPA (e.g., marine spatial closure) within the traditional fishing grounds of indigenous Fijian communities (Mangubhai et al. 2020). Almost half (48%) of the MCAs were simple "no-fishing" MPA agreements, while the other half (52%) had additional bans on reef walking, shell collecting, and/or the use of motorized water sports. Almost half of these tourism businesses (45%) implemented reef enhancement projects such as coral planting and giant clam restocking while over a third (36%) organised the removal of predatory crown-of-thorns starfish when outbreaks occurred.

Realizing the importance of nature-based marine tourism and the uniqueness of shark dives as a tourism experience, Ward-Paige et al. (2020) took a five-year snapshot of Fiji's shark population that may be used to further evaluate and compare future shark populations. In Fiji, also four in five (78% or approximately 49,000) divers are engaged in shark diving each year (Vianna et al. 2010). In 2012, Ward-Paige et al. (2020) worked with 39 dive operators in collaboration with eOceans to start the Great Fiji Shark Count to document sharks (and other species) on 592 dive sites. Eleven shark species were identified from 30,668 dives. The results can be used to guide future scientific research and provide a baseline for future assessments. The studies cited above are examples of how scientific studies can direct policy decisions and better inform tourism operators to be more sustainable. They provide the information needed to make science-based decisions.

Two Pacific SIDS, Fiji and Palau, have recently introduced new taxes aimed at protecting the physical environment. Fiji's Environment and Climate Adaptation Levy (ECAL) is a tax on prescribed services, items, and income. The ECAL funds collected as of 30 April 2018 totaled FJ$ 110.6 million (USD ~52 M), of which FJ$ 106 million (USD ~50 M) had been spent.

The ECAL is levied on different sectors of the tourism industry, from eating places to accommodation and activities providers (Table 6.4). The tax is essentially a tax on the tourism industry. Almost 94% of the ECAL tax revenues are derived from the tax on prescribed services. The prescribed services levied with this 10% tax are the ones offered from the following businesses: licensed hotels, inbound tour operators, licensed bars, tourist vessels operating within Fiji waters, licensed nightclubs, organizers of entertainment programs/product exhibitions, recreational activity operators, cinema operators, licensed rental/hire car operators, bistros and coffee shops, licensed restaurants, aircraft operators, water sports operators, homestay operators, unlicensed service operators.

Sixty percent of the tax revenues are spent on infrastructure development and a further 27.5% is spent on rehabilitation after Tropical Cyclone Winston. Little or none of the tax revenues imposed on the tourism industry are focused directly on sustainable tourism development (or research related to tourism impacts). Under the categories of sustainable resource management, there are several relatively low-value projects such as coastal fisheries development, aquaculture development, food security program (aquaculture), reducing emissions from deforestation and forest degradation, research and development of wood and non-wood species, reforestation of degraded forest and reforestation of indigenous species. Under the category of energy conservation, there are allocations for renewable energy development projects

Table 6.4 Environment and Climate Adaptation Levy (ECAL) Utilization by Thematic Areas (ECAL in Action, Fiji Government https://www.fiji.gov.fj/getattachment/e71b8d61-ce72-48fc-bca2-eeeff2d8739b/Environment-Climate-Adaptation-Levy.aspx)

Infrastructure development	60.0%
Tropical cyclone winston rehabilitation	27.5%
Agricultural development	5.0%
Sustainable resource management	2.0%
Disaster relief and response	1.0%
Meteorology services	1.0%
Rural development	1.0%
Urban development	1.0%
Energy conservation	1.0%
Environmental conservation	0.5%

and supply, installation, and upgrades of solar home systems. These projects are only indirectly related to tourism.

Effective January 1, 2018, Palau has legislated a Pristine Paradise Environmental Fee (PPEF). A fee of US$ 100 is included in the price of every international airline ticket into Palau (Palau Customs 2018). The ticketing airline is responsible for collecting the PPEF. Palauan passport holders are exempt. The PPEF will be used to finance the Palau National Marine Sanctuary (Kesolei 2018). The objective of the tax is to protect the marine sanctuary by preserving 80% (500,238 sq. km) of Palau's Exclusive Economic Zone as the Palau National Marine Sanctuary. The remaining 20% (85,896 sq. km) will serve as a domestic fishing zone.

Compared to Fiji's ECAL, Palau's PPEF will be directly spent on either tourism operations, such as the International Airport or the environment (Protected Are Network or Fisheries Protection Trust Fund). Only a smaller share goes to a general fund (National Treasury and State Governments).

6.4 Discussion

Marine tourism has existed in some form for over one thousand years or more, but became pronounced as Europeans began to pursue coastal recreational activities in the Eighteenth Century (Orams 2002 and references therein). The advent of SCUBA diving, recreational vessels, transportation, and technological growth made access to coastal areas a sought-after attraction for diverse tourists, not just the wealthy (Orams 2002).

Wildlife tourism, especially whale watching, has become a significant and profitable attraction globally and by far the most prominent component of marine tourism (Hoyt 2001; O'Connor et al. 2009). For example, in 2008, the International Fund for Animal Welfare reported that 13 million people from 119 countries and territories engaged in whale-watching activities, amounting to a total expense of USD 2.1

billion (O'Connor et al. 2009). In fewer than one hundred years, humans have transitioned from hunting and killing whales to watching whales, starting in Hawai'i in 1979 (Forestell and Kaufman 1990; Cisneros-Montemayor et al. 2010; Cunningham et al. 2012).

Tourism activities are viewed as a benign substitute to the invasive and extractive whaling, fishing, mining, and oil and gas industries (Bearzi 2017). Yet, for more than two decades (Forestell and Kaufman 1990; IWC 1996; Corkeron 2004; Constantine and Bejder 2008; Christiansen and Lusseau 2015; Machernis et al. 2018), several short- and long-term studies have recorded that uncontrolled whale watching (a collective term for whale, dolphin, and porpoise viewing and swim-with-animal operations) can induce negative behavioral and population-level changes in exposed animals. Constantine and Bejder (2008) argued that the burden of proof must shift from scientists and conservationists to industry, such that the tourism industry would need to substantiate the lack of biological impacts on the species or habitat from whale watching operations. But in smaller nations, and island countries with a less industrialized tourism sector, shifting responsibilities are alone insufficient because of the lack of infrastructure, scientific and resource support, as well as an abdication of safety norms in these regions like the ecotourism issues highlighted by Pasape and Mujwiga (2017) in Tanzania.

Despite the enthusiasm and economic capital for marine tourism, the lack of capacity and support for local tour operators can hamper the ability to assess and mitigate tourism impacts without compromising livelihoods. This is evident in Mauritius and some PICT countries. Therefore, in such situations, governments must invest in the science necessary to inform how to adaptively manage various tourism operations. Systems modeling with stakeholder participation (e.g., Bayesian Belief Networks; Meynecke et al. 2017) or participant modeling (PM) approaches are becoming prevalent to help integrate climate change, socio-economics, policies, and ecological impacts in designing the appropriate management scheme for a specific region (Hedelin et al. 2021). But PM approaches must be preceded by committed investments in comprehensive baseline data collection regarding the area, timing, number, and types of legal and non-legitimate tourism activities in an area.

Tour operators can be excellent citizen scientists with the appropriate training, scientific collaboration, and resources (e.g., GPS, electronic tablets to record data, digital SLR cameras, hydrophones, drones, GoPro underwater cameras). Scientific data collection during tour operations adds tremendous value to rapidly assess seasonal and inter-annual changes in habitat or species behavior, even with the inherent biases in the sampling protocol. Tour operations can generate vast amounts of continuous data that span a full year or season, and across multiple years. Despite many studies that have leveraged platforms of opportunity (POPs), citizen science remains an underutilized resource in the marine and coastal sciences (Roy et al. 2012). Some examples include using POP data in Alaska to study killer whale predation of beluga whales (Shelden et al. 2003), behavioral assessment of common dolphins in Hauraki Gulf, New Zealand (Stockin et al. 2009), bull shark associations at a dive feeding site in Fiji (Bouveroux et al. 2021), and occurrence of rare/endemic corals and reef fishes in Mauritius (McClanahan et al. 2021). Moreover, citizen science can be a huge benefit to marine conservation and allow the public and businesses to serve as environmental stewards and yield societal benefits, including economic gain (Cigliano et al. 2015). Basic longitudinal data collection on marine species occurrence, geospatial information, and behavioral responses to different human-caused stressors should remain the overarching goal. Data collection does not have to be complicated or involve technologically advanced monitoring systems.

Researchers and citizen scientists are encouraged to establish systematic and continuous data collection programs that allow scientists and managers to understand spatiotemporal patterns and trends in abundance, species richness and diversity, distribution, and acute and chronic responses to environmental disturbance that may synergistically or cumulatively affect essential habitat or species population viability.

In small island nations with ocean-dependent economies, it is important that local tour operators have the means to override systemic upheavals or variable tourism demands and are trained and informed environmental stewards. Also, governments should avoid relying exclusively on international scientists and organizations for scientific support and environmental protection. Instead, governments and other authorized agencies, should promote an environment that emboldens the local and independent community of scientists, managers, and stakeholders to create bottom-up co-management conservation models, build local scientific capacity, and oversee scientific studies and implementation of research recommendations. Such an approach does not discount foreign financial support, training, and co-production of data that must happen with experts and invested environmental organizations.

In general, for drastic shifts in tourism management practices to occur, collectively we need to accept that tourism activities are not "benign" and treat them like any other environmental stressor. Such activities need to be managed in the context of other exploitative marine industry practices and appropriate limits imposed through a proper compliance framework. Like any marine industry activity (fish farming, renewable energy development, defense), the first step is to collect scientific evidence to characterize the threat and impacts on marine species and affected habitats, and then adopt and implement an adaptive management framework to modulate activities based on newer data, changing environmental conditions, or animal status at different planning and policy levels and scales (Higham et al. 2009). Higham et al. (2016) similarly argued that tourism should be viewed and managed as a non-lethal consumptive activity, which results in sub-lethal anthropogenic and energetic stress. The treatment of tourism activities as a stressor is an essential step for international, national, and local governing entities to design and construct the appropriate regulatory, management, and scientific models, regardless of a small or big nation status.

The case studies discussed here highlight similarities and disparities across the ocean divide and the struggles to achieve the blue economy dream. At the same time, small island nations benefit and suffer because of their bountiful ocean. Tourism numbers alone reflect the immense attractiveness of small island nations to the global tourist. The rich biodiversity, less-trodden paths, and beautiful seascapes fulfill a tourist's expectation of wanderlust. But the socio-cultural norms, geopolitics (including colonial ties), and foreign investments lead to contrasting styles in marine tourism management and governance. Myopic legislation, multiple ministries with fragmented and sometimes conflicting jurisdictions, and regulations with little or no enforcement is an oft-repeated complaint. The flood of tourism arrivals in places like Mauritius are not supported by concomitant evaluation of the tourism carrying capacity and their effects on trust resources. Overall, there is inadequate recognition that ocean resources are not static and self-replenishing.

Moreover, there is no apportionment of tourism revenue and any associated fees levied by different countries towards science. Science appears to be divorced from tourism management and sustainability rather than a necessity to comprehensively manage tourism impacts. Tourism is irrevocably linked to other marine industries that includes artisanal and commercial fishing operations, oil and gas, shipping, mineral extraction, defense, coastal development, as well as climate change mitigation projects. The adverse effects from these marine users may be compounded by tourism ventures, which overburden a system already irreparably damaged by one or another industry. Thus, ocean resource use planning needs to account for interactive stressor effects on the marine ecosystem and evaluate human impacts holistically rather than sectionally as has being recognized in the Caribbean and Mediterranean regions (CARSEA 2007; Plan Bleu 2014).

Governments and tour operators need to realize that tourism ventures can be drastically cut short due to shifting species distributions, localized population declines or due to global climate change, pandemics, and human-caused perturbations (Higham and Lusseau, 2007; Shelton and McKinley 2007; Higham et al. 2009). The recent oil spill in Mauritius laid bare the consequences of environmental disturbance and the capricious nature of tourism. A thriving dolphin tour industry in Mauritius was forced into closure due to the COVID-19 pandemic, leaving many operators hopelessly searching for alternate occupations. Short-term financial support may help to tide over tourism business operators during desperate times, but it is not a viable solution when tourism operations are likely to be constantly threatened by unpredictable and insurmountable events.

The effects of the oil spill in Mauritius were compounded by the unfavorable location of the spill and an already reeling tourism economy due to the global COVID-19 pandemic. In effect, these events revealed the impermanence of marine tourism that rely on mobile species, pristine habitats, or vulnerable ecosystems. To be agile, an alternate management scheme must be pursued that is resilient to fluctuating markets and environmental change, both human-caused and natural. The suggestions offered here are not new (Higham et al. 2009, 2016), but reinforcing these ideas is important to help revitalize existing tourism models and change mindsets.

A touted measure to promote marine conservation is the creation of Marine Protected Areas (MPAs) (Ban et al. 2012; IUCN 2018). However, the failure or success of MPAs depend largely on the management scheme and local circumstances (Pendleton et al. 2018). Although many governments are tempted into setting up as many MPAs as they can, the effectiveness of these MPAs are irregular. In fact, establishing MPAs does not guarantee marine ecosystem impregnability. Local cultures, stakeholder engagement, economic and education status, livelihood-augmenting schemes, regulatory systems, and ecology are all factors that can derail management of an MPA (Chaigneau and Brown 2016; Pham-Do and Pham 2020). There is no one tourism management system that will work without trial, testing, and modification (Giakoumi et al. 2018). To that end, we provide a list of recommended actions that may fortify existing schemes and allow incremental improvements in tourism governance, especially in small island nations to someday attain the blue economy promise (Box 6.1).

Box 6.1 Recommendations for Realizing the Promise of a Blue Economy in Small Island Nations

Apportion tourism fees and taxes to investigate and monitor impacts from tourism activities and other synergistic stressors.

With scientific rigor, conduct environmental impact assessments of tourism activities to determine which tourism activities are sustainable and which are not in the interest of maintaining healthy and vibrant ecosystems.

Acknowledge that uncontrolled tourism is a sub-lethal stressor comparable to other human disturbance or destructive activities and therefore, subject to impact-dependent mitigation and monitoring requirements.

Implement holistic ocean resource management that evaluate human stressors effects in totality to inform concrete management and conservation solutions and prioritization of ocean space use, wherein, coastal, and marine tourism activities are not treated in isolation.

Establish Marine Protected Areas (MPAs) as test beds for experimentation and evaluation with stakeholder engagement and compare it to control sites with no protections before officially declaring MPAs. The creation and elimination of MPAs can be an adaptive process informed by cost-benefit analysis within and outside MPAs. MPAs need not be a permanent or only solution.

Promote and encourage community-led conservation practices and transmission of local ecological knowledge.

Invest in tourist education and outreach programs. Tour operations must have an educational component to them (see Cheung et al. 2020).

Frequently train (on a prescribed schedule) tour operators on regulations, guidelines, and scientific data collection. An informed and environmentally aware tour operator will ensure safeguards are in place and will be an effective environmental steward.

Limit the number of permits awarded to tour operators and establish conditional permit renewals based on performance evaluations. Both quality and quantity matter in limiting tourism impacts on marine ecosystems.

Invest in tourism infrastructure, tour operator safety, and access to diverse tourism initiatives that are resilient to economic or environmental turmoil.

Build local science capacity to enable the rise of the next generation of scientists and ocean leaders from the community and collaborate with regional and international scientists in the co-production of ocean observation and other ecological, economic, or human dimensions data.

Run public-awareness campaigns about sustainable tourism practices and the importance of valuing and protecting marine life and the broader ecosystem for societal health and economic growth.

Enforce guidelines and regulations. Temporarily exclude from area or activities or collect fines from tourists and tour operators for flouting rules. Consider permanent suspensions of permits or licenses if there is a pattern of negligence.

Disclaimer The scientific results and conclusions, as well as any views or opinions expressed herein, are those of the author M. Srinivasan and do not necessarily reflect those of NOAA or the Department of Commerce.

References

Appadoo C, Rabi FD, Antha S et al (2017) Mangroves of small Islands. In: Bosire JO, Mangora MM, Bandeira S et al (eds) Mangroves of the Western Indian Ocean: Status and Management. WIOMSA, Zanzibar, pp 115–134

Arena M, Wini L, Salcone J et al (2015) National marine ecosystem service valuation: Solomon Islands. http://macbio-pacific.info/wp-content/uploads/2017/05/Solomons-MESV-Report-Digital-LoRes.pdf. Accessed 5 Jan 2020

Bacha Gian S, Munbodhe V, Soogun N et al (2017) Mauritius. In: Obura D, Gudka M, Rabi FA et al (eds) Coral reef status report for the Western Indian Ocean. Global Coral Reef Monitoring Network (GCRMN)/International Coral Reef Initiative (ICRI), pp 78–87. https://nairobiconvention.org/clearinghouse/sites/default/files/Coral%20reef%20status%20report%20for%20the%20Western%20Indian%20Ocean%20%282017%29.pdf. Accessed 18 Aug 2021

Baird WF, Associates (2003) Study on coastal erosion in Mauritius. Final Technical Report 1:462

Ban NC, Cinner JE, Adams VM et al (2012) Recasting shortfalls of marine protected areas as opportunities through adaptive management. Aquat Conserv 22:262–271

Barbesgaard M (2018) Blue growth: savior or ocean grabbing? J Peasant Stud 45(1):130–149. https://doi.org/10.1080/03066150.2017.1377186

Bearzi M (2017) Impacts of marine mammal tourism. In: Blumstein D, Geffroy B, Samia D et al (eds) Ecotourism's promise and Peril. Springer, Cham. https://doi.org/10.1007/978-3-319-58331-0_6

Becken S, Hay J (2007) Tourism and climate change: risks and opportunities. Clevedon: Channel View. Cook Islands Tourism Corporation. (2021). Kitsesurfing. https://cookislands.travel/experiences/water/kitesurfing. Accessed 27 Apr 2021

Beeharry Y, Bekaroo G, Bussoopun D et al (2020) Perspectives of leisure operators and tourists on the environmental impacts of coastal tourism activities: a case study of Mauritius. Environ Dev Sustain 23:10702–10726. https://doi.org/10.1007/s10668-020-01080-7

Bhagooli R, Kaullysing D (2019) Seas of Mauritius. In: Sheppard CCR (ed) World seas: An environmental evaluation, vol II, 2nd edn. The Indian Ocean to the Pacific. Elsevier, Academic Press, London, pp 253–277

Bhagooli R, Mattan-Moorgawa S, Kaullysing D et al (2021a) Status and sustainability of reefs and shorelines of the republic of Mauritius. In: Gunputh (ed) Sustainable development goals, Stars Publication, New Delhi, pp 142–177

Bhagooli R, Kaullysing D, Mattan-Moorgawa S (2021b) Altered coral community and cyanobacterial invasion on a coast-reef scale over a 20-year period: implications of coral reef sustainability at the uninhabited Gabriel islet, Mauritius. In: Gunputh (ed) Sustainable development goals, Stars Publication, New Delhi, pp 178–189

Bhagooli R, Jawaheer S, Dyall SD et al (2021c) Fragment size-dependent coral transplantation of *Acropora muricata* on concrete blocks at Belle Mare: a potential tool for sustaining Mauritian corals. In: Gunputh (ed) Sustainable development goals, Stars Publication, New Delhi, pp 190–198

Bhagooli R, Ramah S, Kaullysing D et al (2017) Field observation of five Stylophora pistillata-like morphotypes near Mauritius Island. WIO J Mar Sci (Special Issue 1/2017):51–53

Bolton JJ, Bhagooli R, Mattio L (2012) The Mauritian seaweed flora: diversity and potential for sustainable utilization. UoM Res J Special Issue (sustainable Marine Environment) 18A:6–27

Bouveroux T, Loiseau N, Barnett A, Marosi ND, Brunnschweiler JM (2021) Companion and casual acquaintances: the nature of associations among bull sharks at a shark feeding site in Fiji. Front Mar Sci 8:678074

Brockington D, Stefano P (2015) The green economy in the global south: experiences redistributions and resistance. Third World Q 36(12):2197–2206. https://doi.org/10.1080/01436597.2015.1086639

CARSEA (2007) Caribbean Sea Ecosystem Assessment (CARSEA). A sub-global component of the Millennium Ecosystem Assessment (MA), J. Agard, A. Cropper, K. Garcia, eds., Caribbean Marine Studies, Special Edition, 2007, 104 pp

Cervigni R, Scandizzo PL (eds) (2017) The Ocean economy in Mauritius: making it happen, making it last. World Bank, Washington, DC

Chaigneau T, Brown K (2016) Challenging the win-win discourse on conservation and development: analyzing support for marine protected areas. Ecol Soc 21:36. https://doi.org/10.5751/ES-08204-210136

Cheung LTO, Ma ATH, Lam TWL et al (2020) Predictors of the environmentally responsible behaviour of participants: An empirical investigation of interpretative dolphin-watching tours. Glob Ecol Conserv 23:e01153

Christiansen F, Lusseau D (2015) Linking behavior to vital rates to measure the effects of non-lethal disturbance on wildlife. Conserv Lett 8:424–431

Cigliano JA, Meyer R, Ballard HL et al (2015) Making marine and coastal citizen science matter. Ocean Coast Manag 115:77–87

Cisneros-Montemayor AM, Sumaila UR, Kaschner K et al (2010) The global potential for whale watching. Mar Policy 34:1273–1278

Constantine R (2014) Whale-watching and behavioural ecology. In: Higham J, Bejder L, Williams R (eds) Whale-watching: Sustainable Tourism and Ecological Management. Cambridge University Press, Cambridge, UK

Constantine R, Bejder L (2008) Managing the whale-and dolphin watch industry: time for a paradigm shift. In: Higham J, Lück M (eds) Marine wildlife and tourism management. Invited book chapter. CABI Publishing (Oxford). Invited book chapter

Corbett HD (1994) The occurrence of cetaceans off Mauritius and in adjacent waters. Rep Int Whal Commn 44:393–398

Corkeron PJ (2004) Whale watching, iconography, and marine conservation. Conserv Biol 18:847–849

Cunningham PA, Huijbens EH, Wearing SL (2012) From whaling to whale watching: examining sustainability and cultural rhetoric. J Sustain Tour 20:143–161. https://doi.org/10.1080/09669582.2011.632091

Digest of International Travel & Tourism (2019) https://statsmauritius.govmu.org/Pages/Statistics/By_Subject/Tourism/SB_Tourism.aspx. Accessed 14 Aug 2021

Duvat V (2009) Beach erosion management in Small Island developing states: Indian Ocean case studies. WIT Trans Ecol Envir 126:149–160. https://doi.org/10.2495/CP090141

Fauzel S, Seetanah B, Sannassee RV (2016) Analysing the impact of tourism foreign direct investment on economic growth: Evidence from a small island developing state. Tour Econ 23:1042–1055. https://doi.org/10.1177/1354816616664249

Fiji Ministry for Industry Trade and Tourism (2019) The Fijian Tourism 2021. http://mitt.gov.fj/wp-content/uploads/2019/04/FT2021.pdf. Accessed 26 July 2021

Fiji Village (2021) Freesoul Real Estate Trial. https://www.fijivillage.com/news/Freesoul-Real-Estate-trial--rx5f48/. Accessed 27 Apr 2021

Forestell PH, Kaufman GD (1990) The history of whalewatching in Hawaii and its role in enhancing visitor appreciation for endangered species. In: Miller ML, Auyong J (eds) Proceedings of the 1990 Congress on Coastal and Marine Tourism, vol 1. National Coastal Resources Research Institute, Corvallis, Oregon

Freeport Act (2004) https://www.mra.mu/download/FreeportAct2004.pdf. Accessed 23 Aug 2021

Giakoumi S, Mcgowan J, Mills M et al (2018) Revisiting "success" and "failure" of marine protected areas: a conservation scientist perspective. Front Mar Sci 5. https://doi.org/10.3389/fmars.2018.00223

Gowreesunkar G, Rycha I (2015) A study on the impacts of dolphin watching as a tourism activity: Western Mauritius as case study. Int J Trade Econ Finance 6:67–72. https://doi.org/10.7763/IJTEF.2016.445

Gutleea KK, Bholah R, Kaullysing D, Bhagooli R (2021) Perception of divers, tourists, residents and boat operators on SCUBA diving in Mauritius: implications for a sustainable marine ecotourism industry, in Sustainable Development Goals, Ed. Prof. RP Gunputh, Chapter 6, pp 105–121, Star Publications Pvt., 264p Ltd., New Delhi, India, 264p

Handbook of Statistical Data on Tourism (2019) https://tourism.govmu.org/Documents/publication/Handbook%20of%20Statistical%20Data%20on%20Tourism%202019.pdf. Accessed 14 Aug 2021

Harrison D (2001) Islands, image and tourism. Tour Recreat Res 26(3):9–14

Harrison D, Pratt S (2013) Tourism in Pacific Island Countries. In: Cooper C (ed) Contemporary tourism reviews. Goodfellows Publishers, Oxford, pp 1–24

Harrison D, Pratt S (2015) Tourism in Pacific Island countries: Current issues and future challenges. In: Pratt S, Harrison D (eds) Tourism in Pacific Islands: current issues and future challenges. Routledge, Abingdon, UK, pp 3–21

Hedelin B, Gray S, Woehlke S et al (2021) What's left before participatory modeling can fully support real-world environmental planning processes: a case study review. Environ Model Softw 143:105073

Higham JES, Lusseau D (2007) Urgent need for empirical research into whaling and whale-watching. Conserv Biol 21:554–558

Higham J, Bejder L, Lusseau D (2009) An integrated and adaptive management model to address the long-term sustainability of tourist interactions with cetaceans. Environ Conserv 35(4):294–302. http://www.jstor.org/stable/44520359

Higham JES, Bejder L, Allen SJ et al (2016) Managing whale-watching as a non-lethal consumptive activity. J Sustain Tour 24(1):73–90. https://doi.org/10.1080/09669582.2015.1062020

Hoyt E (2001) Whale watching 2000: worldwide tourism numbers, expenditures, and expanding socioeconomic benefits. Report to the International Fund for Animal Welfare, Yarmouth Port, Massachusetts

IFAW (2009) Whale watching worldwide: tourism numbers, expenditures and expanding economic benefits. http://www.ecolarge.com/wp-content/uploads/2010/06/WWWW09.pdf. Accessed 27 Apr 2021

IUCN WCPA (2018) Applying IUCN's global conservation standards to Marine Protected Areas (MPA). Delivering effective conservation action through MPAs, to secure ocean health & sustainable development. Version 1.0. Gland, Switzerland, p 4

IWC (1996) Report of the Scientific Committee. International Whaling Commission Meeting 48, Washington, DC
Jiang M, Calgaro E, Klint LM et al (2015) Understanding climate change vulnerability and resilience of tourism destinations: an example of community-based tourism in Samoa. In: Pratt S, Harrison D (eds) Tourism in Pacific Islands: current issues and future challenges. Routledge, London, pp 239–256
Jupiter S, Mangubhai S, Kingsford RT (2014) Conservation of biodiversity in the pacific Islands of Oceania: challenges and opportunities. Pac Conserv Biol 20:206–220
Kesolei OK (2018) Palau Collects $100 Pristine Paradise Fee. https://www.pacificnote.com/single-post/2018/01/11/Pay-Extra-Cost-To-Enter-The-Pristine-Paradise. Accessed 26 Nov 2019
Klint LM, Delacey T, Filep S et al (2015) Climate change and Island tourism. In: Pratt S, Harrison D (eds) Tourism in Pacific Islands: current issues and future challenges. Routledge, London, pp 257–277
L'Express (2016) Activités nautiques: le jet ski banni des eaux mauriciennes. https://www.lexpress.mu/article/277758/activites-nautiques-jet-ski-banni-eaux-mauriciennes. Accessed 14 Aug 2021
Laffoley D, Baxter JM, Day JC et al (2019) Marine protected areas. In: Sheppard CCR (ed) World seas: an environmental evaluation, vol II, 2nd edn. The Indian Ocean to the Pacific. Elsevier, Academic Press, London, pp 549–569
Lewis D (2020) Cleaning up after Mauritius oil spill. Nature 585. https://media.nature.com/original/magazine-assets/d41586-020-02446-7/d41586-020-02446-7.pdf. Accessed 10 Aug 2021
Machernis AF, Powell J, Engleby L et al (2018) An updated literature review examining the impacts of tourism on marine mammals over the last fifteen years (2000–2015) to inform research and management programs
Mallin F, Barbesgaard M (2020) Awash with contradiction: capital, ocean space and the logics of the Blue economy Paradigm. Geoforum 113:121–132. https://doi.org/10.1016/j.geoforum.2020.04.021
Mangubhai S, Sykes H, Manley M et al (2020) Contributions of tourism-based Marine conservation agreements to natural resource management in Fiji. Ecol Econ 171:106607. https://doi.org/10.1016/j.ecolecon.2020.106607
McNamara KE, Clissold R, Westoby R et al (2020) An assessment of community-based adaptation initiatives in the Pacific islands. Nat Clim Change 10(7):628–639
McClanahan T, Munbodhe V, Naggea J et al (2021) Rare coral and reef fish species status, possible extinctions, and associated environmental perceptions in Mauritius. Conserv Sci Pract 3(11):e527. https://doi.org/10.1111/csp2.527
McClanahan TR, Muthiga NA (2021) Oceanic patterns of thermal stress and coral community degradation on the island of Mauritius. Coral Reefs 40:53–74. https://doi.org/10.1007/s00338-020-02015-4
Meynecke JO, Richards R, Sahin O (2017) Whale watch or no watch: the Australian whale watching tourism industry and climate change. Reg Environ Change 17:477–488. https://doi.org/10.1007/s10113-016-1034-z
Ministry of Fisheries and Rodrigues Annual Report (2011) https://blueconomy.govmu.org/Documents/3fisheries_Annual%20report%202011.pdf. Accessed 18 Aug 2021
Ministry of Tourism Annual Report (2019) https://tourism.govmu.org/Documents/publication/Annual%20Report%20Performance1819.pdf. Accessed 14 Aug 2021
Moothien-Pillay R, Terashima H, Venkatasami A et al (2002) Field guide to corals of Mauritius. Albion Fisheries Research Centre, Albion
Moothien Pillay R, Bacha Gian S, Bhoyroo V, Curpen S (2011) Adapting coral culture to climate change: the Mauritian experience. W Indian Ocean J Mar Sci 10:155–167
Moreno A, Amelung B (2009) Climate change and coastal & marine tourism: Review and analysis. J Coast Res 56:1140–1144. https://www.jstor.org/stable/25737965
Murphy SE, Campbell I, Drew JA (2018) Examination of tourists' willingness to pay under different conservation scenarios: Evidence from reef manta ray snorkeling in Fiji. PLoS ONE 13(8):e0198279. https://doi.org/10.1371/journal.pone.0198279

Newsroom (2019) Fiji revokes big Chinese resort's rights. https://www.newsroom.co.nz/2019/04/09/527968/fiji-revokes-chinese-resorts-rights. Accessed 8 May 2019
Nurse LA, McLean RF, Agard J et al (2014) Small islands. In: Barros VR, Field CB, Dokken DJ et al (eds) Climate change 2014: impacts, adaptation, and vulnerability. Part B: regional aspects. Contribution of working Group II to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, pp 1613–1654
O'Connor S, Campbell R, Cortez H et al (2009) Whale watching worldwide: tourism numbers, expenditures and expanding economic benefits, a special report from the International Fund for Animal Welfare, Yarmouth MA, USA, prepared by Economists at Large
Orams M (2002) Marine tourism: development, impacts and management. Routledge, London
Orams MB (1999) The economic benefits of whale watching in Vava'u, the kingdom of Tonga. Massey University at Albany, North Shore, New Zealand, Centre for Tourism Research
Palau Customs (2018) Palau pristine paradise environmental fee. http://www.palaucustoms.org/files/common_unit_id/c8672894-ba61-43f7-b6c4-6a69acbd1b61/PUBLIC%20NOTICE.pdf. Accessed 26 Nov 2019
Panakera C (2007) World War 11 and the tourism development in Solomon islands. In: Ryan C (ed) Battlefield tourism: History, place and interpretation. Routledge, USA, pp 125–141
Parkinson P (2020) Towards a global agreement on plastics and plastic pollution for the pacific islands. http://www.sas.com.fj/ocean-law-bulletins/towards-a-global-agreement-on-plastics-and-plastic-pollution-for-the-pacific-islands?utm_medium=email&_hsmi=139784787&_hsenc=p2ANqtz-9RIzbzjzMKywjaXcYPS1wzT7xGkfp0dwTebsfk_V2HNrpH-g5X7olSALNwCbTOP88YV-AbcecaVrMpb0m84sFW0mq5g0ZpMpOeAtkc2KWLJY35vCY&utm_content=139784787&utm_source=hs_email. Accessed 23 July 2021
Pasape L, Mujwiga S (2017) Towards success of ecotourism networks in Tanzania: a case of Tanzania association of tour operators. J Hosp Tour Manag 8(2):14–24
Pascal N, Leport G, Molisa V et al (2015) National Marine ecosystem service valuation: Vanuatu. http://macbio-pacific.info/wp-content/uploads/2017/08/Vanuatu-MESV-Digital-LowRes.pdf. Accessed 5 Jan 2020
Pathak A, Van Beynen PE, Akiwumi FA et al (2021) Impacts of climate change on the tourism sector of a Small Island Developing State: a case study for the Bahamas. Environmental Development 37:100556
Paupiah CN, Mosaheb JI, Mangar V et al (2000) Present status of seagrass at Albion and Pointe aux Cannoniers, Mauritius, Indian Ocean—A preliminary study. Rep Mar Ecol Res Inst 99301:1–12
Pelesala S, Petaia M, Takataka O (2020) A National Oceans Policy for Tuvalu: 3 experts consider the process to get there. http://www.sas.com.fj/ocean-law-bulletins/a-national-oceans-policy-for-tuvalu-3-experts-consider-the-process-to-get-there?utm_campaign=Sample%20-%20My%20first%20inbound%20campaign%20in%20HubSpot&utm_medium=email&_hsmi=92150889&_hsenc=p2ANqtz-_7xthAXphTtqxRejGY30g24cfOO-qWjagjaNEuo4PECcpos4_w_UpBzMpfufRaf-
Pendleton LH, Ahmadia GN, Browman HI et al (2018) Debating the effectiveness of marine protected areas. ICES J Mar Sci 75(3):1156–1159. https://doi.org/10.1093/icesjms/fsx154
Pham-Do KH, Pham TTT (2020) Tourism in marine protected areas: a view from Nha Trang Bay. Vietnam. Tour Manag Perspect 33:100623. https://doi.org/10.1016/j.tmp.2019.100623
Plan Bleu (2014) Economic and social analysis of the uses of the coastal and marine waters in the Mediterranean, characterization and impacts of the Fisheries, Aquaculture, Tourism and recreational activities, Maritime transport and Offshore extraction of oil and gas sectors, Technical Report, Plan Bleu, Valbonne
Pratt S, Suntikul W (2016) Can marine wildlife tourism provide an "edutaining" experience? J Travel Tour Mark 33(6):867–884. https://doi.org/10.1080/10548408.2015.1069778
Ramah S, Chung Voon AT, Beetul K (2019) First encounter of a stranded Loggerhead marine turtle entangled in a ghost net on the Southeast coast of Mauritius Island. Indian Ocean Turtle Newsletter 30:8–9

Ramah S, Etwarysing L, Auckloo N et al (2014) Prophylactic antioxidants and phenolics of seagrass and seaweed species: A seasonal variation study in a Southern Indian Ocean Island. Mauritius. Internet J. Medical Update 9(1):27–37

Republic of Fiji (2021) National Ocean Policy 2020–2030. https://library.sprep.org/sites/default/files/2021-05/Fiji-National-Ocean-policy-2020-2030.pdf. Accessed 23 Jul 2020

Rodgers K, Cox E, Newtson C (2003) Effects of mechanical fracturing and experimental trampling on Hawaiian corals. Environ Manage 31:377–384. https://doi.org/10.1007/s00267-002-2831-3

Rouatu I, Leport G, Pascal N et al (2017) National Marine ecosystem valuation report: Kiribati. http://macbio-pacific.info/wp-content/uploads/2017/08/Kiribati-MESV-Digital-LowRes.pdf. Accessed 5 Jan 2020

Roy HE, Pocock MJO, Preston CD et al (2012) NERC Final Report on behalf of UK-EOF. & Museum, C. for E. & H. and N.H. (2012) Understanding citizen science and environmental monitoring. Final Report on Behalf of UK-EOF. NERC Centre for Ecology & Hydrology, Wallingford, Oxfordshire

Sala E, Mayorga J, Bradley D et al (2021) Protecting the global ocean for biodiversity, food and climate. Nature 592:397–402. https://doi.org/10.1038/s41586-021-03371-z

Salcone J, Tupou-Taufa S, Brander L et al (2017) National Marine ecosystem valuation report: Tonga. http://macbio-pacific.info/wp-content/uploads/2017/08/Tonga-MESV-Digital-LowRes.pdf. Accessed 5 Jan 2020

Seveso D, Louis YD, Montano S et al (2021) The Mauritius oil spill: what's next? *Pollutants* 1:18–28. https://doi.org/10.3390/pollutants1010003

Shelden KEW, Rugh DJ, Mahoney BA et al (2003) Killer whale predation on belugas in Cook Inlet, Alaska: implications for a depleted population. Mar Mamm Sci 19(3):529–544. https://doi.org/10.1111/j.1748-7692.2003.tb01319.x

Shelton E, McKinley B (2007) Shooting fish in a barrel: tourists as easy targets. In: Higham JES, Lück M (eds) Marine wildlife and tourism management: insights from the natural and social sciences. CABI Publishing, Oxford, pp 219–230

Silver JJ, Gray NJ, Campbell LM et al (2015) Blue economy and competing discourses in international oceans governance. J Environ Dev 24(2):135–160. https://doi.org/10.1177/107049651558

Sloan J, Chand K, Samuela E (2020) Fiji's first national ocean policy analysis and submission. http://www.sas.com.fj/ocean-law-bulletins/fijis-first-national-ocean-policy-analysis-and-submission?utm_source=hs_email&utm_medium=email&utm_content=88257619&_hsenc=p2ANqtz-8haNbAN7d4cH5usL5Qx7Fxak-tTw2SgPNonS1dhiPpI9dFyez29GanjFwyDtEykPSPHQG5OAMROGBJjRKFWQGApnoaQBzocH5cVfJ38JhIk_JL4ak&_hsmi=88257619. Accessed 23 July 2021

Sloan J, Samuela E (2020) Fiji's ministry of fisheries has amended and shortened the seasonal ban on the capture of species of Kawakawa (Grouper) and Donu (Coral Trout). http://www.sas.com.fj/ocean-law-bulletins/fijis-ministry-of-fisheries-has-amended-and-reduced-the-seasonal-ban-on-the-capture-of-species-of-grouper-and-coral-trout?utm_medium=email&_hsmi=139784787&_hsenc=p2ANqtz-91gQxSzidGfG2W5YSaYGcPcuV-K5G3f9eiuiQ4rg3Ov08NT35sutGBaEqrV-ec8oHhmuj1VFpitFxwOoZE7mr7c2xVY6JckeFOw4yzgMVK8l7xCAA&utm_content=139784787&utm_source=hs_email. Accessed 23 July 2021

Solomon Islands Government (2015) The Solomon Islands National Tourism Development Strategy 2015–2019. http://macbio-pacific.info/wp-content/uploads/2017/08/National-Tourism-Strategy-2015.pdf. Accessed 26 July 2021

SPREP (2008) Pacific Islands regional guidelines for whale and dolphin watching. http://www.sprep.org/att/publication/000647_whale_watch_guidelines_en.pdf. Accessed 15 Aug 2021

SPREP (2018) Pacific Marine Action Plan: Marine Litter 2018–2025. https://www.sprep.org/sites/default/files/documents/publications/MAP-Digital-small.pdf. Accessed 23 July 2021

SPTO (2017) Annual review of tourist arrivals in Pacific Island countries 2016. https://corporate.southpacificislands.travel/wp-content/uploads/2017/02/2016-Annual-Visitor-Arrivals-ReviewF.pdf. Accessed 26 Sept 2017

SPTO (2020) 2019 Annual review of visitor arrivals report. https://pic.or.jp/ja/wp-content/uploads/2019/07/2018-Annual-Visitor-Arrivals-ReportF.pdf. Accessed 12 Aug 2021

SPTO (2021) The Pacific 2030 sustainable tourism policy framework. https://southpacificislands.travel/wp-content/uploads/2021/07/Pacific-Sustainable-Tourism-Policy-Framework.pdf. Accessed 23 July 2021

Stockin KA, Binedell V, Wiseman N et al (2009) Behaviour of free-ranging common dolphins (Delphinus sp.) in the Hauraki Gulf New Zealand. Mar Mamm Sci 25:283–301

Sykes H, Reddy C (2009) "Sacred Water"; 10 years of community managed marine protection supported by ecotourism-based income generation at Waitabu Marine Park, Fiji Islands. https://www.marineecologyfiji.com/wp-content/uploads/2010/04/PSI2009_584_Waitabu_MPA_-Sykes_H.pdf. Accessed 26 July 2021

The Fisheries and Marine Resources Act (2007) http://extwprlegs1.fao.org/docs/pdf/mat85779.pdf. Accessed 14 Aug 2021

Tiddy IC, Kaullysing D, Bailey DM et al (2021) Outplanting of branching Acropora enhances recolonization of a fish species and protects massive corals from predation. Coral Reefs 40:1549–1561. https://doi.org/10.1007/s00338-021-02147-1

Tourism Authority (Dolphin and Whale Watching) Regulations (2012). http://extwprlegs1.fao.org/docs/pdf/mat116851.pdf. Accessed 14 Aug 2021

Tourism Authority (Prohibition of Jet Ski) Regulations (2016) http://www.tourismauthority.mu/userfiles/file/tourismauthority/legislation/regulations/Tourism%20Authority%20(Prohibition%20of%20Jet%20Ski).pdf. Accessed 14 Aug 2021

Vanuatu Ministry for Tourism Industry and Commerce & Ni-Vanuatu Business (2013) Vanuatu Tourism Action Plan 2014–2018. https://www.nab.vu/document/vanuatu-strategic-tourism-action-plan-2014-2018. Accessed 26 July 2021

Vianna GMS, Meekan MG, Pannell D et al (2010) Wanted dead or alive? The relative value of reef sharks as a fishery and an ecotourism asset in Palau. https://www.pewtrusts.org/-/media/assets/2011/05/02/palau_shark_tourism.pdf. Accessed 5 Jan 2020

Voyer M, Genevieve Q, McIlgorm A et al (2018) Shades of blue: what do competing interpretations of the Blue economy mean for oceans governance? J Environ Policy Plan 20:595–616. https://doi.org/10.1080/1523908X.2018.1473153

Ward-Paige CA, Brunnschweiler J, Sykes H (2020) Tourism-driven ocean science for sustainable use: a case study of sharks in Fiji. bioRxiv, 2020.2002.2004.932236. https://doi.org/10.1101/2020.02.04.932236

Webster I, Cockcroft V, Cadinouche A et al (2020) Cetacean diversity of Mauritius. J Cetacean Res Manag 21:45–58

World Bank and United Nations Department of Economic and Social Affairs (2017) The Potential of the Blue economy: increasing long-term benefits of the sustainable use of marine resources for small Island developing states and coastal least developed countries. World Bank, Washington, DC

Chapter 7
Energy Transition to the Blue Economy: The Role of Science and Technology

Verônica J. Pereira, Fabio P. Nascimento, Deividson S. Santos, Ravenna L. Matos, Gloria M. N. Costa, Silvio A. B. Vieira de Melo, and Ying Guo

Abstract Offshore oil and gas (O&G) production represents 25% of the "blue economy" market and is an important source of income for many coastal nations. This chapter discusses how the O&G offshore industry can lead a sustainable transition from a "brown economy" to a "blue economy", especially with research funding and government commitment, as well as broader partnerships and diverse investment strategies. An overview of the world's current and future energy situation, the challenges and environmental risks of offshore O&G production, as well as different types of offshore renewable energy options are also presented. The role of science and technology is crucial in this transition process (as demonstrated by two cases studies:

V. J. Pereira · F. P. Nascimento · D. S. Santos · R. L. Matos · G. M. N. Costa · S. A. B. Vieira de Melo (✉)
Programa de Pós-Graduação em Engenharia Industrial, Escola Politécnica, Universidade Federal da Bahia, Rua Aristides Novis, 2, Federação, Salvador, Bahia 40210-630, Brazil
e-mail: sabvm@ufba.br

V. J. Pereira
e-mail: veronica.pereira@ufba.br

F. P. Nascimento
e-mail: fabio.pedro@ufba.br

D. S. Santos
e-mail: deividson.santos@ufba.br

R. L. Matos
e-mail: ravenna.matos@ufba.br

G. M. N. Costa
e-mail: gmeyberg@ufba.br

S. A. B. Vieira de Melo
Centro Interdisciplinar em Energia e Ambiente, Campus Universitário da Federação/Ondina, Universidade Federal da Bahia, Rua Barão de Jeremoabo, S/N, Ondina, Salvador, Bahia 40170-115, Brazil

Present Address:
Y. Guo
Department of Technology, Norwegian Research Centre—NORCE, 4068 Stavanger, Norway
e-mail: ying.guo@norceresearch.no

E. R. Urban Jr. and V. Ittekkot (eds.), *Blue Economy*,
https://doi.org/10.1007/978-981-19-5065-0_7

Brazil and Norway) to overcome the O&G industry challenges and ensure economic profitability, while reducing environmental impacts in the ocean and coastal areas.

Keywords Fossil fuels · Energy transition · Enhanced oil recovery (EOR) · Carbon capture utilization and storage (CCUS)

7.1 Introduction

Offshore oil and gas (O&G) production represents 25% of the blue economy market, with the possibility of expansion (Choudhary et al. 2021). Recent new oil and gas fields found in coastal areas of developing countries, including deep-water exploration in South America and Africa (de Sant'Anna Pizarro and Branco 2012; da Costa Fraga et al. 2015) and continuing societal demand for hydrocarbon-based products, indicate that O&G production could continue for decades.

"Energy transition" is a term commonly used to describe the shift from a fossil fuel-based economy to a cleaner energy economy. That means moving from a fragmented energy sector that relies on high carbon-intensive activities to an integrated energy sector, in which multiple elements (oil and gas, renewables, transport, heating, and others) are interconnected (Hassan 2021).

In a "brown economy", economic growth depends primarily on environmentally harmful activities such as fossil fuels (coal and O&G). Massive levels of greenhouse gases (GHG) such as carbon dioxide (CO_2) and methane are by-products of this type of economy. Air and water quality, as well as harmful impacts on biodiversity, are key factors in this type of economy (Matthews 2013). On the other hand, a "blue economy" supports clean and healthy oceans, including the coastal environment and other aquatic ecosystems. This type of economy recognizes that water quality is crucial to our society, directly impacting financial, biological and cultural well-being. Furthermore, this term can also be applied when referring to a comprehensive sustainable regime (Matthews 2013). Several types of offshore renewable energy are currently under development to support the transition to a blue economy. Offshore wind energy, floating solar photovoltaic, and ocean energy (wave energy, tidal energy, ocean thermal energy conversion and salinity gradient energy) are some of the examples presented here.

Although the O&G industry is often associated with a "brown economy", its economic importance for sustainable O&G gas production in the ocean may play a major role in the development of other activities in the blue economy, such as the renewable energies that are considered "blue energy" or even traditional activities such as fishing and tourism, in addition to new opportunities such as blue biotechnology (Smith-Godfrey 2016).

The fact that fossil energy sources are finite reinforces the trend over the last several decades, in which the major O&G companies have expanded their business models and declare themselves energy companies increasingly concerned with the broader issues of renewable energy, climate change, GHG emissions, and processes for the capture and geological storage of CO_2. Examples include European initiatives in the North Sea, led by Norway, discussed in more detail in this chapter. In addition, energy companies are increasingly striving to contribute to a carbon–neutral society and embracing innovative principles such as those of a circular economy (Jensen et al. 2020).

As recognized worldwide, O&G companies have traditionally contributed a considerable amount of research funding for the development and application of science and technology to improve production efficiency and mitigate environmental impacts resulting from their activities. In this context, the prominent role that science and technology currently, and must continue to, play in advancing blue energy is indisputable. Therefore, the major energy companies have the opportunity to lead this process of sustainable transition from a brown economy to a blue economy, especially with multidisciplinary research funding.

This chapter discusses how science and technology can continue to contribute to offshore O&G production, increasing technical efficiency and economic profitability, combined with the adoption of best practices for minimizing environmental impacts in ocean and coastal areas. To improve understanding of the environmental aspects of oil and gas production, the interrelationships between production and other activities that constitute the blue economy are addressed from the perspective of sustainable development, the transition to renewable energies, and new business opportunities.

Sustainable development must allow the exploitation of O&G potential based on the principles of economic and social inclusion, environmental preservation, and the encouragement of technological innovation so that the core business is viable in the short, medium, and long terms. At the end of its life cycle, offshore O&G production should leave a positive legacy for the communities near production areas and the surrounding ecosystems.

The transition to sustainable energies cannot be postponed but should be properly planned for the best execution of all the steps necessary for its successful implementation. For example, offshore oil production platforms can be re-used as sites for wind power units (Sedlar et al. 2019), generating low-cost electricity to be used in ongoing operations and in the future to be used in the electrolysis of seawater, to produce "Green Hydrogen". Currently, the production of "Green Hydrogen" is not economically viable. However, offshore wind energy costs are continually decreasing, as a result of advances in science and technology, expanding the range of innovative new businesses. Therefore, decarbonizing energy sources, increasing operational energy efficiency, identifying new investment priorities and deploying new technologies are some of the key strategies required for a successful transition of industrial sectors (Porter et al. 2020).

CO_2 production is an integral part of normal O&G operations and could provide opportunities for new businesses (L. Li et al. 2020). The capture and injection of CO_2 to the subsurface can be done using the facilities existing on offshore platforms, which can also serve as a reception station for CO_2 coming from the land through pipelines, for storage purposes. "Green Hydrogen" combined with CO_2 capture and storage is another upcoming technological solution for clean natural gas production. Moreover, part of the CO_2 can be converted into other chemicals, such as methanol, by catalytic hydrogenation, taking advantage of the “Green Hydrogen” produced offshore (Tidona et al. 2013).

Environmental impacts must be monitored throughout the life cycle of offshore O&G activity, including exploration, production, and decommissioning. These impacts involve chemical and noise pollution, the disruption of seafloor areas, and interference with the biological cycles of ecosystems. These impacts vary according to the depth of the sea (shallow water, deep water, and ultra-deep water) and the distance from the point of the disturbance, in some cases reaching 3 km away (Cordes et al. 2016). Conversely, there is evidence that the infrastructure of offshore facilities has a positive impact by creating refugia for fish and other ocean organisms; either submerged structures of the platforms serve as habitat for marine species or because fishing activities are not allowed in the surroundings (Claisse et al. 2015).

The following sections present an overview of the past situation and projections for the world’s energy supply and demand, different types of offshore renewable energy, as well as the challenges and environmental risks of offshore O&G production. Moreover, a discussion about the role of the O&G industry in the transition of the energy sector to a blue economy is presented, emphasizing how it has been employing science and technology to support O&G offshore production, improving technical efficiency and economic profitability, combined with the adoption of best practices for minimizing and reducing environmental impacts in the ocean and coastal areas. Two case studies (Brazil and Norway) are also presented to exemplify how this transition is starting and will continue for the next decades until alternative energy sources are technically and economically viable.

7.2 Global O&G Distribution, Supply and Demand

In the last 30 years, primary energy consumption worldwide has significantly increased from 482.82 exajoules (EJ) in 1990 to 583.90 EJ in 2019. In 2019, the largest share was generated by oil (33%), followed by coal (27%) and natural gas (24%) (BP 2020). Although the total oil share will likely decrease by 2040, it should still have the largest share (28%) among all energy sources, with a continuous increase in its absolute demand (despite intensification in the use of renewable sources and developments in energy efficiency) (IEA 2018; Godoi and dos Santos Matai 2021).

The Middle East region holds the largest proven oil reserves (48%), followed by South and Central America (19%) and North America (14%) (BP 2020). About 30% of the total oil produced in the world is extracted offshore. For several countries, such as Saudi Arabia, Brazil, Mexico, United Arab Emirates, and Angola, which are among the world’s top offshore oil producers, this represents a major source of income (Statista 2019).

Figure 7.1 shows the oil production and consumption by region since 1995 (BP 2021). Global oil production has been rising steadily over the years. The Middle East is the biggest producer, but in the last decade, oil production has consistently increased in the United States. In 2019, global oil production fell slightly as the

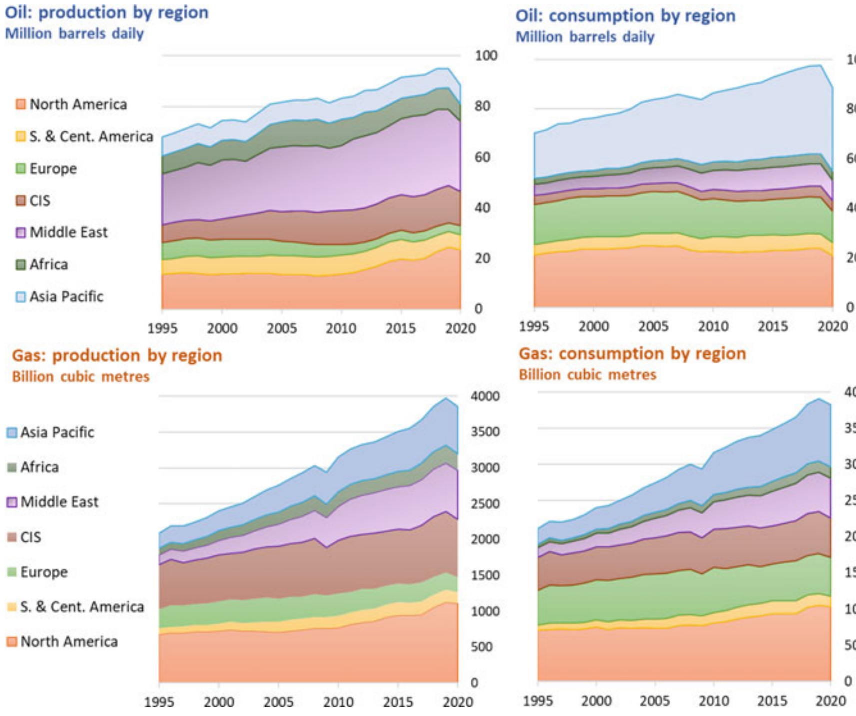


Fig. 7.1 Oil and natural gas production and consumption by region (Adapted from BP 2021)

production growth led by the United States was offset by a sharp decline in the Organization of the Petroleum Exporting Countries (OPEC) output. In 2020, Norway and Brazil were some of the few countries that increased oil production (BP 2021).

Global oil consumption has also increased over the last three decades, except for 2008 and 2009, due to the financial crisis, and in 2020 as a result of the coronavirus pandemic. In the last decade, the Asia Pacific region has experienced rapid growth in oil consumption, while in the European Union and North America there was a slight increase. Demand in China, Iran, and India led to an increase of 0.9% in the global oil consumption in 2019 compared to the previous year. In 2020, oil production and consumption were affected by the COVID-19 pandemic; China was one of the few countries where energy demand grew (BP 2021).

Most of the natural gas production comes from conventional sources (extracted from wells or produced in association with crude oil). In this context, offshore production, especially in deep water, accounts for an increasing share of conventional production, rising to almost half of it by 2040 (IEA 2018).

Figure 7.1 also presents the history of natural gas production and consumption by region from 1995 to 2020. Worldwide natural gas production and consumption have been increasing over the last decade. The largest natural gas producers are the United States, Russia, Iran, and Canada (BP 2021). The United States, the Middle East, and

Russia accounted for more than three-fifths of the natural gas production in 2019. In that year, the consumption of natural gas increased 2% (driven by the United States and China), but it stayed below the strong growth seen in 2018 (5.3%) (BP 2020). The European Union contributed to this result since the efforts to achieve the new goals of energy efficiency and renewable energy led to a reduction in gas demand (IEA 2018). In 2020, natural gas production and consumption also declined (3.3% and 2.3%, respectively) due to the pandemic. In most regions, gas consumption fell, except in China, where demand grew by 6.9% (BP 2021).

Global energy demand is estimated to have decreased by 4.5% in 2020 compared to the previous year, but despite the fall in the overall energy demand, renewable energy production continued to grow, led by wind and solar energy (Fig. 7.2). Although oil and coal continue to hold the largest share of the energy matrix, natural gas and renewables increased their share, reaching their historic highs (24.7% and 5.7%, respectively) in 2020 (BP 2021).

Countries have increased their ambitions to decarbonize since the Paris Conference of Parties (COP21) to the United Nations Framework Convention on Climate Change (UNFCCC) in 2015. However, this ambition has yet to be converted into a significant reduction in carbon emissions (BP 2020, 2021). Global primary energy demand should expand over 25% by 2040, led principally by developing economies (IEA 2018). However, without advances in energy efficiency, the rise would be twice as large.

Attention should be given to the contribution of oil and gas on the direct (extraction) and indirect (producing, transporting, and processing oil and gas) CO_2 emissions, since indirect greenhouse gas emissions from O&G operations contribute 15% of the total emissions of the energy sector. Some strategies that can be used to reduce emissions are the combination of CO_2 capture facilities with enhanced oil recovery projects, the use of steam methane reforming with carbon capture, utilization and

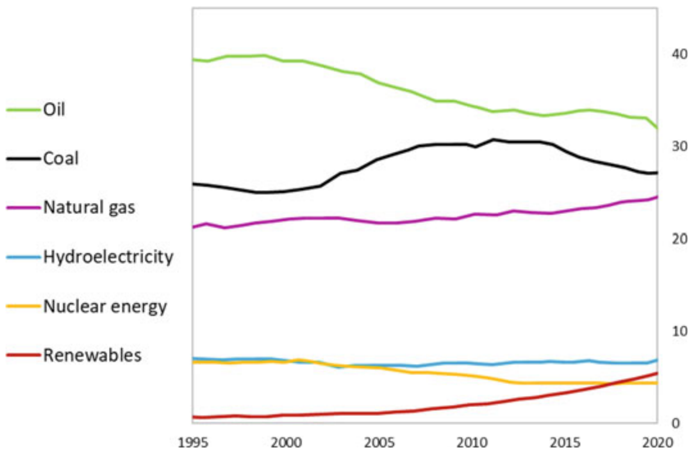


Fig. 7.2 Shares of global primary energy (percentage) (Adapted from BP 2021)

storage (CCUS) instead of electricity to produce low-emissions hydrogen, the reduction of the consumption of fossil fuels for O&G extraction by using wind and solar energy, etc. Thus, the O&G industry can employ its vast knowledge and financial resources to deploy zero-carbon technologies and drive the energy transition (IEA 2018).

7.3 Net-Zero Carbon and Energy Options

Global climate change is mainly caused by the carbon dioxide that is released through many different types of human activities. According to estimates, the world population will increase from approximately 7.8 billion (2020) to 10 billion in 2050 (Scharf et al. 2021). As a direct consequence of social and industrial development, a progressive rise in CO_2 levels in the atmosphere has been recorded and is predicted to rise.

Net-zero carbon technology is the term for technologies that result in no net CO_2 emissions. Under the Paris Agreement, countries agreed to limit global warming well below 2 °C (3.6 °F), ideally to 1.5 °C (2.7 °F). More recent research indicates that to keep 1.5 °C as a limit, the following schedule must be followed: net-zero CO_2 must be reached between 2044 and 2052, and total GHG emissions must reach net-zero between 2063 and 2068. In this scenario, renewables are projected to provide 70–85% of the world's electricity by 2050 (Levin et al. 2019). In addition to limiting global warming and air pollution, net-zero emissions are extremely important to avoid irreversible damage caused by climate change (Levin et al. 2019).

Marine renewable energy consists of different technologies for the production of renewable energy, such as offshore wind energy, floating solar photovoltaic (FPV), and ocean energy, which includes wave energy, ocean tidal energy (high and low tides) as well as energy created from temperature differences in the ocean water (ocean thermal energy conversion, OTEC) and differences in salinity (European Commission 2021).

7.3.1 Ocean Energy

Given the need for more energy from renewable and ecologically acceptable sources and the fact that the ocean covers more than 70% of Earth's surface, energy from the ocean may be one of those new sources and should indeed play a more significant role in the coming years. Theoretically, the energy potential of the ocean is sufficient for present and future global electricity needs (IRENA 2020).

However, the activities involved in the various stages of construction and operation of ocean energy devices will have various effects on the environment (species-specific response to habitat change, entanglement of marine mammals, turtles, larger fish, and seabirds). For this reason, the environmental implications of ocean energy systems must be understood to mitigate or adjust impacts to acceptable levels (Uihlein and Magagna 2016).

7.3.1.1 Tidal Energy

Tidal energy is a type of hydropower that transforms the movement of the tides into electricity or other practical forms of power and is one of the best existing sources of renewable energy: clean, predictable, quantifiable, both spatially and temporally, and not depleting (Vikas et al. 2016).

The theoretical electricity generation potential of tidal energy is the lowest of all ocean energy technologies, at around 1,200 TWh per year (Huckerby et al. 2016). By 2020, the global installed capacity of tidal energy was 22.4 MW, 76% of the installed capacity being deployed in Europe (JRC 2020). Extreme tides are found in many locations across the globe. Some of them are the Pentland Firth, Scotland; the Severn estuary; the Aleutians; the fjords of Norway; the Philippines; the Bay of Fundy, Canada; the Straits of Messina, Italy; the Bosporus, Turkey; the English Channel; Indonesia, and the straits of Alaska and British Columbia (Vikas et al. 2016).

Tidal technologies can be considered at the pre-commercial stage. Significant electricity generation and many projects and prototypes are being deployed across Europe and worldwide. The expansion has been slow, due to significant challenges associated with the deployment of the technology (tidal energy turbines need to be much sturdier than wind turbines, because of the high density of water), limited site availability, high capital investment, as well as challenges regarding the transmission from remote locations to higher energy demand regions (Vikas et al. 2016). Roughly 20 MW of tidal current projects are scheduled for deployment in the next two years, and this number is expected to exceed 1 GW by 2025 (IRENA 2020).

Compared to other marine energy sources, tidal energy has the advantage of being less vulnerable to climate change, as it is the case of wind and wave energy, which are affected by extreme weather alterations (changes in ocean circulation, more erratic winds, and sea-level rise) (Harrison and Wallace 2005). On the other hand, it has a location-specific nature, being influenced by the speed and volume of the currents. Regarding environmental impacts, tidal energy may harm wildlife habitats due to changes in the flow of water, sediment dynamics, and composition of substrate leading to the displacement and alteration of ecosystems (Uihlein and Magagna 2016).

7.3.1.2 Wave Energy

Ocean wave energy can be obtained from the kinetic and potential energy resulting from the natural oscillations of ocean waves (Uihlein and Magagna 2016). There is an incredible potential in this type of energy, theoretically estimated at 29,500 TWh per year (Mørk et al. 2010); however, most technologies are still at the R&D stage

(Uihlein and Magagna 2016). At the start of 2020, the global wave energy installed capacity was 12 MW, with 8 MW (66%) installed in the EU (OEE 2020). Areas of great potential for its exploitation include the western coast of Scotland, northern Canada, southern Africa, Australia, and the northwestern coasts of the United States.

Similar to wind power that is affected by weather conditions, the amount of wave energy that can be harnessed is contingent upon the size of the waves at any given time. An advantage, on the other hand, is the small environmental impact caused by ocean wave energy devices, in comparison with tidal energy devices (Uihlein and Magagna 2016).

7.3.2 Offshore Wind Energy

Offshore wind with a bottom-fixed foundation represents the most widely developed ocean renewable energy technology among the ones previously cited (European Commission 2021). The stable and higher wind speeds in marine areas and the unlimited area to be explored make offshore wind energy resources and potential power generation higher compared with onshore wind farms (J. Li et al. 2020). Regarding their ecological impact, offshore wind installations are advantageous since damage to forests or cultivated land caused by the land-based wind can be avoided (Costoya et al. 2020), although these can affect marine life.

According to experts' forecasts, offshore wind capacity could reach 228 GW by 2030 and nearly 1,000 GW by 2050 globally. At that time, 60% of the installations will be located in Asia, 22% in Europe, and 16% in North America (IRENA 2019).

Difficulties implementing offshore wind systems in deep waters are being overcome by the development of floating foundations, allowing facilities to be installed up to 140 km offshore. Equinor (a Norwegian energy company) is planning an 88 MW floating offshore wind farm which will start operations in 2022 to supply electricity for offshore O&G operations in the Norwegian North Sea (IRENA 2020). The design and construction experience from the O&G industry can be used to aid foundation design for offshore wind energy converters. An example of the use of the O&G industry experience is the Poshydon Project, contemplating offshore wind, offshore gas, and offshore facility to produce hydrogen from seawater on a platform in the Dutch North Sea (Neptune Energy 2020).

7.3.3 Floating Solar Photovoltaic Energy

A floating solar photovoltaic energy (FPV) installation is an emerging technology with the potential for rapid growth and consists of a floating structure on which traditional solar panels are installed.

FPV is predominantly at the R&D and demonstration phase. The global cumulative installed capacity of floating solar PV plants is 1.1 GW (GlobalData 2018).

The world's top ten plants are located in Asia, in China, Japan, and the Republic of Korea, in addition to projects developed in the Netherlands and France, where this technology has drawn the interest of many O&G companies (Radowitz 2018).

7.4 Role of O&G in a Transition Economy

The O&G industry faces opposition from a general public concerned about the environmental impact of fossil fuels, skeptical shareholders, and challenges from policymakers seeking to simultaneously address decarbonization targets and expected demand for oil and gas. Amid a global energy transition, the financial and social future of oil and gas companies, as well as the demand for their products, are in question (Johnston et al. 2020).

Still, despite these obstacles, O&G remains a significant part of the energy matrix (Fig. 7.3), especially in developing countries. Engaging and adapting to a new policy and investment landscape is the main challenge for the oil and gas industry. Supporting, contributing to and perhaps leading efforts to decarbonize the energy system is crucial (Johnston et al. 2020).

The energy transition is one of the vital areas that take up time at the discussion tables for many major O&G companies. The oil and gas era will not last forever, but it is commonly accepted by global institutions such as the World Bank and the IEA (International Energy Agency) that the transition will take time. Oil and gas

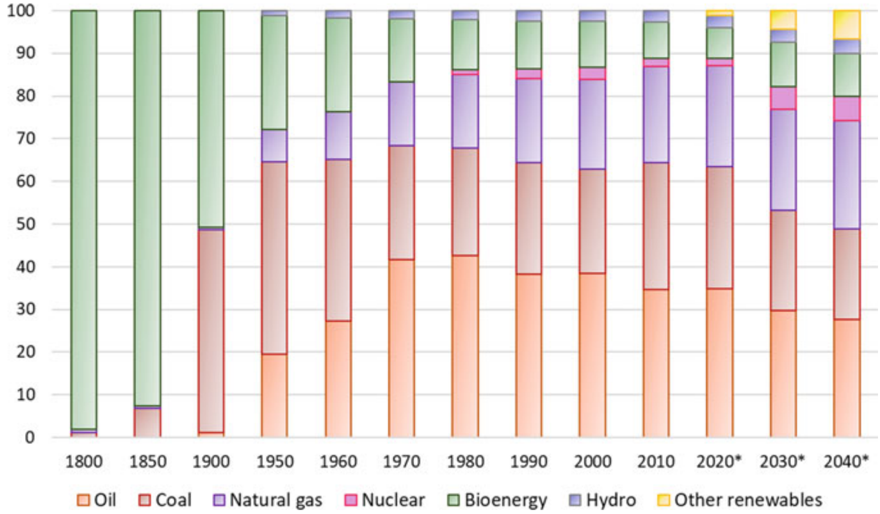


Fig. 7.3 Share of global primary energy consumption by type of fuel (percent) (*forecasts) (Adapted from Hassan et al. 2020)

should continue to play an important role in the energy matrix in the coming decades (Hassan et al. 2020).

The IEA Sustainable Development scenario and Shell's Sky scenario are aggressive predictions of decarbonization and, in both cases, O&G shows a continuous and long-term share, even with demand levels being reduced. In the United States, India and China (the three largest emitters of greenhouse gasses), depending on policy mechanisms and technologies, natural gas is likely to remain an important element of the low-carbon energy transition in the coming decades (Johnston et al. 2020).

The more important question is whether oil and gas companies will successfully transition to broader energy companies to respond to changes in the future oil and gas industry, and how will they make that transition. It is a common belief that economics will play a key role in the transition. O&G companies can decarbonize their operations and seek to advance in alternative energies, but society also plays a key role; we are very dependent on hydrocarbons, not only in terms of energy but also in the products we consume (Hassan et al. 2020).

A study carried out during the COVID-19 crisis on energy transition (Beck et al. 2021) showed that the transition of O&G companies to a low-carbon energy system is no longer in doubt, but the pace and path are unknown. While renewable energy companies such as Enel, Iberdrola, and NextEra have seen their market capitalization increase by more than 200% over the past ten years, leading O&G companies such as BP, Chevron, ExxonMobil and Shell have seen their combined capitalization drop 40%. Some of these companies have already set net-zero emissions targets and are developing different strategies, based on their aspirations to achieve them. Building more resilient core businesses, expanding low-carbon businesses and adapting the business operating model are key challenges for the energy transition. Companies will need to adapt, engage and articulate their transition plans to achieve emission targets. Defining baseline emissions is the first step in developing aggressive and credible transition plans to avoid, reduce and eventually remove emissions.

Porter et al. (2020) also argued that, despite the uncertainties brought by COVID-19, O&G companies continue to progress towards a low-carbon future. For instance, in May 2020 members of the Oil & Gas Climate Initiative reaffirmed their commitment to accelerate efforts to reduce emissions, support the development of low-carbon technologies, and invest in opportunities to expand the CCUS. However, different companies are taking different approaches, with their reduction targets differentiated by size. Most of them have made progress in reducing their carbon intensity and are evaluating which investments and technologies can further drive progress. Their approach will likely need to be holistic, looking at the entire value chain, including sourcing, operations, and sales. Even after taking these steps, it is likely to be challenging to achieve net-zero emissions by 2050.

The strategies of the O&G majors regarding the energy transition vary significantly. Leading European companies (particularly Repsol and Shell) have made more progress than American ones (such as Chevron, ExxonMobil, and ConocoPhillips), while national companies (such as Pemex, Lukoil, and CNPC) are more restricted in their ability to diversify due to government policies and regulatory frameworks (Hassan et al. 2020).

A recent study shows that 15 major O&G companies invest in a wide and growing range of clean and renewable energy technologies (Hassan 2021). Wind and solar are the most common, with almost all companies investing in both. All companies invest in CCUS, usually in advanced oil recovery projects. Most companies are also investing in "Green Hydrogen" and biofuel projects. Hydroelectric and geothermal technologies are less common, with most companies surveyed not investing in these two segments. Liquefied Natural Gas (LNG) is also considered by some to be a transitional fuel. It is commercially viable and offers a good future framework for hydrogen development. Leading O&G companies are major players in this process due to their in-depth knowledge of gas (Hassan 2021).

Concerns of consumers and executives about GHG emissions have already generated global investments of more than US$350 billion a year in wind, solar, and other alternative energies, reducing dependence on fossil fuels. For example, Equinor spends 25% of its research and development budget on low-carbon and energy-efficient technologies. They plan to operate, by 2026, a power plant capable of producing up to six gigawatts of renewable electricity. TOTAL has announced that it will participate in a British offshore wind project, while Shell increases its renewable electricity operations and invests in new energy companies (Porter et al. 2020).

For a successful transition of industrial sectors, which include oil and gas companies, from the "Brown Economy" to the "Blue Economy", the following six key strategies need to be addressed (Porter et al. 2020):

- decarbonizing energy sources;
- increasing operational energy efficiency;
- identifying new investment priorities;
- deploying new technologies;
- adjusting to new policy mandates; and
- managing consumer and shareholder expectations.

In the long term, the transition to a low-carbon future remains on track, especially for the largest integrated O&G companies. This is due in part to the need for these companies to maintain their competitive position as energy suppliers in a market where newcomers compete to provide cleaner energy for consumers and businesses (Porter et al. 2020).

7.5 Challenges and Environmental Risks of Offshore O&G Production

The continued contribution of offshore oil extraction as a blue economy resource brings a new set of challenges for the oil industry (especially from reservoirs in ultra-deep waters), requiring innovative solutions and efforts in technology development.

Exploration and production of oil and gas have the potential to cause a variety of environmental impacts, including damage to ecosystems, human health, and local

Table 7.1 Potential environmental impacts of offshore oil and gas exploration and production. Adapted from Mariano (2007)

Potential impact	Activity	Affected component
Noise: Acoustic source that causes disturbance of marine organisms	Seismic operation	Biosphere
Effluents: Discharge to the ocean of mud, production water, sewage, spills, and leaks. The combustion and burning of gasses. Effluents are leading to changes in water and air quality	Ship operations Operation in exploratory and appraisal drilling activities Operation and production in development activities	Human Biosphere Aquatic Atmospheric Terrestrial
Traces: Inappropriate control of activities resulting in contamination of water and sediment, damage to pelagic and benthic organisms' habitats, and biodiversity	Operation in exploratory and appraisal drilling activities Decommissioning in development activity	Biosphere Aquatic
Socioeconomic and Cultural: Chronic and long-term effects of effluents on benthic and pelagic fauna, sediments, and water quality. Impact of cuttings, drilling mud, and production water, etc. Gas emissions into the atmosphere	Decommissioning in development activity	Human Biosphere Aquatic Atmospheric Terrestrial

culture. Such potential impacts occur due to noise, effluents, residues, socioeconomic and cultural interference observed in the activities of the production chain (see Table 7.1) (Mariano 2007).

As shown, impacts on the marine environment are possible, beginning with the initial phase of investigating the feasibility of an offshore O&G production project. For example, seismic surveys are commonly used to determine the location of oil and gas deposits under the seabed. In this methodology, sound waves are emitted to the seabed. The reflections are then captured and analyzed to determine geologic structures of interest. The sound waves generated by seismic surveys can have a variety of harmful effects on local wildlife, such as disorientation and, in some cases, death (Udoinyang and Igboekwe 2011; Prideaux and Prideaux 2013). Well drilling usually begins when a seismic survey shows the presence of oil and gas structures. In this stage, petroleum-based drilling fluids are used, which are commonly dumped into the sea after use, damaging the local ecosystem (Adewole et al. 2010).

During the process of hydrocarbon recovery, submarine pipelines are used to pump oil, gas, and produced water. The rupture of one of these pipelines has severe consequences. A leak of CO_2, for instance, during operation can affect the marine environment: CO_2 dissolved in water forms a weak acid, reducing the pH (and increasing the partial pressure of the gas) and creating a corrosive environment (POSTnote 2005; Carruthers 2014).

One way forward to minimize such impacts is developing management systems, operating practices, and engineering technologies that minimize harmful effects and reduce environmental accidents. In this context, the world oil industry has sought to adopt science and technology-based policies that seek to preserve the environment.

7.6 S&T for Sustainable O&G Offshore Production

Science and Technology (S&T) will play a major role in the transition of the energy sector to a blue economy. This section presents a discussion of how S&T can contribute to more sustainable O&G offshore production, improving production efficiency and mitigating environmental impacts. Two case studies (Brazil and Norway) are then given as examples of how this transition is successfully starting.

7.6.1 Role of EOR and CCUS

CO_2 is responsible for nearly 77% of the total global GHG emissions and is considered the most important GHG, although its molecules have lower warming potential compared to other GHGs. Carbon dioxide Capture and Storage (CCS) has been proposed as an alternative to reduce CO_2 emissions to the atmosphere, consisting of the separation of the CO_2 from industrial sources or the atmosphere, transporting it to a storage location, and securely isolating it so that it does not threaten the environment. When the captured CO_2 is reused (for instance, in industrial processes), the term Carbon Capture, Utilization, and Storage (CCUS) is employed (Zhang et al. 2019).

Since CO_2 is often found combined with natural gas (NG) in oil reservoirs, the application of technologies aimed at capturing the CO_2 present in the gas stream on production platforms has become indispensable in the offshore environment. In addition to adjusting the CO_2 concentration in the NG to those stipulated by government agencies, it reduces the volume of gas to be transported, increases the energy content of the NG, and avoids CO_2 emissions during NG combustion (Cremer 2009; Reis 2017; Zhang et al. 2019).

Among several separation technologies available, the most appropriate one to be implemented in Floating Production Storage and Offloading (FPSO) units will be determined by the CO_2 content in the raw NG, the operating and investment costs, and the footprint and weight of equipment required (Godoi and dos Santos Matai 2021).

When it comes to CO_2 utilization, its chemical transformation into valuable materials has been extensively investigated; however, many technologies are still in an early stage of development. Some chemical processes use CO_2 as a carbon source to generate materials of interest for the chemical, pharmaceutical, polymer, and automotive industries. In carboxylation reactions, for example, CO_2 is employed as a precursor for organic compounds such as carbonates, polymers, and acrylates. By chemical reduction of CO_2, formic acid, methane, urea, and syngas are generated, while methanol can be obtained through CO_2 hydrogenation using catalysts. Electrochemical and photoelectrochemical methods have also been reported to produce chemicals such as formaldehyde, formic acid, methanol, diphenyl carbonate, acrylic acid, methane, isopropanol, glyoxal, ethanol, and butanol (Norhasyima and Mahlia 2018).

Transportation costs of chemicals and space limitations in FPSOs are the biggest obstacles for developing and implementing CO_2 capture/separation and conversion technologies offshore. Therefore, research on energy efficiency and process intensification is of great relevance for the development of economically feasible offshore solutions. Environmental aspects of producing and transporting toxic chemicals in the sea area also need to be taken into account, requiring detailed risk assessment (CSLF 2017; Kumar et al. 2020).

The cultivation of macroalgae has been studied as a possible alternative for carbon utilization offshore. Not only can macroalgae directly capture CO_2 (from the atmosphere or soluble carbonates in the seawater) and solar energy via photosynthesis, but also, the harvested material might be used as feedstock to produce biofuels in biorefineries offshore (Fernand et al. 2017). Structural requirements to withstand ocean currents and the action of waves have been demonstrated to hinder the viability of previous offshore macroalgae cultivation projects; however, developments in materials science (corrosion-resistant and strong free-floating composite materials) are promising (Greene et al. 2020).

Enhanced Oil Recovery (EOR) using carbon dioxide (CO_2-EOR) is another example of direct utilization of CO_2 already in operation offshore. EOR techniques have been employed for many years in land-based reservoirs, mostly in North America, aiming to increase oil production, also resulting in the underground storage of CO_2.

After primary oil recovery, driven by the natural pressure of the reservoir, either water (water flooding) and/or natural gas (gas flooding) are injected into the reservoir to repressurize it and maintain high production rates (secondary recovery). However, only around 20–40% of the original oil-in-place is typically recovered at the end of both stages. Since it is getting harder to discover new oilfields, tertiary recovery methods or EOR techniques are being increasingly employed by many countries in mature basins ("brownfields") to enable the extraction of additional amounts of oil, potentially increasing the recovery up to 70% (Muggeridge et al. 2014). The productive life of the reservoir is therefore extended, helping to support job provision and maximize the economic benefits in the region (FGV Energia and ANP 2021). Moreover, additional time is given for the development of alternative energy sources and technologies able to supply the global energy demand (Muggeridge et al. 2014), projected to increase nearly 50% by 2050 (IEO 2020).

Compared to other gas injection techniques, where air, dry natural gas, nitrogen, and liquefied petroleum gas are used, carbon dioxide injection (CO_2-EOR) presents many advantages, including the low market value of CO_2, its higher density (closer to the typical oil density) and viscosity, which facilitates oil miscibility and improves oil mobility throughout the reservoir's pore space (Godoi and dos Santos Matai 2021). Therefore, CO_2-EOR is one of the most attractive and most widely used EOR methods offshore, being the most important CO_2 geo-sequestration method, with the potential to recover up to 375 billion barrels of additional oil and storage of up to 360 Gton of CO_2 in the next 50 years (Godoi and dos Santos Matai 2021). This shows that the oil industry can have a positive impact by supplying global energy needs, as well as helping to address climate change challenges.

The requirements for treatment and separation of materials during CO_2-EOR onshore and offshore are the same, despite differences in reservoir and well conditions. However, offshore operations bring new challenges, which increase significantly as operations move to ultra-deep waters (CSLF 2017). These challenges naturally result in higher capital expenditure and greater economic risks. Operational maintenance is also more expensive offshore than onshore, and operating costs are higher since a major infrastructure to supply CO_2 to the EOR processing facility (usually by pipeline or by ship) needs to be implemented when the amount of recovered gas from the production well is insufficient. However, the increase in oil production and the potential to store CO_2 has attracted the industry's interest in CO_2-EOR, as it presents a possibly greater financial return. Moreover, the creation of regulations and economic/fiscal incentives by governments linked to the reduction in CO_2 emissions can increase the viability of such projects (POSTnote 2005). While regulatory requirements must be fulfilled by companies to avoid penalties, technology and innovation subsidies implemented through tax credits/rebates or direct public funds can be employed to support the deployment of more sustainable, low-carbon or emission reduction technologies (Newell 2021).

When the maximum amount of hydrocarbon has been extracted from a reservoir, it can then be used for CO_2 storage. Different from EOR projects that use naturally occurring CO_2, CCS projects typically use anthropogenic CO_2 obtained from power plants, ammonia production plants, biomass fermentation facilities, and natural gas processing plants (CSLF 2017; Novak Mavar et al. 2021), requiring safe and cost-effective CO_2 transportation to the storage site.

Apart from the high initial costs of EOR and CCS projects, there are still concerns about the health, safety and environmental (HSE) risks in the long term when it comes to subsurface leakage of CO_2. Therefore, it is necessary to have a better understanding of the CO_2 retention capacity in the long term, to develop new technologies capable of properly monitoring any CO_2 leakage and assess how it could impact the ocean floor (POSTnote 2005). Nanotechnology, for example, can be used as a new measurement technique to provide more information about the reservoir. By injecting nanosensors into oil reservoirs, it will be possible to map them more accurately, increasing the amount of oil recovered and CO_2 storage capacity, identifying CO_2 leakage, and minimizing environmental impacts (Ayatollahi and Zerafat 2012).

Some technological improvements to enable the implementation of CCS projects on a large scale are still necessary to reduce costs and make processes even more efficient. The following areas require further development (ZEP 2017):

- Subsurface pressure management to increase CO_2 storage capacity and injectivity;
- Low-cost drilling technologies for wells and dedicated Plugging and Abandonment technology;
- Low-cost monitoring and mitigation technology, as well as improving leak detection and quantification;
- Reduction of operating costs for CO_2 storage sites. For offshore sites, this can be achieved by deploying subsea technology; and
- Ensuring the storage flexibility of the system, in such a way that it can deal with the volatility in the supply and demand for CO_2.

CCUS has the potential to reduce the overall mitigation costs of global warming and increase flexibility in reducing CO_2 emissions. Projects should focus on keeping the implementation risks as low as possible, as well as minimizing changes at the production facilities and supply logistics (Vieira et al. 2020).

Although worldwide offshore exploration and production of O&G have been happening since the 1960s, offshore CO_2-EOR projects are still very limited. Malaysia (the southern South China Sea—Petronas K5 Project), Vietnam (Rang Dong Oilfield), Gulf of Mexico (Quarantine Bay, Timbalier Bay, Bay St. Elaine Field, Weeks Island Field, and Paradis Field), Abu Dhabi (Persian Gulf), South China Sea (Pearl River Mouth Basin; Huizhou 21-1 Field) have implemented varied EOR/CCUS projects; such projects in Brazil and Norway (CSLF 2017) are discussed in more detail in the upcoming section.

An international collaboration between interdisciplinary groups will play an important role in disseminating experiences globally, for instance, through conferences and workshops, leading to faster development of technologies to solve such major energy and environmental problems.

7.6.2 Case Studies: Brazil and Norway

Norway and Brazil are great examples of successful implementation of offshore CO_2-EOR and CCUS projects. In Brazil, there are 465 offshore wells, 118 of which are located in the pre-salt[1] area. Brazilian pre-salt carbonate reservoirs have unique and non-trivial characteristics which impose great technological challenges, as summarized in Table 7.2. For comparison purposes, the challenges and characteristics of Norway offshore projects are presented in the same table as well as the practiced solutions, strengths and weaknesses, S&T needs, and regulatory framework. Since production started in 1971, O&G has been produced from a total of 115 fields on the Norway Continental Shelf (NCS).

---

[1] Pre-salt layer: a series of sedimentary geological formations formed more than 100 million years ago, characterized by the deposition of salt. Pre-salt reservoirs are located below this thick layer of salt (Pré-sal Petróleo 2021).

Table 7.2 Comparison between Brazilian pre-salt and Norway O&G production

Case study	Brazilian pre-salt	Norway	Remarks
Unique characteristics	Light oil with 28 and 30°API High GOR of 200–300 m^3/m^3 Variable content of CO_2 in associated gas (8–15%)	Light oil with 38°API Low content of CO_2, exceptions are the gas field Sleipner and Snøhvit (Snow White) which contains around 10% CO_2	
Site-specific challenges	Located about 300 km offshore Brazil (Fig. 7.4) Ultra-deep waters at approximately 1,500–3,000 m depth Large exploratory areas Variable thickness salt layer above the reservoirs Carbonate reservoir with heterogeneities Flow assurance constraints related to wax deposition CO_2 effect on asphaltene precipitation, and the potential formation of calcium carbonate in the reservoir	There are some gigantic oil and gas fields located 80–200 km offshore Norway Water depth varies from 70 to 1100 m Some are sandstone reservoirs, while a few large fields in the southern part of Norway Continental Shelf (NCS) are in carbonate rock, mainly chalk reservoirs Sleipner and Snøhvit requires separation of CO_2 from the gas before the sale	Commercial natural gas has 3.0% allowed CO_2 content in Brazil, while in Norway it has 2.5%. In Norway, this requirement is often achieved by mixing low-CO_2 content gas with high-CO_2 content gas through the pipeline network before transport to the customers, unlike for the Brazilian pre-salt gas that requires separation by membrane technology
Potential/practiced solutions	Reinject the CO_2 produced CO_2 capture made directly from the associated gas in the Floating Production Storage and Offloading (FPSO) unit Treatment of produced water in the FPSO unit by electrostatic method	After the introduction of CO_2 tax in NCS in 1991, Sleipner became the first offshore field capturing and storing its produced CO_2 to the Utsira saline aquifer In 2007, the subsea development of Snøhvit started its development of gas with captured CO_2 at shore and transport pipeline back to its gas reservoir for permanent CO_2 storage MEG (monoethylene glycol) injection is applied in the CO_2 pipeline to prevent hydrate formation due to the low temperature of the seafloor	The CO_2-EOR in the Brazilian pre-salt reservoir is justified by the high volume of CO_2 available in the field itself The CO_2-EOR process currently not viable technically and economically for the NCS oil and gas fields, due to lack of the import of CO_2 of sufficient volume, offshore capture of CO_2 has too high cost and requires equipment with a large footprint

(continued)

Table 7.2 (continued)

Case study	Brazilian pre-salt	Norway	Remarks
Strength and weaknesses	High technological knowledge and possibility of investment in low-carbon technologies Low representation of wind and solar sources (8.5% and 2%, respectively) in the Brazilian energy matrix	CO_2 capture and storage from a technology point of view and with commercial value within the policy framework in Norway	
S&T needs	Acquisition of new equipment on the platform to separate CO_2 from oil Development of equipment with corrosion-resistant alloys, protective coating, and chemical products for aggressive environment	Innovative solutions must be developed to overcome the technical challenge is related to the acidification of chalk field reservoir rock by CO_2 injection	
Regulatory framework	CO_2-EOR activities in Brazil are regulated by existing oil and gas laws Regulatory requirements at the government level are needed for the long-term use of pre-salt reservoirs for CCS	Commercial CO_2-EOR is not viable economically without other incentives such as high CO_2 taxation, legislation, or public pressure The Norwegian parliament sanctioned the CCS value chain project Longship (Norwegian Ministry of Petroleum and Energy 2020)	

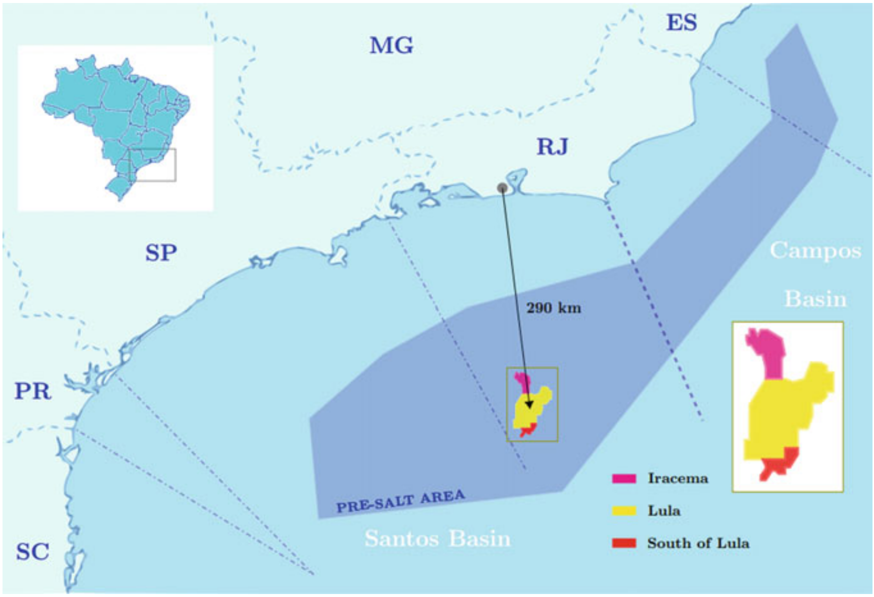


Fig. 7.4 Location of Brazilian pre-salt fields in ultra-deep waters (Adapted from da Costa Fraga et al. 2015)

7.6.2.1 Brazilian Pre-Salt Case Study

Since the beginning of oil exploration in the Brazilian pre-salt reservoirs (Fig. 7.4), preliminary numerical simulations showed that CO_2-EOR would be a promising technique for several reasons: high gas-oil ratio and CO_2 concentration, strategic decision for environmental reasons not to vent CO_2 to the atmosphere, light and low viscosity oil, and miscible injection in the pressure and temperature condition of the reservoir, which favors displacement and recovery. On the other hand, due to the presence of CO_2, there are serious corrosion problems in carbon steel caused by the formation of carbonic acid resulting from the dissolution of CO_2 into water. Therefore, a rigorous selection of materials must be considered as well as chemical products for corrosion inhibition (Beltrao et al. 2009; Cezar et al. 2015; De Andrade et al. 2015; da Costa Fraga et al. 2015; Geraci et al. 2017).

Due to environmental issues and the limited amount of gas to be flared, imposed by the Brazilian National Agency of Petroleum, Natural Gas and Biofuels (Godoi and dos Santos Matai 2021) the oil companies decided to separate and reinject the CO_2 from the natural gas stream. Therefore, the CO_2-EOR method with Water Alternating Gas was considered (de Sant'Anna Pizarro and Branco 2012; Godoi and dos Santos Matai 2021). In this context, the use of two abundant resources available (seawater and produced or imported gas) in the pre-salt reservoir development created opportunities for connecting EOR and CCS methods. In addition to CO_2-EOR increasing of oil recovery, it avoids CO_2 emission to the atmosphere and provides its storage in geological formations permanently. Thus, this strategy results in a synergistic effect of maximizing oil production and reducing environmental impacts due to offshore activities (IPIECA 2007).

Currently, ten fields have been operated in the pre-salt area and they are responsible for 73.1% of the total oil produced in Brazil (ANP 2021). The amount of CO_2 reinjected in the pre-salt Santos Basin fields is around 3.0 Mt per annum, and the ambition is to expand the capacity of the FPSO units to reinject more than 40 Mt CO_2 by 2025 (Godoi and dos Santos Matai 2021).

A combination of offshore O&G and offshore wind may be possible in many sectors of the O&G industry in the future. The electric energy supplied by the combination of existing O&G platforms with offshore wind power may even result in exports of the remaining production to land electricity grids as an advantage in the decrease of regional GHG emissions. Another relevant development is floating wind turbine technology that allows for the use of oil production exploration in deep waters (Legorburu et al. 2018). In 2019, the Energy Research Office, with the Ministry of Mines and Energy, undertook the challenging task of including offshore wind in the Brazilian energy planning assessments. This research indicates a technical potential of around 700 GW in sites that extend up to 50 m deep and all coastal regions have areas with high potential for wind offshore farms (Energy Research Office 2020).

7.6.2.2 Norway Case Study

Norway is the largest exporter of natural gas in the world, with 109 billion cubic meters of gas and 6.6 billion cubic meters of LNG exported in 2020. The gas is exported through about 7,800 km of transport pipes on the whole NCS to customers through the receiving terminals in the UK, Germany, France, and Belgium, as illustrated by Fig. 7.5. In the beginning, the large oil fields on NCS were developed using concrete fixed-bottom platforms and steel structures where the water depth was shallow. Later, the fields with deeper water were developed using semi-submersible or tension leg platforms. New subsea technology contributes to hosting smaller fields around the fixed platforms, which allow field developments in the nearby areas up to 50 km away.

There is strict regulation on gas flaring on NCS; flaring of associated gas is allowed only with exception and special permission. The CO_2 tax on NCS was introduced in 1991 by the Norwegian Government for environmental protection, set to 500 NOK/ton (~70$/ton) in that year. Due to this high taxation, Sleipner became the first offshore field capturing and storing its produced CO_2 in the Utsira saline aquifer, which is about 1,000 m below the seafloor and above the Sleipner gas reservoirs at 3,450 m deep.

Later, in 2007, the subsea development of Snøhvit gas field started its development of gas with ~10% CO_2 to produce LNG. The field is located 148 km away from the processing facility at Melkeøya, which was built from material from a landfill from a small fish town called Hammerfest. The Snøhvit gas, contained within five main geological structures, was extracted using fifteen subsea wells and transported with

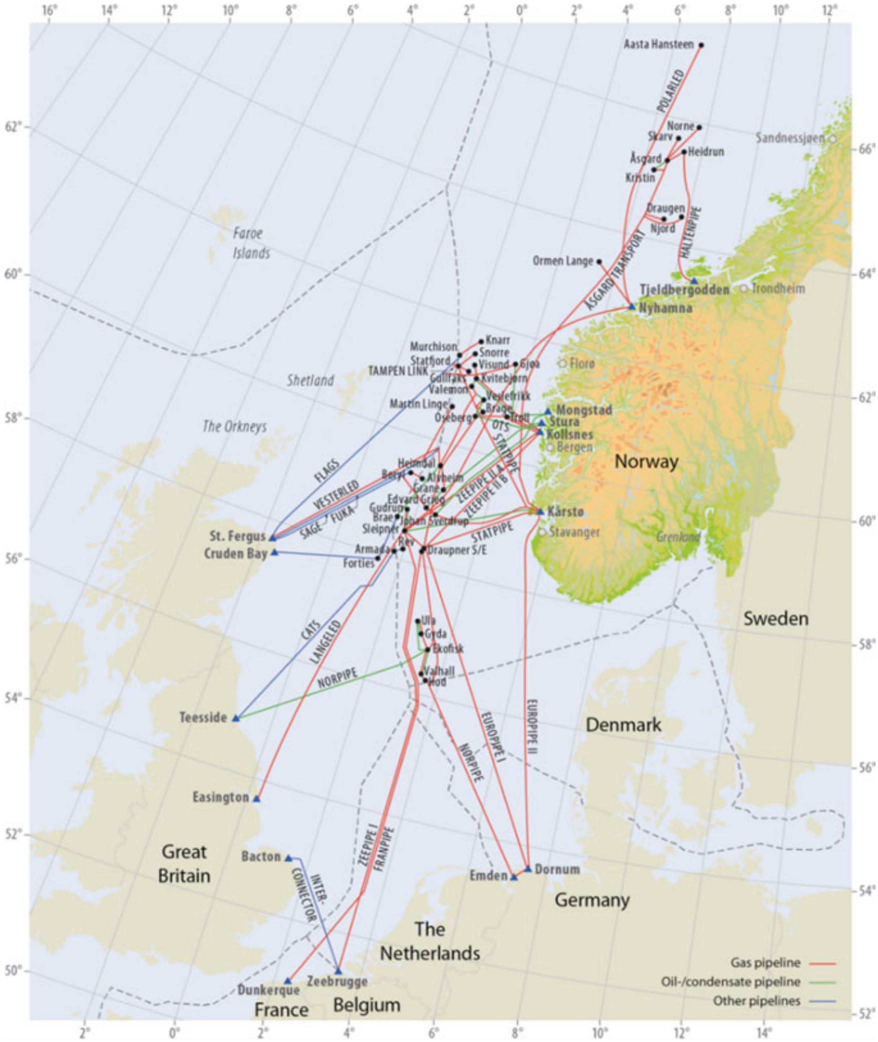


Fig. 7.5 Norwegian oil and gas transport network to Europe (*Source* NPD [2014] CO_2 Atlas for the Norwegian Continental Shelf, https://www.npd.no/en/facts/publications/co2-atlases/co2-atlas-for-the-norwegian-continental-shelf/)

the gas pipeline to Melkeøya for processing to produce LNG; CO_2 is separated and transported back to the field with a dedicated 7 inches CO_2 transport pipeline for permanent CO_2 storage (White et al. 2018).

A study carried out by the Norwegian Petroleum Directorate (NPD) in 2005 and updated in 2012 on fields in the North Sea, indicated a large potential for additional oil recovery of more than 370 Mt oil from 19 fields in the North Sea, with an injection of 80Mt/y CO_2. The amount of potential stored CO_2 in oil and gas fields is more than 1.5

Gt and the amount stored in aquifers is 1.9 Gt CO_2. Realistically, the matured chalk fields on NCS might be a candidate for a late-life boost in combination with CCS, which will not require large investment if the focus is to inject CO_2 for permanent storage.

There is significant technical potential for storing CO_2 in geological formations on NCS. Producing oil and gas fields, abandoned oil and gas fields and geological formations such as saline aquifers might all be candidates for such storage. Storage in reservoirs that are no longer in operation can be a good solution in terms of geology since these structures are likely to be impermeable after having held oil and gas for millions of years.

The NPD created, with large effort, the Norwegian CO_2 storage Atlas (NPD 2014), which gives an overview of possible geological structures, both saline aquifers and existing HC reservoirs suitable for CO_2 storage, based on a thorough methodology. The Norwegian North Sea has a potential CO_2 storage capacity of 70 Gt, which is far more than Norway's CO_2 emission of about 50 Mt/year. In 2019, NPD awarded the first CO_2 storage license for the Northern Lights project for transport and storing 1.5 Mt/year of CO_2 captured from 2 industrial emitters (1 cement plant, 1 waste incineration plant). Then in 2020, an appraisal well was drilled to confirm the reservoir quality and storage capacity. The captured CO_2 will be shipped to the pipeline terminal on the west coast of Norway, then transported by a 12 inch pipeline to the planned CO_2 store in the North Sea about 110 km away.

Field electrification with renewable energy from land is one of the measures to reduce emission from field operation, in addition offshore wind power is now under development and some projects are under construction. Wind power may provide electricity to O&G operations and can also be used to produce hydrogen which, in turn, can be used as an energy source or catalysts for CO_2 conversion. It is therefore a great opportunity for the Norwegian oil and gas industry to transform NCS into a new and sustainable value creation ground in the near future.

Research and technology development (R&D) is crucial for the O&G industry in Norway for offshore oil and gas exploitation as a new industry on NCS from the 1960s. Since the very beginning, the Norwegian government has invested in education, research, and new technology development with public funding, which also enforces and encourages private investment in R&D. The Research Council of Norway has invested 4.8 B NOK (~ 670 M USD) in the recent 10 years (2008–2018) through 677 projects. Additionally, the public funding also triggered private R&D funding in the same order of magnitude for technology implementation. Each 1 NOK in R&D funding has generated 30 NOK in value, and the research activities have contributed significantly to the additional recovery of the oil and gas resources, cost savings, and GHG emission reduction. This is one important reason that has made Norway one of the leading nations in cost-effective and clean O&G production. It has also contributed to international operations and industrial export. For CO_2 handling, already back in 1986, the first research project for capturing CO_2 from a gas power plant and geological storage was sponsored by Equinor (Statoil) and proposed CO_2 geological storage as a feasible way to reduce emission to the atmosphere. Later, in 2005, the state-owned organization Gassnova was formed to manage the publicly funded R&D within CO_2 handling, through its CLIMIT research program, with large public funding. For example, CLIMIT funded 233 M NOK (~32 M USD) for 169 projects in 2019. Norway is also an active member in the European CO_2 research arena and participates in several EU-funded projects in collaboration with European research partners. These research activities throughout more than 30 years have formed the basis of the ongoing CCS projects on NCS.

7.7 Lessons Learned

The case studies about offshore O&G production in Brazil and Norway are examples of the balancing of economically and environmentally sustainable production with the mitigation of global warming through CO_2 capture and storage.

In the Brazilian pre-salt, the high CO_2 content in the associated gas stands out (up to 40% in the Lula field), which requires the separation of CO_2 from the NG and its reinjection into the reservoir. As the fields are not mature yet, this is an unusual situation, in which enhanced oil recovery (CO_2-EOR) is carried out in the initial phase of the productive life. However, a major portion of CO_2, after the abandonment of the field, has the possibility of being permanently stored in the geological structures of the pre-salt.

In the case of the Norwegian Continental Shelf, typical values of CO_2 content in natural gas or the associated gas is on average well below 2.5%, with exception of a few gas fields which have higher CO_2, such as Sleipner and Snøhvit fields with around 10 vol%. Due to the national taxation on emitted CO_2, these two high-CO_2 content gas fields implemented CO_2 separation and storage solutions since the start of field development in 1996 and 2003, respectively. The amount of produced CO_2 is not enough to meet the demand for economical EOR applications for the nearby fields. The experiences gained from the CO_2 capture and storage at these two fields, however, paved the way for the geological storage of CO_2 captured from other industrial sources, to meet the goals of reducing greenhouse gas emissions. In this case, CO_2 must be supplied by pipelines or transported by ships to the injection well(s) at the storage site. There is large potential to re-purpose the gas and oil transport pipeline network on the Norwegian Continental Shelf to transport CO_2 from the European continent in the future (Eide et al. 2019; Cauchois et al. 2021) to benefit from the gigaton geological storage capacity identified (NPD 2014). The national LongShip project (Norwegian Ministry of Petroleum and Energy 2020) is underway, with operation starting from 2023. Several large trans-European projects are now under evaluation and preparation is underway for transport of captured CO_2 from the European continent to offshore storage sites (CCS Norway 2021).

From the viewpoint of health, safety, and environmental (HSE) impacts, both Brazil and Norway have more similarities than differences in offshore oil production. According to Oldenburg (2012), HSE impacts related to CO_2 injection and storage decrease as depth increases. For example, groundwater quality can be affected by the penetration of CO_2 into a potable aquifer, forming carbonated water. However, in the case of offshore basins, such as in Norway and Brazil, this type of water is not viable to be used in the potable form. Also, according to Oldenburg (2012), HSE impacts are predictably greater the closer to the surface the CO_2 leakage occurs. For example, increasing the concentration of dissolved CO_2 in seawater near the ocean surface can affect the surrounding fauna and flora as well as humans, which is typically a local impact. However, given the distances from offshore platforms (300 km off the Brazilian coast and 80–300 km off the Norwegian coast), the risk to people or human activities is very low. On the other hand, considering the global risk, if part of the CO_2 dissolved in seawater passes into the atmosphere, this can impact global warming, depending on the amount of the leakage.

Although there are never truly zero risks, it is possible to mitigate them. For example, continuously monitoring both the injection process and the geological storage of CO_2 allows for safe injection, detecting failures, and interrupting leaks. One of the possibilities is seismic monitoring (Daley et al. 2008; Ringrose 2020). It should be emphasized, however, that injection projects must be carefully designed, including effective and continuous monitoring programs for large-scale safe and effective applications.

7.8 Final Remarks

Offshore oil and gas production plays a major role in the “Blue Economy”, and can contribute to the sustainable transition to a net-zero carbon society. A realistic and important pathway is the combination of CO_2-EOR and CO_2 capture and storage, which have been applied in both Brazil and Norway, with differences and similarities addressed in this chapter. It shows that it is feasible to match both economic outcomes and environmental requirements, provided that science and technology are continuously developed to overcome the industry challenges and supported by a regulatory framework.

As the African coast (between Gabon and Angola) shares geological characteristics similar to the Campos and Santos Basins on the Brazilian coast, this region presents a great potential for oil production in the African pre-salt and relevant opportunity for technology transfer. In Angola, for instance, activities have intensified since 2011, when the Angolan government granted 11 pre-salt blocks in the Kwanza Basin to several multinationals—including BP, Conoco Phillips, Petrobras, Statoil, and Total. Other developing economies where O&G has been recently discovered—such as Mozambique, Tanzania, Kenya, and Uganda—could greatly benefit from technology transfer. However, the lack of local skilled labor, political instability and regulatory restrictions imposed by governments are still major barriers to investors. In the short term, O&G technology transfer to developing countries to meet blue economy goals will likely be limited to the larger and more developed developing countries (Brazil, India, etc.)

New technology solutions, such as offshore renewable energy production to provide power to offshore oil and gas production, “Blue Hydrogen” from reforming natural gas, "Green Hydrogen" by electrolysis of seawater, conversion of CO_2 to chemicals, etc., represent great opportunities to contribute to economic growth and at the same time reduce climate change. These new technological solutions, however, are still under development and feasible adoption will require a larger scale, higher efficiency, and lower cost. A major issue is the energy consumption with low emission. Offshore wind power can be used to generate renewable electricity for both O&G production as well as the electrolysis of seawater for "Green Hydrogen" and natural gas reforming to produce "Blue Hydrogen". Hydrogen may in turn be used in catalytic hydrogenation of CO_2 into liquid fuels, such as methanol and formic acid. Although this is not economically feasible yet, science and technology continually contribute to reducing the costs. This example of a very promising solution for the offshore industry shows how O&G production is linked to a sustainable transition to a net-zero carbon society. Similar ideas can also be explored in the context of offshore biorefineries.

As extensively discussed in this chapter, the transition to a net-zero carbon society cannot be postponed. Therefore, the best strategy should be to take advantage of special situations, for instance, offshore O&G production combined with CO_2 capture, storage, and utilization. More research, development and technology adoption are needed to reach the goals of technical efficiency and economic profitability to minimize the environmental impacts of O&G production in the ocean and coastal areas. The perspective of sustainable development, especially with the support of governments, should be the mainspring to a safe transition to renewable energies. In this context, investments by large energy companies, as well as multidisciplinary research funding, are needed to overcome the hurdles and flourish by opening new business opportunities. Economic and social inclusion, environmental preservation, and short-, medium- and long-term benefits to the surrounding population should be assured to all.

References

Adewole GM, Adewale TM, Ufuoma E (2010) Environmental aspect of oil and water-based drilling muds and cuttings from Dibi and Ewan off-shore wells in the Niger Delta, Nigeria. Afr J Environ Sci 4:284–292

ANP (2021) Boletim Da Produção de Petróleo e Gás Natural. https://www.gov.br/anp/pt-br/centrais-de-conteudo/publicacoes/boletins-anp/bmp/2021/2021-03-boletim-pdf.pdf

Ayatollahi S, Zerafat MM (2012) Nanotechnology-assisted EOR techniques: New solutions to old challenges. Paper presented at the SPE international oilfield nanotechnology conference and exhibition. SPE, Noordwijk, The Netherlands, pp 1–15. https://doi.org/10.2118/157094-MS

Beck C, Bellone D, Hall S et al (2021) The big choices for oil and gas in navigating the energy transition. McKinsey's Oil & Gas Practice

Beltrao RL, Sombra C, Lage A et al (2009) Challenges and new technologies for the development of the Pre-Salt Cluster, Santos Basin, Brazil. Paper presented at the Offshore Technology Conference, Houston, Texas, May 2009. https://doi.org/10.4043/otc-19880-ms

BP (2020) Statistical review of world energy. https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf

BP (2021) Statistical review of world energy 2020 70th edition, British Petroleum Corporation. https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2021-full-report.pdf

Carruthers K (2014) Environmental impacts of CO_2-EOR: the offshore UK context. Scottish Carbon Capture & Storage. https://era.ed.ac.uk/bitstream/handle/1842/15716/SCCS-CO2-EOR-JIP-WP4-Environmental-Impacts.pdf

Cauchois G, Simon M, Dale D et al (2021) Potential for re-use of oil and gas infrastructure on the Norwegian Continental Shelf. In: Proceedings of the 15th greenhouse gas control technologies conference. https://doi.org/10.2139/ssrn.3820790

CCS Norway (2021) CO_2 transport and storage: Northern lights project. 2021. https://ccsnorway.com/transport-storage-northern-lights/

Cezar A, Paulo S, Pereira AR et al (2015) Subsea solutions in the pre-salt development projects. Proceedings of the Annual Offshore Technology Conference 2:1434–1453. https://doi.org/10.4043/25773-ms

Choudhary P, Subhash GV, Khade M et al (2021) Empowering blue economy: from underrated ecosystem to sustainable industry. J Environ Manage 291:112697. https://doi.org/10.1016/j.jenvman.2021.112697

Claisse JT, Pondella DJ, Love M et al (2015) Impacts from partial removal of decommissioned oil and gas platforms on fish biomass and production on the remaining platform structure and surrounding shell mounds. PLoS ONE 10(9):1–19. https://doi.org/10.1371/journal.pone.0135812

Cordes EE, Jones DOB, Schlacher TA et al (2016) Environmental impacts of the deep-water oil and gas industry: a review to guide management strategies. Front Environ Sci 4:58. https://doi.org/10.3389/fenvs.2016.00058

Costoya X, Carvalho D, Gómez-Gesteira M (2020) On the suitability of offshore wind energy resource in the United States of America for the 21st century. Appl Energ 262:114537. https://doi.org/10.1016/j.apenergy.2020.114537

Cremer C (2009) Carbon capture and storage. In: Ball M, Wietschel M (eds) The hydrogen economy: opportunities and challenges, pp 168–198. https://doi.org/10.1017/CBO9780511635359.007

CSLF (2017) Enabling large-scale CCS using offshore CO_2 utilization and storage infrastructure developments, carbon sequestration leadership forum technical group task force on offshore CO_2-EOR. https://www.cslforum.org/cslf/sites/default/files/documents/OffshoreEORTaskForce-FinalReport.pdf

da Costa Fraga CT, Pinto ACCP, Branco CCM et al (2015) Brazilian pre-salt: an impressive journey from plans and challenges to concrete results. Proc Annu Offshore Technol Conf 1:746–760. https://doi.org/10.4043/25710-ms

Daley TM, Myer LR, Majer EL et al (2008) Time-lapse crosswell seismic and VSP monitoring of injected CO_2 in a brine aquifer. Environ Geol 54:1657–1665. https://doi.org/10.1007/s00254-007-0943-z

de Andrade AMT, Vaz CEMV, Ribeiro J et al (2015) Offshore production units for pre-salt projects. In: Proceedings of the annual offshore technology conference 1:557–570. Houston, Texas, USA. https://doi.org/10.4043/25691-ms

de Sant'Anna Pizarro JO, Branco CC (2012) Challenges in implementing an EOR project in the Pre-Salt Province in deep offshore Brasil. In: Society of petroleum engineers—SPE EOR conference at oil and gas West Asia. SPE, Muscat, Oman. https://doi.org/10.2118/155665-MS

Eide LI, Batum M, Dixon T et al (2019) Enabling large-scale carbon capture, utilisation, and storage (CCUS) using offshore carbon dioxide (CO_2) infrastructure developments—a review. Energies 12(10):1–21. https://doi.org/10.3390/en12101945

Energy Research Office (2020) Brazilian offshore wind roadmap. https://storymaps.arcgis.com/stories/1565a407d4a443029e035b1844c8437b

European Commission (2021) The EU blue economy report. Publication Office of the European Union, Luxembourg. https://op.europa.eu/en/publication/Ob0c5bfd-c737-11eb-a925-01aa75ed71a1
Fernand F, Israel A, Skjermo J (2017) Offshore macroalgae biomass for bioenergy production: Environmental aspects, technological achievements and challenges. Renew Sustain Energy Rev 75:35–45. https://doi.org/10.1016/j.rser.2016.10.046
FGV Energia, ANP (2021) Decommissioning in Brazil—opportunities, challenges and solutions. Notebook FGV Energia, vol 11. Rio de Janeiro
Geraci M, Ali SJ, Romolt C et al (2017) The environmental risks and oversight of enhanced oil recovery in the United States: an overview of Class II well trends and regulations in EPA's Underground Injection Control Program. https://www.cleanwater.org/sites/default/files/docs/publications/The%20Environmental%20Risks%20and%20Oversight%20of%20Enhanced%20Oil%20Recovery%20in%20the%20United%20States.pdf
GlobalData (2018) Solar PV module, update 2018—Global market size, competitive landscape and key country analysis to 2022
Godoi JMA, dos Santos Matai PHL (2021) Enhanced oil recovery with carbon dioxide geosequestration: first steps at pre-salt in Brazil. J Petrol Explor Prod 11(3):1429–1441
Greene JM, Gulden J, Wood G et al (2020) Techno-economic analysis and global warming potential of a novel offshore macroalgae biorefinery. Algal Res 51:102032. https://doi.org/10.1016/j.algal.2020.102032
Harrison GP, Wallace AR (2005) Climate sensitivity of marine energy. Renew Energ 30(12):1801–1817. https://doi.org/10.1016/j.renene.2004.12.006
Hassan M (2021) Energy transition: the evolving role of oil & gas companies in a net-zero future. https://www.lexology.com/library/detail.aspx?g=1ecc924c-e3c6-4684-90f0-7e3efadeb11f
Hassan M, Wisely N, Majumder-Russell D et al (2020) Energy transition: Evolution or revolution? CMS EEIG, no. January: 1–48
Huckerby J, Jeffrey H, de Andres A et al (2016) An international vision for ocean energy. Version III. Published by the Ocean Energy Systems Technology Collaboration Programme: www.ocean-energy-systems.org
IEA (2018) World energy outlook 2018: highlights. International Energy Agency 1:1–661
IEO (2020) U.S. Energy Information Administration's international energy outlook 2020—United States Milestones in meeting global energy consumption, vol 2020
IPCC (2005) Carbon dioxide capture and storage. https://doi.org/10.1002/9783527818488.ch15
IPIECA (2007) Oil and natural gas industry guidelines for greenhouse gas reduction projects. Ipieca API, no. March: 104
IRENA (2019) Navigating the way to a renewable future: solutions to decarbonise shipping—preliminary findings. https://www.irena.org/publications/2019/Sep/Navigating-the-way-to-arenewable-future
IRENA (2020). Fostering a blue economy, offshore renewable energy. The International Renewable Energy Agency. https://irenea.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Fostering_BLue_Economy_2020.pdf
Jensen PD, Purnell P, Velenturf APM (2020) Highlighting the need to embed circular economy in low carbon infrastructure decommissioning: The case of offshore wind. Sustainable Production and Consumption 24:266–280. https://doi.org/10.1016/j.spc.2020.07.012
Johnston RJ, Blakemore R, Bell R (2020) The role of oil and gas companies in the energy transition. Atlantic Council, Washington, DC
JRC (2020) Facts and figures on offshore renewable energy sources in Europe
Kumar S, Foroozesh J, Edlmann K et al (2020) A comprehensive review of value-added CO_2 sequestration in subsurface saline aquifers. J Nat Gas Sci Eng 81:103437. https://doi.org/10.1016/j.jngse.2020.103437
Legorburu I, Johnson KR, Kerr SA (2018) Multi-use maritime platforms—North Sea oil and offshore wind: opportunity and risk. Ocean Coast Manage 160:75–85. https://doi.org/10.1016/j.ocecoaman.2018.03.044

Levin K, Fransen T, Schumer C et al (2019) What does 'net-zero emissions' mean? 8 Common Questions, Answered. World Resources Institute. https://www.wri.org/insights/net-zero-ghg-emissions-questions-answered?nlid=&sara_ecid=nl_upd_1jtzCCtmxpVo9GAZr2b4X8GquyeAc9
Li J, Wang G, Li Z (2020) A review on development of offshore wind energy conversion system. Int J Energ Res 44:9283–9297. https://doi.org/10.1002/er.5751
Li L, Ruzzo C, Collu M et al (2020) Analysis of the coupled dynamic response of an offshore floating multi-purpose platform for the Blue Economy. Ocean Eng 217:107943. https://doi.org/10.1016/j.oceaneng.2020.107943
Mariano JB (2007) Proposta de Metodologia de Avaliação Integrada de Riscos e Impactos Ambientais Para Estudos de Avaliação Ambiental Estratégica Do Setor de Petróleo e Gás Natural Em Áreas Offshore UFRJ, Rio de Janeiro
Matthews R (2013) Environmental implications of three types of economies: brown, blue and green. The Green Market Oracle. https://thegreenmarketoracle.com/2013/10/04/environmental-implications-of-three/
Mørk G, Barstow S, Kabuth A et al (2010) Assessing the global wave energy potential. In: 29th international conference on ocean, offshore mechanics and arctic engineering (OMAE2010). Shanghai. https://doi.org/10.1115/OMAE2010-20473
Muggeridge A, Cockin A, Webb K et al (2014) Recovery rates, enhanced oil recovery and technological limits. Phil Trans R Soc A 372:20120320. https://royalsocietypublishing.org/doi/10.1098/rsta.2012.0320
Neptune Energy (2020) The world's first offshore green hydrogen plant. https://www.neptunenergy.com/esg/new-energy/poshydon-hydrogen-pilot
Newell R (2021) Federal climate policy 101: reducing emissions. March 2021. https://www.rff.org/publications/explainers/federal-climate-policy-101/
Norhasyima RS, Mahlia TMI (2018) Advances in CO_2 utilization technology: a patent landscape review. J CO_2 Util 26:323–335. https://doi.org/10.1016/j.jcou.2018.05.022
Norwegian Ministry of Petroleum and Energy (2020) Meld. St. 33 (2019–2020) Report to the Storting (White Paper). Longship—Carbon Capture and Storage
Novak Mavar K, Gaurina-Međimurec N, Hrnčević L (2021) Significance of enhanced oil recovery in carbon dioxide emission reduction. Sustainability (switzerland) 13(4):1–27. https://doi.org/10.3390/su13041800
NPD (2014) CO_2 Atlas for the Norwegian Continental Shelf. https://www.npd.no/en/facts/publications/co2-atlases/co2-atlas-for-the-norwegian-continental-shelf/
OEE (2020) Ocean energy—key trends and statistics 2019. https://www.oceanenrgy-europe.eu/wp-content/uploads/2020/03/OEE_Trends-Stas_2019_Web.pdf
Oldenburg CM (2012) Geologic carbon sequestration: sustainability and environmental risk. In: Meyers RA (ed) Encyclopedia of sustainability science and technology. Springer, New York, pp 4119–4133
Porter S, Dickson D, Hardin K et al (2020) Oil, gas, and the energy transition: how the oil and gas industry can prepare for a lower-carbon future. Deloitte Insights
POSTnote (2005) Carbon capture and storage (CCS). https://www.parliament.uk/globalassets/document/post/postpn238.pdf
Pré-sal Petróleo (2021) Pré-Sal Petróleo S.A. PPSA—Welcome! https://www.presalpetroleo.gov.br/ppsa_eng/the-pre-salt/characteristics
Prideaux G, Prideaux M (2013) Seismic Seas: understanding the impact of offshore seismic petroleum exploration surveys on marine species. Wild Migration Technical and Policy Review, vol 3. Wild Migration, Australia. https://doi.org/10.13140/RG.2.1.1405.0322
Radowitz B (2018) South Korea plans world's largest floating solar plant in Yellow Sea. https://www.rechargenews.com/transition/south-korea-plans-world-s-largest-floating-solar-plant-in-yellow-sea/2-1-719765
Reis A de C (2017) Remoção de CO_2 de Gás Natural Em Plataforma Offshore via Otimização de Trens de Permeação Em Membranas, Absorção Química, Absorção Física e Híbridos. Universidade Federal do Rio de Janeiro

Ringrose P (2020). How to store CO_2 underground: insights from early-mover CCS Projects, Springer Press. http://link.springer.com/10.1007/978-3-030-33113-9
Scharf H, Arnold F, Lencz D (2021) Future natural gas consumption in the context of decarbonization—a meta-analysis of scenarios modeling the German energy system. Energy Strateg Rev 33:100591. https://doi.org/10.1016/j.esr.2020.100591
Sedlar DK, Vulin D, Krajačić G et al (2019) Offshore gas production infrastructure reutilisation for Blue Energy production. Renew Sustain Energy Rev 108:159–174. https://doi.org/10.1016/j.rser.2019.03.052
Smith-Godfrey S (2016) Defining the Blue Economy. Marit Aff 12(1):58–64. https://doi.org/10.1080/09733159.2016.1175131
Statista (2019) Distribution of onshore and offshore crude oil production worldwide from 2005 to 2025. https://www.statista.com/statistics/624138/distribution-of-crude-oil-production-worldwide-onshore-and-offshore/#:~:text=Offshore oil production is mainly, oil production worldwide in 2015
Tidona B, Koppold C, Bansode A et al (2013) CO_2 hydrogenation to methanol at pressures up to 950 Bar. J Supercrit Fluid 78:70–77. https://doi.org/10.1016/j.supflu.2013.03.027
Udoinyang I, Igboekwe M (2011) The impacts of seismic activities on marine life and its environment. Int Arch Appl Sci Technol 2:1–10
Uihlein A, Magagna D (2016) Wave and tidal current energy—a review of the current state of research beyond technology. Renew Sustain Energy Rev 58:1070–1081. https://doi.org/10.1016/j.rser.2015.12.284
Vieira RAM, Pizarro JOS, Oliveira LA et al (2020) Offshore EOR initiatives and applications in Brazil: An operator perspective. Proceedings of the Annual Offshore Technology Conference 2020-May. https://doi.org/10.4043/30780-ms
Vikas M, Subba R, Kumar SJ (2016) Tidal energy: a review tidal energy: a review. In: Proceedings of international conference on hydraulics, water resources and coastal engineering (Hydro2016). Pune
White JC, Williams G, Chadwick A (2018) Seismic amplitude analysis provides new insights into CO_2 plume morphology at the SnØhvit CO_2 injection operation. Int J Greenh Gas Con 79(July):313–322. https://doi.org/10.1016/j.ijggc.2018.05.024
ZEP (2017) Future CCS technologies. European Zero Emission Technology and Innovation Platform 1–126
Zhang Y, Lu X, Ji X (2019) Carbon dioxide capture and storage. In: Deep eutectic solvents: synthesis, properties, and applications, pp 297–319. https://doi.org/10.1002/9783527818488.ch15

Chapter 8
Coastal and Nearshore Minerals: Blue Economy Potential and Prospects

Absai Vatuva, Gabriel Filippelli, Anup R. Gujar, Sridhar D. Iyer, and P. Udayaganesan

Abstract Minerals found in coastal sand dunes, beaches, near shore, and throughout a nation's exclusive economic zone are important assets that contribute to national blue economies. Extracting minerals in a manner that adheres to blue economy principles can be challenging because of the difficulties in mining minerals in environmentally and socially sustainable ways. The positive effects of extraction need to be finely balanced with negative effects on other blue economy resources, such as fisheries and tourism. Yet, we cannot ignore mineral extraction in a book on blue economy because several countries include minerals in their blue economy plans. Scientific knowledge and modern technology that are necessary as foundations to achieve sustainable extraction may be lacking in the mineral resource development plans of many nations. This chapter discusses two primary types of mineral extraction: (1) heavy minerals and diamonds that are carried by fluvial means into coastal areas where they form deposits by natural physical processes and (2) phosphate minerals that are formed in place through natural chemical processes in some coastal areas of the world. The chapter will describe environmental and social implications of mineral recovery, including ways by which these resources can play an important role in blue economies.

A. Vatuva (✉)

University of Namibia, Windhoek, Namibia
e-mail: avatuva@unam.na

G. Filippelli
Department of Earth Sciences, Indiana University-Purdue University Indianapolis (IUPUI), Indianapolis, IN, USA
e-mail: gfilippe@iupui.edu

A. R. Gujar · S. D. Iyer
CSIR-National Institute of Oceanography, Dona Paula, Goa, India
e-mail: anup.gujar@gmail.com

S. D. Iyer
e-mail: sdiyer2001@gmail.com

P. Udayaganesan
Alagappa Government Arts College, Alagappa University, Karaikudi, Tamil Nadu, India

E. R. Urban Jr. and V. Ittekkot (eds.), *Blue Economy*,
https://doi.org/10.1007/978-981-19-5065-0_8

Keywords Placer deposits · Marine diamonds · Marine phosphates

8.1 Introduction

Minerals found in coastal and nearshore locations can contribute to local and national economies and are already being mined in many places around the world. Many countries still have untapped mineral resources available in coastal areas (Hannington et al. 2017), but mining activities can face technological, environmental, and social barriers. Chapter 1 notes that there are many different definitions of "blue economy", but for the purposes of this book, blue economy is defined as achieving a balance of economic development, environmental protection, and sustainability of local populations. Mining can conflict with fisheries, tourism, and societal stability, but may also be one of a small number of potential sources of income in a region or country. Therefore, most countries pursue some development of mineral resources. In order to qualify as a blue economy resource, mining must be carried out in a sustainable manner that does not damage other resources or harm local communities.

In this chapter, we discuss the minerals separately based on their occurrence, the type of mining needed, and the specific challenges in their exploitation: (1) minerals that are on beaches or are underwater but are derived from land (placer minerals and diamonds) and (2) minerals that form within the ocean (phosphates/phosphorites).

8.2 Placer Minerals

"Placer minerals" (also known as "black sands" and "heavy-mineral sands") weather out of rocks in catchment basins, and because they are resistant to weathering, they remain intact when carried by streams and rivers downstream to the ocean. Placer minerals occur on beaches, in river mouths, sand dunes, and in nearshore and offshore regions. In coastal areas, deposits of placer minerals are formed by the action of wind, waves, currents, and tides. Deposits can be emplaced in current/recent times and conditions, or when sea levels were significantly different in the past. Marine placers that are now found on the continental shelf were originally emplaced in continental or tidal environments when sea level was lower than present (Van Gosen et al. 2014; Hou et al. 2017). In some cases, narrow bands of placer minerals can be moved to beaches after significant storms (Van Gosen and Ellefsen 2018). Placer minerals typically have specific gravities of more than 2.89. To be commercially viable, the deposits usually include at least 2% heavy minerals.

For the purpose of this chapter, we exclude placer deposits far inland from the sea, but include onshore coastal deposits along the present shoreline, since their mining is considered a blue economy activity in many countries, and their mining can affect other blue economy resources. We do not include sand and gravel mining, which is an important source of construction materials in some areas. The environmental impacts and scientific approaches for sand and gravel mining are the same as for other placer mining.

Placer minerals have attracted attention for several reasons. They can be less expensive to mine than terrestrial minerals because they have little or no "overburden" material that must be removed, may be pre-sorted by density through natural processes, and may replace terrestrial mineral resources that are being depleted. Thus, no crushing or blasting is involved, and these deposits are easy and rapid to process using gravimeter and magnetic separation techniques, with few, if any, chemicals required. The waste materials—sand and silt—can be returned to the open pit and these materials can be recontoured and replanted with native vegetation. Placer minerals are often unconsolidated, making mining simpler than for hard rock mining. Terrestrial mining can be expensive and damage large areas of land, because of the need to remove overburden. Hard-rock mining often has limited ability to remediate the areas it has disturbed, and remediation is very expensive when mining is completed.

Environmental impacts may be more easily remediated off shore than on shore, although studies have been limited. Marine and coastal systems are able to eventually recover physically and biologically after some period of time (e.g., van Aarde et al. 1996), although systems may recover slowly if the area mined is too large or is impacted by other human uses. Yet, concerns remain about the impact on the environment of mining placer deposits, and societal effects. These concerns are discussed later in the chapter.

8.2.1 Types of Placer Minerals

Placer minerals fall into 3 categories based on their specific gravities (Emery and Noakes 1968):

1. **heavy minerals** include gold, platinum, and tin (from cassiterite) with specific gravities of 6.8–21. These minerals are smelted for use.
2. **light heavy minerals** include ilmenite and rutile (containing titanium), magnetite (contains iron), monazite (contains phosphate and Rare Earth Elements (REEs), but also radioactive thorium), zircon (contains zirconium), and others with specific gravities of 4.2–5.3. Most of the titanium extracted from the placer minerals ilmenite and rutile is used to make titanium dioxide pigment for paint, rather than production of the pure metal. Titanium dioxide is also used in varnishes, printing inks, plastics, rubber, paper, glass, enamel and ceramics, and artificial fibers. Zircon is mostly used in the ceramic industry because of its high heat stability and light reflectivity (Van Gosen and Ellefsen 2018). REEs extracted from monazite include cerium, dysprosium, erbium, europium, gadolinium, lanthanum, neodymium, praseodymium, samarium, terbium, and

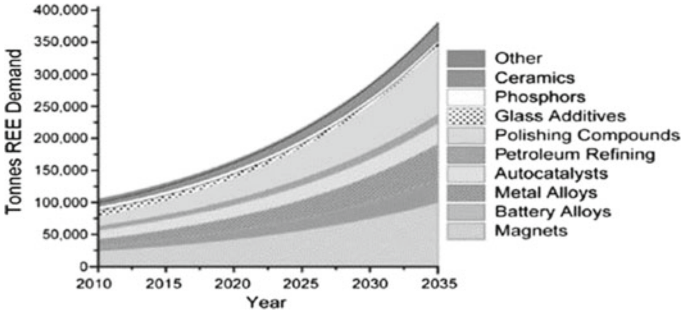


Fig. 8.1 Projected growth in total REE demand, assuming historical growth. Reprinted with permission from Alonso E, Sherman AM, Wallington TJ et al. (2012) Evaluating rare earth element availability: a case with revolutionary demand from clean technologies. Environ Sci Technol 46:3406–3414. Copyright (2012) American Chemical Society

yttrium, which have a variety of applications (Fleischer et al. 1991). Many countries are seeking new sources of REEs to reduce dependence on imported REE minerals (Fig. 8.1, see also Sengupta and van Gosen 2016).

3. **gemstones and native metals** (diamond, sapphire, and emerald, amongst others) with specific gravities of 2.9–4.1. These are not typically smelted, but are used in industrial applications, in addition to use in the jewelry industry.

REEs from placer minerals are gaining attention because they are important in several electronic products used by consumers and industry (Sengupta and van Gosen 2016). Globally, annual demand for placer minerals is growing at the rate of 2–3%, and in India, China and other Southeast Asian countries the growth is nearly twice as much. The global production of REE in 2018 was 170,000 tons; production grew at 40% average annual growth from 64,000 tons in 1994 (Mazumdar and Khurana 2020).

8.2.2 Global Distribution of Placer Deposits

Placer minerals have been found worldwide on every continent so far, except Antarctica, where they may also eventually be found, but not mined (Van Gosen et al. 2014). The five major placer mining regions in the world are southwestern Australia, southeastern United States, southeastern Africa, parts of Brazil, China, and the coastlines of India and Sri Lanka. These regions contain the most important placer deposits, as summarized in the following section. (It is sometimes difficult to separate coastal placer mining activities from the total mining activities in the countries discussed below, when reviewing documents about available and mined resources.)

An important feature of REE mining and the economics of the extraction industry is that the REEs typically occur together and mining of any given REE affects the supply, and thus the price, of the other REEs (Alonso et al. 2012). The current

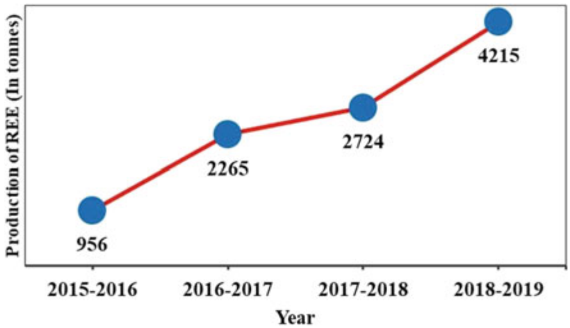


Fig. 8.2 Production of rare earth elements in India (*Source* Data from Indian Minerals Yearbook 2019)

demand for two REEs, dysprosium and neodymium, is being driven by the need for these elements for high-temperature magnets used in wind turbines and electric cars. Scarcity of these REEs will hinder the development of decarbonized technologies, so there is a trade-off between the negative impacts of mining and the benefits of technologies that reduce human carbon dioxide emissions.

Australia—Mineral sands have been mined in Australia since 1934 (Hou et al. 2017). They are mainly mined for titanium found in ilmenite and rutile, zirconium from zircon, and REEs found in monazite. Monazite has the disadvantage of containing significant amounts of radioactive thorium, which can present human health and environmental concerns. Many commercial deposits of mineral sands in Australia are paleo-deposits found inland and so are not considered here as part of the blue economy. Australia is responsible for a significant portion of the global titanium mineral and zircon production, not all from mineral sands in coastal areas. Most of the mineral sands mined are on the southwestern and southeastern coasts of the country, with some proven reserves being off-limits because they are in environmentally sensitive areas.[1]

Brazil—The central Brazilian coast has 12 placer deposits of ilmenite, rutile, zircon and many of these are presently mined mainly for monazite. The highest monazite concentration of around 8% occurs in the coastal sands, for example, at the beaches of Espirito Santo. The REE oxide content of the monazite from this deposit is around 60% (Dillenburg et al. 2004).

India—India has significant placer deposits in some places along its 7,517 km-long coastline and 1,208 islands within the Indian Exclusive Economic Zone (EEZ) (Atmanand et al. 2019). Extensive deposits of ilmenite, magnetite, and zircon occur along the coasts and in nearshore areas of the states of Maharashtra (Gujar et al. 2010; Iyer et al. 2021), Kerala, Tamil Nadu, Andhra Pradesh, and Odisha (Jagannadha Rao et al. 2018). India is conducting major efforts to mine placer deposits of REE minerals (Fig. 8.2).

People's Republic of China—China dominates world production of REE minerals, mostly from terrestrial sources (Xie et al. 2016; Van Gosen et al. 2019).

[1] https://www.ga.gov.au/scientific-topics/minerals/mineral-resources-and-advice/australian-resource-reviews/minerals-sands.

Placer deposits occur as ilmenite, rutile, and zircon while monazite and xenotime are by-products of mineral processing (Van Gosen et al. 2019). China has adopted policies regarding production and use of REE minerals, including environmental protection measures, but environmental damage is particularly a problem with illegal mining (Yuzhou et al. 2020). Reduction in REE exports from China is stimulating exploration for REEs in other countries and driving up REE prices.

South Africa—In the early 2000s, about 25% of the global supply of zircon, rutile and ilmenite was from the sand dunes of Richards Bay on the east coast of South Africa; other projects are underway in southern Mozambique, Madagascar, Kenya, and Sierra Leone (Tyler and Minnitt 2004).

United States—The extensive heavy-mineral deposits in the southeast U.S. coastal plain represent an enormous, under-utilized domestic source that include titanium minerals (Van Gosen and Ellefsen 2018), zircon, and monazite (Th-REEs-phosphate mineral). Active heavy-mineral sands operations occur in southeast Georgia and northeast Florida, but inland. Yet, the U.S. also imports such minerals that are critical to its economy and security. Commercial operations are located well inland, but commercially viable resources occur in beach and coastal areas also.

8.3 Offshore Diamond Mining

Offshore diamond mining takes place exclusively off the shores of Namibia and South Africa, mostly in the former. However, Russia has reported diamond deposits in the Laptev Sea of the Arctic Ocean as partial justification for extension of its EEZ in this area. Diamonds offshore the African continent originated from diamond zones located inland. The Kaapvaal Craton, more than 2.5 billion years old, is the source of southern Africa's diamond-bearing kimberlites (Bluck et al. 2005). This area contains some of the richest diamond pipes ever discovered. Due to weathering and erosion of the diamond-bearing pipes (diatremes), diamonds washed into the Orange–Vaal–Kaapvaal river system to produce "mega-placers" off shore of Namibia and South Africa (Bluck et al. 2005; Spaggiari et al. 2006). Marine diamond mining began in 1962 in South Africa on its northwest coast, between the Orange and Olifants rivers (Atkinson and Sink 2008) and has now increased in area as terrestrial diamond mines become depleted.

As part of its blue economy efforts, Namibia has sought to harvest offshore minerals, including diamonds. According to *DSM* Observer,[2] offshore diamond mining in deep water started in Namibia in 2002 and is carried out by 6 ships owned by the De Beers Corporation, in a joint venture with the Namibian government called "Debmarine Namibia".

Diamond-bearing marine sediments are patchy and are discovered by prospecting with drilling ships, remotely operated vehicles, and submersibles. The use of manned submersibles for direct seafloor observation allows the creation of extremely detailed

[2] http://dsmobserver.com/2019/05/diamond-mining-moves-offshore-and-into-the-deep/.

maps of the seafloor, with very high-resolution interpretation of the orebody character verified through observations (Corbett and Burrell 2001). Mining is accomplished using a drill bit or crawler tool that sucks up material approximately up to 1 (one) meter in thickness of sediments from the seafloor. The sediment is automatically graded onboard the mining ship by a variety of methods to extract diamonds, and the tailings are dumped back into the sea, with heavier materials falling rapidly to the seafloor and silt creating a plume for some kilometers dispersed by the dynamic physical environment in the Benguela Current Large Marine Ecosystem (BCLME).

The BCLME is a biologically productive system that supports a vast array of marine mammal, fish, and invertebrate species; hence, any effects of mining on the ecosystem need particularly careful attention. According to Atkinson and Sink (2008), the effects of tailings on water clarity and phytoplankton production are minimal, and the main adverse biological effects are on organisms dwelling in and on the seafloor that are killed through being sucked onto the ship; there may also be some burial of benthic organisms under the outflow of tailings. Rogers and Li (2002) found that diamond mining increases the normal patchiness of benthic environments, in terms of sediment particle sizes, but does not leave narrow troughs in the sediment, as found after bottom trawling for fish. The area mined off Namibia is subject to periodic events of ecologic disruptions other than mining (Steffani 2011). Savage et al. (2001) found that, 1 month to 3 years after mining, annelid worms were less abundance in areas mined off the coast of Namibia and molluscs were more abundant, compared to a control site, perhaps due to better recolonization abilities and higher survivability of molluscs than annelids.

Marine diamond mining and commercial fishing have co-existed harmoniously in the same marine ecosystem for more than 25 years, with adequate mechanisms in place to monitor, control, and evaluate their impacts on the marine environment. Fortunately, there is no significant overlap between commercial fishing grounds, or known fish spawning, feeding, or nursery areas and the diamond mining locations. However, there may be effects of mining in nearby areas as sediment plumes drift. Because of the discovery of substantial offshore phosphate resources in Namibia, there is currently a heated debate about whether the existing diamond and fishing industries can coexist in harmony with phosphate mining (see Sect. 8.4).

As of 23 May 2019, De Beers had mined 129.5 sq km (50 square miles) of seafloor for diamonds, of their 6,024.3 sq km (2,326 square mile) lease. Most offshore diamond mining takes place off Namibia's southern coast near the mouth of the Orange River. Marine operations account for 75% of Namibian diamond production (Fig. 8.3), and Namibia is the largest producer of offshore diamonds. Diamond mining produces appropriately 10% of Namibia's annual GDP.[3] The Namibian government plans to expand the range and value of gemstones and jewelry products, securing the maximum benefit for its citizens through the Harambee Prosperity Plan,[4] in

---

[3] https://www.washingtonpost.com/world/africa/a-new-frontier-for-diamond-mining-the-ocean/2017/07/01/a04d5fbe-0e40-4508-894d-b3456a28f24c_story.html.

[4] http://www.ag.gov.na/publications/Harambee%20Prosperity%20Plan.pdf.

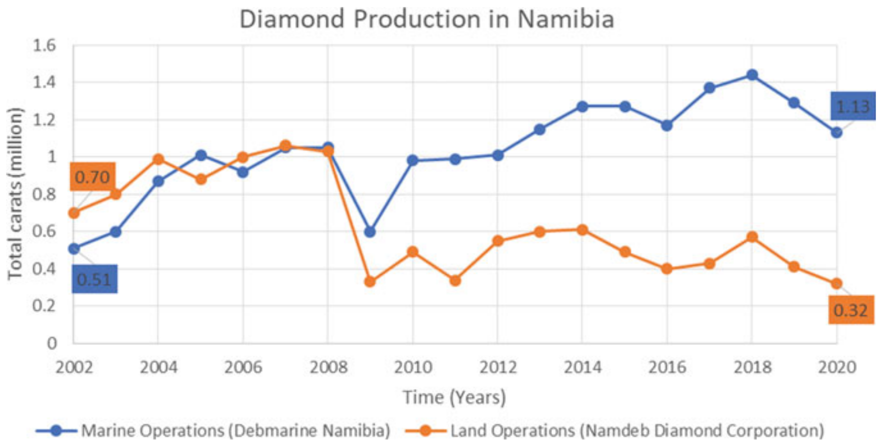


Fig. 8.3 NAMDEB Holdings production (*Source* Namibia Chamber of Mines). NAMDEB Holdings is a conglomerate between NAMDEB (onshore mining) and DEBMARINE (offshore mining). In the past, DEBMARINE only accounted for 10% of diamond production in Namibia. Currently, it accounts for about 75% of the total diamond production. NAMDEB has been mining diamonds onshore for over 100 years; they may be depleting. However, the proportion may largely be related to huge investment in innovative science and technology, which enabled mining and processing diamonds from the seabed

particular through increased value addition to natural resources rather than sending raw materials abroad to be processed. This is also aligned with the vision of the African continent expressed in the African Mining Vision[5] and Agenda 2063.[6] The annual value of unprocessed Namibian diamonds is 430 million Namibian Dollars (approximately 32 million USD). So far, Namibia has developed an internationally competitive diamond industry, emerging as the leading nation in marine diamond mining in the late 1980s. However, there is still room for improvement to maximize benefits, while minimizing impacts on the BCLME, and balancing economic benefits with environmental protection and social equity.

8.4 Offshore Phosphorite Mining

The identification, characterization, and perhaps even exploitation, of off-shore phosphate deposits is becoming increasingly critical, as the ever-growing demand for phosphate-fueled grains are coming into impending conflict with the limiting and ever-depleting resource of phosphate rocks on land. Off-shore deposits will continue

[5] https://au.int/en/ti/amv/about.

[6] https://au.int/en/agenda2063.

to be a target of interest, and perhaps even ultimately a target of necessity, to maintain global food systems (Filippelli 2011, 2018). Thus, it is important to characterize what we know, and do not know, about offshore phosphates and their potential to influence blue economies.

8.4.1 Phosphorus and the Modern Food System

Organisms need a multitude of elements to survive, including a myriad of systems that require phosphate. These phosphate-dependent functions include the basic batteries of cells comprised of adenosine triphosphate, cell walls made of a phospholipid bilayer, and skeletons made of hydroxyapatite (Filippelli 2016). Unlike many other key ingredients—such as water, carbon, and nitrogen—phosphate is very limited in supply and its chemical states, which is why phosphorus is considered the ultimate limiting nutrient for many freshwater and terrestrial ecosystems on the planet. One sector where this limitation is becoming more and more apparent is in our food production systems, which have been supported through the Green Revolution on chemical fertilizers, including phosphate (Fig. 8.4; Table 8.1). An expanding global population, increasingly turning toward livestock (which is very inefficient in terms of phosphate) as a key protein source, has raised concerns among some scientists and resource modelers. These concerns revolve around how much phosphate reserve remains, how we can extract phosphate from currently marginal reserves, and how we should revolutionize our use of phosphate such that it is not washed off farm fields and into wastewater systems and coastal waters, where it is transformed from a vital resource to a serious environmental pollutant.

8.4.2 Phosphate Rock Formation and Distribution

Phosphate rock is present in a variety of environments, but economically viable deposits are relatively rare. Much of the early sources of phosphate were high-grade guano deposits, the products of thousands to millions of years of feces and urine excreted by birds on limestone islands, where diagenetic alteration results in high-grade carbonate fluorapatite minerals. Because these guano deposits were on the surface of the islands with very little overburden, the deposits were prime targets for early exploitation. Indeed, the demand was so high that nearly all of these deposits have already been mined out, leaving entire islands, like Banaba (Ocean Island) and Nauru in the Pacific Ocean, looking like moonscapes of tailings. Some of the early tailings still have enough phosphate in them that they will become a viable target for re-mining if the price of phosphate rock trends upward to the point at which the benefits of mining outweigh the costs of extraction.

Most phosphate rock, though, is now being mined from former marine deposits on land, which are being depleted. It is critical to understand the genesis and

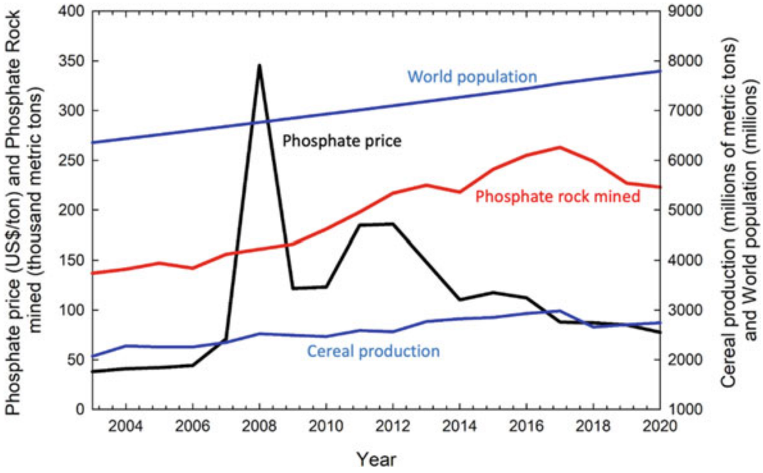


Fig. 8.4 Increase in world population, annual phosphate rock mining, annual cereal production, and price of phosphate from 2003 to 2020 (updated from Filippelli 2018). The world population increase is being supported by increased food production and greater global demand for phosphate rock fertilizer which, in turn, has resulted in an increase in the price of phosphate, although the latter is also strongly influenced by the market volatility of global trade. The total amount of phosphate reserves is 68,000 thousand metric tons, indicating that reserves will be 50% depleted under the current annual rate of extraction by about the year 2150. This assumes, of course, that we have accurately characterized reserves and can accurately predict future demand. There is wide scatter in various published estimates of the 50% depletion timeframe and they should be viewed with caution

current distribution of these deposits to assess the viability of underwater mining for phosphate minerals. Marine "phosphorites" are deposits with phosphorus concentrations exceeding 9% (Blatt and Tracy 1996), and are the prototypical "phosphate reserves" from which the ore is mined. Most marine sediments have relatively constant concentrations of phosphorus, whereas the phosphorus concentration in phosphorites on land is about 100 times higher than phosphorus deposits on continental shelves (Table 8.1). The typical marine setting for phosphorite formation is a continental shelf-slope environment with extremely high phytoplankton productivity in the upper ocean, limited dilution by terrigenous sedimentation , and periodic winnowing and reworking (Fig. 8.4; Filippelli 2011). A current example of this ideal environment is the Peru Margin. This setting has high coastal upwelling, which produces tremendous phytoplankton blooms and high burial rates of organic matter with incorporated phosphorus. Terrigenous input is limited by terrestrial dynamics—the Andes Mountains create a rain shadow effect for easterly storm jets, and thus the western Andes are extremely arid, resulting in little river input into the Pacific Ocean. Finally, variations in sea level, resulting from long-term glacial cycles, drive periodic migration of longshore and along-margin eddies. This allows for the accumulation of organic-rich material and related phosphogenesis within these sediments, followed by high current activity and winnowing of the lighter clay and

Table 8.1 Components of the phosphorus cycle with respect to modern demands. MT = million metric tons. Reprinted from *Chemosphere*, Volume 84(6), Gabriel M. Filippelli, Phosphate rock formation and marine phosphorus geochemistry: The deep time perspective, pages 759–766. Copyright (2011), with permission from Elsevier

Material	P content (%)	Reservoir (MT)	Production/formation (MT/yr)
Average continental rocks[a]	0.09		
Marine sediments[b]		8.4×10^{11}	
Continental margins	0.11		
Phosphorites	10–20		
Deep Sea	0.18		
Hydrothermal	0.6–1.5		
Soils[c]	0.015	40–50	
Ocean[b]	~ 0	93,000	
Phosphate Rock Ore[d]	13	2,300	20
Morocco and Western Sahara		820	3.4
China		531	7.9
USA		158	3.9
Manure (cow)[e]		0.4	> 15
Sewage[e]		2–3	3
Human demand of phosphate rock ore			
Human demand 2000[e]			20
Human demand 2050[e]			30
Time to reserve exhaustion 2010 demand	115 years		
Time to reserve exhaustion 2050 demand	77 years		

[a]Blatt and Tracy (1996)
[b]Ruttenberg (2003)
[c]Schlesinger (1997)
[d]USGS (2009)
[e]Cordell et al. (2009)

organic material away from (in this case, off-shore of) the sediments. These combined processes allow the concentration of phosphatic materials into hardgrounds and lag deposits characteristic of phosphorites (Filippelli 2016). This dynamic, multi-stage process of sedimentation, phosphogenesis, and winnowing, repeated many times, yields the characteristic sedimentology of phosphorites and results in their extremely high phosphorus concentrations (Fig. 8.5).

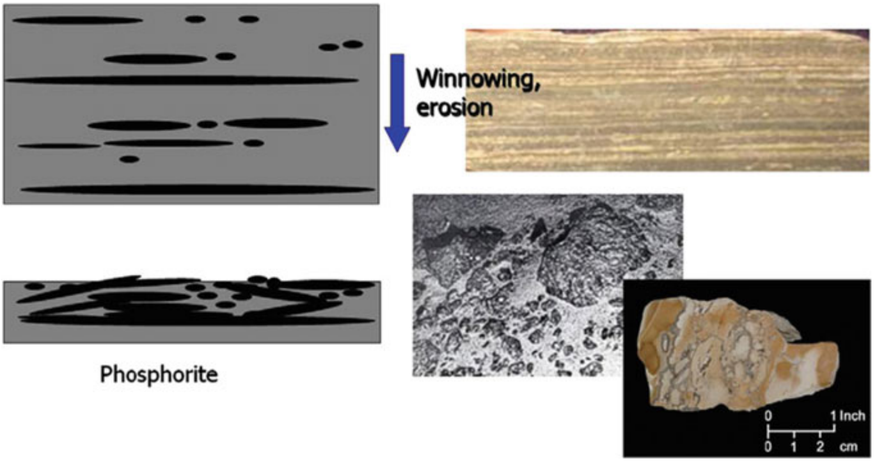


Fig. 8.5 The sediment reworking process of converting sediments into phosphorite deposits that have undergone high rates of phosphogenesis are shown in the left-hand diagrams in the phosphatic shale model and example in the upper section (black lenses are phosphatic laminae and the gray is shale). The middle right photo shows off-shore phosphatic crusts (black and white photo, Blake Plateau; the vertical scale is about 2 feet) and the lower right photo is a high-grade phosphorite hand sample (Bone Valley Member, Hawthorne Formation, Florida). Reprinted from Chemosphere, Volume 84(6), Gabriel M. Filippelli, Phosphate rock formation and marine phosphorus geochemistry: The deep time perspective, pages 759–766. Copyright (2011), re-use with permission from Elsevier

8.4.3 Future of Land-Based Phosphate Mining

Most of the terrestrial phosphate reserves with the highest economic viability have been exploited. Many of the more phosphate-rich deposits from standard phosphate rocks have also been depleted, resulting in the average phosphorus content of mined phosphate ore to decline from 15% phosphorus in 1970 to less than 13% phosphorus by 1996 (IFA 1998). Additionally, many of the known economically viable terrestrial phosphorus reserves are located in Morocco and the Western Sahara, where the legal frameworks and disputed international borders have the potential to hinder production. The political instability of these reserves, plus the relatively limited amounts of global reserves (Table 8.1) point to the need to diversify the identification of phosphate rock reserves. The declining quality of current reserves and the inherently low economic viability and environmental consequences of extraction for other potential phosphate rock resources signals a need for a careful examination of phosphorus usage.

8.4.4 Offshore Mining of Phosphorus—The Needs, Challenges, and Opportunities

Offshore phosphate deposits have been identified in several areas including, notably, the Chatham Rise in New Zealand and the continental shelves of Namibia, western Mexico, and Peru. Many are of high phosphate grade. The deposits are phosphate-rich nodules or pellets in a matrix of sand or silt, making potential dredge mining relatively straightforward. Furthermore, because they are relatively close to the shoreline, there is a potential for rapid transport of the raw material to nearby ports of consolidation. Nearshore phosphate can be shipped as a raw resource or processed into phosphate products onshore, such as phosphoric acid or salts.

Clearly, economics engenders innovation, and we will see technologies and environmental controls in the next century that will open up some phosphate rock resources to extraction that are currently uneconomic. However, off-shore mining of phosphorites will be a top target as land-based reserves are depleted and price increases. It is clear that there is no technological solution for the depletion of terrestrial phosphorus reserves. There simply are limited resources on Earth's surface, there is no biological replacement for elemental phosphorus, and the global demand for phosphorus continues to increase with global population (Fig. 8.4; Gilbert 2009).

8.4.4.1 Case Study—Namibia

Off-shore Namibia and South Africa, there are large, estimated phosphorus reserves with very high phosphorus contents related to reworked Neogene phosphorites on the middle and outer shelf. These reserves are being targeted for potential mining by Namibian Marine Phosphate,[7] a joint venture between several Australian and Namibian companies. Taking the Namibian offshore deposits as a promising example (also one for offshore diamond mining, as described earlier), this region is seeing perhaps the first real commercial interest in major phosphate mining operations. Based on recovered cores from two particularly phosphate-rich areas of the Namibian shelf and extrapolations of thickness and area of deposits, Compton and Bergh (2016) estimate that the total phosphate rock resource is on the order of 7,800 million metric tons at an average grade of 19 wt.% phosphate (Fig. 8.6). Thus, the Namibian marine deposits represent 2–5% of the estimated global phosphate rock resources (Compton and Bergh 2016). Based on this promise, and the various proposals for mining offshore diamond deposits in the region, several mining licenses have been issued. In 2012, Namibian Marine Phosphate submitted an Environmental Impact Assessment Report and an Environmental Management Plan for the Sandpiper Phosphate Project[8] (7,000 km^2 of Namibia's 540,000 km^2 EEZ), which proposed to dredge

[7] www.namphos.com.

[8] www.namphos.com/project/sandpiper.html.

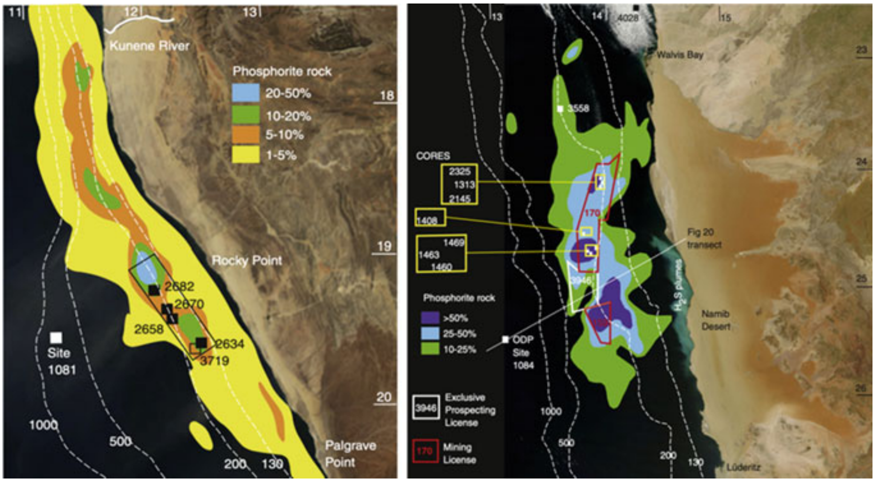


Fig. 8.6 Extent of phosphorite-rich deposits outcropping on the northern (left panel) and central/southern (right panel) portions of the Namibian shelf (Compton and Bergh 2016). The milky area inshore of the deposit on the right panel is an H_2S plume (image from NASA). Longitude (˚E) is shown on the top of the maps and latitude (˚S) is shown on the right-hand side of the maps. Right figure reprinted from *Marine Geology*, Vol. 380, John S. Compton and Eugene W. Bergh, Phosphorite deposits on the Namibian shelf, pages 290–314, Copyright (2016), with permission for re-use from Elsevier

phosphate-enriched sediments south of Walvis Bay, Namibia, in water depths of 180–300 m. However, mining activities have not started due to a Namibian moratorium on mining phosphorite deposits pending further understanding of how activities might impact fisheries in the area. The Namibian legal system is currently considering a legal challenge to the mining permit by the Namibian fishing industry. This is an example of wise decisions in the face of a lack of information. Marine fisheries are a major resource in Namibia, so offshore mining must be developed in a way compatible with maintaining fisheries (see Chap. 4).

8.4.5 Marine Phosphate Mining and Environmental Impacts

As noted earlier, all of the currently targeted offshore phosphate deposits occur as largely unconsolidated sand-pebble mixtures occurring at shallow depths. This makes the potential for recovery by dredging quite attractive, as it would borrow similar processes used by the offshore diamond mining operations occurring in a similar seafloor structure. Indeed, in the case of the Namibian deposit, diamond recovery operations are occurring just south of the phosphate deposits.

However, for all of the promise of off-shore phosphate mining comes a host of significant environmental and fisheries concerns that need to be considered in the balance between resource utilization and environmental protection. Dredging operations involve extreme disturbance of the seabed and potentially of the benthic ecosystems that reside there. Indeed, dredging might have long-term ecosystem recovery implications, as physical and biological impacts that may persist well after the mining finishes. Recovery times are likely to vary greatly and be species dependent (Foden et al. 2009). Debmarine Namibia monitoring results suggests 2–10 years is required for benthic ecosystems to recover, or more if more rocky substrates are mined. Operations aboard the dredge vessel typically involve washing and sieving of the phosphate sands and nodules, with the finer-grained material discarded to surface waters. This siltation of the ocean surface can negatively impact biological production and ecosystems, for example, by smothering of benthic organisms, leading to death or impaired function. Cumulative impacts from climate change and other human impacts may also affect recovery timing. Additionally, phosphates tend to co-occur with a number of potentially toxic trace metals, such as radioactive cadmium and uranium, which may be released during the dredging or washing processes. Most offshore phosphate resources are near active fisheries—this is not a coincidence, as the same high primary productivity that catalyzed algal production and phosphate deposition in the past currently fuels high-yield coastal fisheries. Thus, any mining activities that impact the environment might also negatively impact valuable fisheries resources.

Marine mining of phosphate is certainly achievable with current technologies. Indeed, many of the current continental shelf deposits have in a sense been pre-concentrated, due to the presence of highly concentrated meters-thick sand and nodule beds. The marine dredging technologies currently applied to off-shore diamond mining in the shallow marine environment can be readily transferred to off-shore phosphate mining. Some particularly promising examples include the Namibian Shelf, the southern portion of which already has current diamond dredging operations, and the Chatham Rise region of New Zealand.

All resource extraction comes with certain trade-offs, and it seems clear at the moment that at least the potential negative impacts of off-shore phosphate mining are perceived to outweigh the current benefits, based on the decline in the number of mining permit applications. But it seems likely that market pressures from phosphate commodity pricing may at some point make off-shore mining an attractive, and indeed imperative, practice to maintain food production.

8.5 Legal Frameworks Governing Mining

Laws and regulations governing mining activities are generally not specific to marine mining but cover all types of terrestrial and marine mining. There is a paradigm shift from the traditional approach of governments focusing solely on financial benefits and ignoring the environment to a modern approach of balancing financial benefits with protection of ocean environments. Several countries with marine mining are now framing laws with these twin objectives. A brief review of the laws in different countries will help to understand these efforts.

China implemented *The First Industrial Standards* for air and water pollution to protect air and water resources. The *Environment Protection Tax Law* was passed in 2018 to compel mining firms to internalize their environmental costs and combat illegal production (Hu et al. 2020). In Australia, the *Environment Protection and Biodiversity Conservation Act* was passed in 1999, which makes environmental authorization a prerequisite at all stages of mining and requires mined areas to return to their original condition (Wood and Malanie 2019). Brazil aims for innovative, competitive, and sustainable mining and thus in 2018 the Government framed strict environment protection and enforcement of mine closure plans (Jamasmie 2018). In May 2019, the South African Government passed a law to implement a *Carbon Tax* in 2022. This law will tax miners 137 Rand ($9.35) per ton of carbon dioxide produced during mining operations (Anonymous 2019). In India, a notice was issued by the government in 2019, by which only government corporations are permitted to undertake beach/shoreline mining, in order to avoid illegal mining and over-exploitation of placer minerals. India's Council of Scientific and Industrial Research-National Institute of Oceanography, Geological Survey of India, and Atomic Mineral Division are involved in exploration and survey of these minerals. In the United States, one of the primary environmental laws is the *National Environmental Policy Act*, which was adopted in 1969 to promote enhancement of the environment and establish the President's Council on Environmental Quality. The U.S. government also passed the *Comprehensive Environmental Response Compensation and Liability Act* in 2018 (Kehalley 2019). In Namibia, the *Minerals Policy* lays out a vision for the responsible development of Namibia's mining sector to ensure that the sector makes a sustainable contribution to the country's socioeconomic development.[9] Diamond mining holds a unique and important place in the Namibian mining sector and, as such, the *Diamond Act 13* of 1999 was passed to enable participation of the Namibian people in the diamond industry through trading, tooling, and research licensing. Namibia's *Environmental Management Act* of 2007 and the *Environmental Impact Assessment Regulations* govern the environmental aspects of the mining life cycle, including exploration, construction, production, closure and post-closure.[10] The policies are regulated by inter-ministerial committees mainly composed of staff from the Ministry of Mines and Energy, the Ministry of Fisheries and Marine Resources, and the Ministry of Environment, Forestry and Tourism. There are no legal provisions for mine closure accounting or for securing funds for closure.

The effectiveness of these laws depends on development and enforcement of appropriate regulations. In some developing countries, government ministries with oversight of resource extraction have better funding and/or more political influence than ministries with oversight of environmental protection.

---

[9] https://www.iisd.org/system/files/publications/namibia-mining-policy-framework-assessment-en.pdf.

[10] Ibid.

8.6 Environmental and Social Impact of Marine Mining

Mining of marine minerals is typically conducted by removal of unconsolidated mineral-bearing sands, creating pits and changing the morphology of coastal areas. The potential environmental and social impacts of mining should be anticipated and project approval is dependent on satisfaction by regulators that effects can be minimized and/or mitigated. Potential impacts include the following:

Physical Impacts: Coastal mining results in diversion of streams, geomorphological changes, alteration of shorelines, enhanced sand erosion in one sector and deposition in another, interaction between groundwater and freshwater, and related effects. If mining is carried out beyond sustainable limits, it can result in drastic morphological changes along the beach as well on the inner shelf, as noted along Kerala on the southwest coast of India (Prakash et al. 2016; Sheela Nair et al. 2018). In addition, offshore mining pits and furrows can modify hydrodynamic processes and seabed morphology, which can vary the speed of currents, and affect sediment transport (Ashraf et al. 2011). Discharge of tailings into the sea during mineral processing can change the sediment grain size which, in turn, can influence organic content, pore water chemistry, microbe abundance, and composition. Underwater heritage structures and ship wrecks in the vicinity of mining activities can be affected.

Biological Impacts: By making water more turbid from disposal of waste sediment, mining can decrease photosynthesis in aquatic plant life, reducing the growth of phytoplankton, seagrasses, and seaweeds. Fine sediments discharged during mining activities can decrease the abundance and diversity of benthos due to reduction in plant life—particularly in low-energy near-coastal environments—and clogging of the feeding apparatus of suspension feeders. If conducted off shore, mining uses dredges that raise bottom sediments to the surface for sorting; benthic organisms are entrained with the sediment and killed in the process. Changes in plants and benthic organisms can alter marine food chains and reduce fish production, and decrease dissolved oxygen concentrations, thus increasing fish mortality and disrupting fish migration and breeding activities. Marine species generally experience low levels of noise, but seabed mining will increase underwater ambient noise and this will affect marine animals (Miller et al. 2018; Koehnken and Rintoul 2018).

Chemical Impacts: The water quality and toxicity of water bodies can be altered due to sediment loading and by discharge of chemicals that are used during mining. For example, high toxicity was observed in salmon in the downstream areas of Vyenka River in Kamchatka Peninsula, Russia, where platinum open-cast mines are located (Chalov 2012). For the effective extraction of gold particles, cheap and effective chemicals like sodium cyanide are used. If this solution leaks, it has serious environmental and public safety impacts. In the past 25 years, more than 30 major cases of cyanide leakage into water bodies have been reported from different countries. In some cases, mercury is also used in place of cyanide, which is also equally harmful for the environment and public health. The worst accident was reported from the Baia Mare Gold Mines in Hungary, wherein a large number of fish were found dead in the Tisza River. The effect of the cyanide spill was felt even in rivers in Romania (Hamar and Sarkany-Kiss 2000; Marmorat 2008; Laitos 2013).

Climate Impacts: Mining is an energy-intensive process that results in the emission of carbon dioxide (CO_2) and other greenhouse gases. Large-scale and long-term mining projects contribute significant amounts of CO_2 and also reduce vegetation cover of mined regions, leaving CO_2 in the air that would have been taken up by these plants (Anonymous 2010). However, the limited data available are insufficient to draw a direct connection between climate change and mining (Ruttinger and Sarma 2016).

Socio-Economic Impacts: Mining is vital to sustain an increasing population and functioning of national and global economies but it can also be detrimental to human society. Mining can be a major contributor to the GDP of a country as it creates wealth, helps to develop infrastructure in the mining locality, is a source of direct and indirect employment, and raises the living standard of people residing near the mining areas. However, mining also creates several issues due to human displacement, adverse health outcomes, loss of ownership of land, delay in their compensation and rehabilitation, depletion of local water resources, consequences for biodiversity, and contamination of soils, groundwaters, and surface waters due to the chemicals used and toxic minerals in the mined deposit that are released by the mining process (e.g., cadmium, chromium, copper, nickel, lead, strontium, vanadium and zinc (Gnandi and Tobschall 1999).

Impacts on Other Uses of Coastal Areas: The consequences of mining can also affect fisheries, coastal tourism, marine transport, offshore wind farms, and shipping industries (transport of goods, ship building and salvage), to name a few other blue economy activities.

The above issues (though not exhaustive) need to be addressed if and when they occur, jointly by the government and mining companies, so that mining can be sustainable. Each potential mining area, with its own uniqueness, needs to be assessed separately and a judicious approach is needed before mining commences, to strike a blue economy balance among economics, environmental protection, and social equity. Public input and buy-in for mining processes is very important for implementation of mining activities within a blue economy framework.

8.7 Regional and National Approaches

Several benefits can be gained by considering national mining activities in a regional context. For example, in August 2015, the *Goa Declaration* was issued by the Indian Ocean Rim Association (IORA), in which participants identified the thrust areas of blue economy activities in the Indian Ocean region. Later, the Blue Economy Working Group was initiated during the IORA Leaders' Summit that was held on 5–7 March 2017 in Jakarta, Indonesia. The meeting also adopted the *Jakarta Concord*, which reiterates IORA's commitment to promote blue economy activities in the region as a key source of inclusive economic growth, job creation, and education, based on the evidence-based sustainable management of marine resources[11] (Mukhopadhyay et al. 2021). IORA adopted Seabed Exploration and Minerals as one of its 6 “Priority Pillars”.[12]

At a national level, the National Institution of Transforming India, India’s policy think-tank, held discussions with stakeholders during 2018 to identify potential blue economy activities that could be of national interest. Several national ministries were involved in this effort, such as Earth Sciences, Shipping and Maritime, Fisheries, Environment & Forests and Climate Change, and others. In order to synergize the multi-ministry efforts, seven working groups were formed by the Indian Government to recommend ways to tap the huge potential and opportunities in the blue economy sectors (Atmanand et al. 2019). The Blue Economy Working Group of India has suggested several policy actions towards sustainable development of offshore minerals. Some of these are creation of a “*National Placer Mission*”, adoption of the United Nations Framework Classification for Resources (UNFC) for each workable placer deposit, development of a comprehensive database on reserve potential that could be accessible to the industries, adoption of best practices in indigenous mining methods and environmental conditions, development of value-added products from placer minerals, protection of socio-economic values, and formation of a “*Centre of Excellence*” to meet the indigenous technology supports to Indian industries (Nayak 2019).

Internationally, Namibia adheres with the Convention of Biological Diversity (CBD)[13]; as a result, the National Marine Information and Research Centre plays a major role in identifying the Ecologically or Biologically Significant Areas (EBSA) in the marine environment. These are areas of natural value and are selected according to criteria defined by the CBD and are categorized into management and conservation areas. Ministry of Fisheries and Marine Resources does not recommend any licenses to be granted within any EBSA, while guidelines for activities eligible within the EBSA are still being developed. Furthermore, a regional intergovernmental partnership, the Benguela Current Commission (BCC), was established in March 2013 between Namibia, South Africa, and Angola to promote a coordinated approach to the long-term conservation, protection, rehabilitation, enhancement and sustainable use of the Benguela Current Large Marine Ecosystem, in order to provide economic, environmental and social benefits. The BCC provides a legal framework for cross-border cooperation between the three BCC countries.

---

[11] https://www.iora.int/en/priorities-focus-areas/blue-economy.

[12] https://www.iora.int/media/24141/20191022-draft-concept-note-first-meeting-iora-wgbe-final1-min.pdf.

[13] https://www.cbd.int/convention/.

8.8 Challenges and Science and Technology Response Options

Science has a major role to play in identifying potential mining areas that fulfill the triple goals of economic development, environmental protection, and social equity. Science can be applied to mining issues through the following activities:

8.8.1 Exploration for Minerals

Scientific prospecting helps to identify commercially viable mineral deposits. Mining companies usually conduct extensive site characterization activities to ensure that mining focuses on areas in which the value of the mineral resource exceeds the cost of recovering it, for both economic and environmental reasons. This can be considered as characterization of the geology of the target area(s) and detailed mapping should be encouraged by host governments to effectively mine the resource while minimizing the total area affected when defining the extent of the deposits.

8.8.1.1 Site Characterization

After potentially exploitable areas are identified, it is important that baseline studies characterize the physical, chemical, and biological characteristics of the area to be mined and adjacent areas. If sufficient baseline studies have already been conducted, mining companies can gather available information, rather than doing new field work.

Physical characterization should include an understanding of the climatology of ocean currents, tides, eddies, and other physical oceanography features of the area for at least one year. The physics should be characterized from the ocean surface to the seafloor. This information is important to make it possible to predict how mining wastes will be dispersed and how quickly the mined areas might be re-colonized by the planktonic larvae of some benthic organisms.

The chemistry of the area should be assessed, including heavy metals and other elements contained in the sediments to be mined, which might be liberated through mining processes. Additionally, phosphate deposits typically contain relatively high concentrations of potentially toxic trace metals (radioactive cadmium and uranium). With on-shore mining, these are extracted during enrichment via a gypsum trap, and these gypsum waste piles are typically stored on-site because they pose a low-level radiation risk (Filippelli 2011). Although ore processing would not occur alongside the actual dredging operations, there is a potential for the release and transport of some of these metals during the mining process. In a case study from Togo, Gnandi and Tobschall (1999) found that the dumping of phosphorite mine waste into the sea was a source of coastal pollution with trace amounts of the cadmium, chromium, copper, nickel, lead, strontium, vanadium and zinc. Instantaneous trace metal pollution of seawater occurred during the processing and dumping of tailings into the sea by the release of easily mobilizable cadmium. Therefore, several million tons of metal-rich tailings contained in sediments lie on the seafloor in the region, posing significant concerns for long-term ecosystem health and recovery. In addition, it is important to determine whether the area is subject to extreme chemical events, such as the hypoxia and hydrogen sulfide eruptions that occur in Namibian coastal waters (Ohde and Dadou 2018). Ecosystems in such areas may be adapted to episodic disruptions, but mining may also be an additional acute impact added to periodic natural impacts that are already experienced by coastal ecosystems.

For biological baseline data, fishery agencies may have long-time series of fish abundance and distribution data for both benthic and pelagic species. The same agencies may also be responsible for surveys of endangered species such as marine mammals, turtles, and seabirds. Some countries may have conducted biodiversity assessments through environmental agencies, universities, or natural history museums. International resources are also available, such as databases of marine species distributions made available through the Ocean Biodiversity Information System (OBIS). OBIS[14] is an excellent source of information for each nation's EEZ, although it does not contain information on species' abundance. OBIS information can be cross-referenced with satellite data on ocean chlorophyll, temperature, and other parameters to understand how species distributions are related to various parameters.

If no pre-existing information is available, some countries require environmental impact assessment reports that may compile information about potentially affected marine organisms and ecosystems, and independent groups may also issue assessments (Kaikkonen et al. 2018).

In the two most promising offshore phosphate regions (Chatham Rise and Namibia), substantial concerns exist about whether sufficient baseline data are available. In the case of Namibia, this is particularly acute as the country has few national research vessels and scientific observations of the continental shelf are limited. Geologic data available are from mining-related surveys and several deep cores recovered by the Ocean Drilling Program Leg 175 in 1997. Biological data also are available from regular monitoring conducted by DebMarine, as well as the Namibian National Marine Information and Research Centre in the Ministry of Fisheries and Marine Resources.

In New Zealand, the first marine consent application to mine phosphorite nodules on the Chatham Rise was proposed by Chatham Rock Phosphate Ltd. The application was rejected by a decision-making committee; the major reasons given included uncertainty about the baseline environment, the nature and extent of adverse effects on biological communities, and impacts on existing interests (e.g., fisheries; Ellis et al. 2017). Benthic communities in this area include potentially unique protected stony coral communities that represent rare and vulnerable ecosystems. Further gaps in knowledge include potential impacts of deposition of sediment on areas adjacent to the mining blocks and on the wider marine ecosystem.

[14] https://obis.org/.

Environmental impact assessment (EIA) studies were carried out by the National Institute of Oceanography in selected areas along the Indian coasts, focused upon the potential effects of onshore and offshore placer mining at Kalbadevi, Maharashtra and at Paradip Island, off Odisha, by creating experimental disturbances (suction and discharge) in the offshore regions. The study showed only short-term changes in the topography and benthic community in the mid-tide region. The environment returned to baseline status within a few months. In the offshore region, no major variation in the heavy mineral concentrations, nutrient concentrations, or suspended matter was seen. The results of placer mining experiments differ along the East Coast (Paradip in Orissa) and West Coast (Kalbadevi in Maharashtra) due to different oceanographic and geomorphological conditions. In the bay beach of Kalbadevi, no effect on the grain size and percentage of heavy mineral concentration are noticed. In contrast, in Paradip, variable sediment textures and heavy mineral contents are reported. This could be due to the dynamic environmental conditions as the beach exposed to the open sea conditions (Valsangkar and Fernandes 2008; Fernandes et al. 2015). Therefore, baseline information could help in developing a rational approach towards sustainable harnessing of resources with minimum damage to the ecosystem.

In South Africa, the Department of Minerals and Energy is responsible for oversight of diamond mining (terrestrial and marine). An Environmental Management Programme Report must be submitted with any application for prospecting or mining. National legislation requires the mining company to include in their proposed budget the funds available for remediation of any environmental damage caused by the mining (Atkinson and Sink 2008).

Exploration and mining for diamonds at the coast of Namibia follows a strict procedure, regulated by *The Environmental Management Act (Act No. 7 of 2007)* and *Mineral Act of 2002*, through the Ministry of Mines and Energy (MME), the Ministry of Fisheries and Marine Resources (MFMR) and the Ministry of Environment, Forestry and Tourism (MEFT). The MFMR is requested by the MME to provide recommendations for applications for Exclusive Prospecting Licenses (EPLs) and Mining Licenses (Shivute 2021, email communication[15]). For any EPL granted, an environmental clearance must be obtained according to the *Environmental Management Act No. 7 of 2007*, with consent from MFMR before any prospecting activities begin. There is thus an inter-ministerial committee that deals with applications of EPLs/Mining Licenses, where the three ministries are represented. Shapefiles of EPL applications are provided by MME, which are mapped, and conflicting areas are identified. For example, EPL applications that overlap EBSAs or Marine Protected areas demarcated by MFMR are not recommended for exploration or mining activities. MFMR is consulted by MEFT or the competent authorities (MME) to provide input in EIAs before any final recommendations are made to the environmental commissioner. During the scoping or EIA process, the appointed EIA consultant may contact MFMR to obtain spatial data on fisheries resources and related data.

[15] Personal communication with Latoya Shivute, Senior Fisheries Biologist at the Namibian Ministry of Fisheries and Marine Resources.

Consultants further engage MFMR scientific staff through stakeholder meetings or smaller focused group meetings to identify the EIA, particularly for areas that may overlap mining/ fishing grounds/ sensitive areas.

8.8.2 *Mitigation of Mining Impacts*

When government managers are unsure of the impacts of mining on the affected ecosystems and other resources, a phased approach to mining may be advisable, with small-scale mining and monitoring of the economic, environmental, and social impacts. The results of such studies should be evaluated by independent scientists or organizations.

A host of mitigation measures are being used with proper dredging operations (United Nations 2016), including, but not limited to:

- The use of silt curtains to contain dredge plumes;
- The return of overflow waste to the seabed rather than in the water column;
- Locating mining activities away from known migratory pathways and calving or feeding grounds;
- Limiting the number of vessels or operations in given areas;
- Requiring reduced boat speeds in areas likely to host marine mammals to reduce risk from ship strikes;
- Engineering to reduce the noise of the primary recovery and ore-lift operations;
- Limiting unnecessary use of platform and vessel flood lights at night and ensuring that those that are required are directed approximately vertically onto work surfaces to avoid or mitigate seabird strikes;
- Leaving patches within a mining site un-mined to increase the rate of recolonization and recovery of benthic fauna;
- Excluding areas from mining if they support unique populations of marine life;
- Excluding areas of mining if they are potential sites of cultural heritage;
- Depositing tailings within as small an area as possible surrounding the mining block, or onshore;
- Avoiding the need for re-mining areas by mining target areas to completion during initial mining; and
- Identification of "environmental windows" during times of the year when breeding and other significant life cycle events do not occur, so that mining might be tested during these periods. The ability to identify environmental windows depends on the collection of adequate baseline information, by identifying species present and any special ecological features of potential mining areas.
- Link biodiversity with mining activities, to acknowledge their interdependence. Biodiversity is generally given scant attention by miners and sometimes even by the affected people. The Convention on Biological Diversity and the Intergovernmental Platform on Biodiversity and Ecosystem Services could help provide insights on procedures that mitigate environmental concerns raised by placer

mining. The International Forum of Mining, Minerals, Metals and Sustainable Development might become a vital platform for countries and industries to consider relationships between mining and biodiversity and help to develop an integrated policy action plan (Sonter et al. 2018).
- Build in experiments for remediation as part of every mining project so that new knowledge in remediation will be gained from each one.

8.8.2.1 Monitoring During Mining

Monitoring should continue after mining commences. In the case of offshore diamond mining, Debmarine Namibia's Environmental Management system has been certified to the international ISO 14001 standard[16] since 2002. The system ensures that operations meet legal compliance requirements; the mining company should strive for continual improvement in environmental management, based on best practice. Debmarine Namibia's environmental research focuses on obtaining greater knowledge of the natural variability of the environment, understanding the consequences of marine mining, and monitoring changes over time. The company has full-time environmental scientists on staff. Ongoing monitoring surveys are conducted by independent scientists and the results are published in an annual report that is peer-reviewed by internationally recognized marine scientists, available upon request. Following analysis, Debmarine Namibia's benthic samples are shared with other local and international entities, such as the universities and the Ministry of Fisheries and Marine Resources, to facilitate education, capacity building, and the training and development of marine researchers within Namibia. A large number of records can be found in OBIS from the Namdeb Diamond Corporation Limited Marine Monitoring Programme and other sources for the Namibian EEZ.[17]

8.8.2.2 Establishment of Adequate Observing Systems

Observing systems are key to establishing baseline conditions and monitoring environmental effects of mining. Many developing countries have not yet invested in systems to conduct regular observations to either provide base-line data or monitor the effects of mining on humans.

8.8.2.3 New Research and Modeling Needed

Effects of coastal and offshore mining is an important research area that should be pursued globally. Research should be conducted to determine how much time must elapse before mined areas recover. In an example of land-based coastal mining, van

---

[16] https://www.iso.org/standard/60857.html.

[17] https://obis.org/dataset/8d23af49-296a-4777-8e31-8b2c2dedad26.

Aarde et al. (1996) found that the succession of dune forests to resemble unmined dunes was progressing increasingly from newly mined to dunes mined 16 years previously, in terms of species composition and density. Compilations of research on mining effects could be useful to guide new projects, although each site has its own unique characteristics that must be considered. Another important area of research relates to modelling of mining impacts. Models of mined areas, patchiness of mining, frequency of mining, and other factors should be taken into account.

8.9 Summary

Given the potential to gain economic benefits and reduce dependence on other countries for strategic elements, it is difficult for many developing countries to resist developing mining activities. For countries that decide to adopt mining industries, mitigation should be put in place to reduce negative impacts and move these activities toward blue economy ideals. Also, objective scientific observations should be obtained to understand the short- and long-term environmental impacts of mining

Sustainable agriculture, clean energy, and other aspects of modern society require increased exploitation of minerals from coastal areas. Some countries are resource-poor without the exploitation of their coastal mineral and living resources. The mining of phosphate rock has underpinned global food production development since the middle of the Twentieth Century and will continue to do so in the foreseeable future. Annual demand will exceed annual supply of easily minable phosphate rock in the near future. One approach to partially defer this future demand crisis is to reduce excess phosphorus use (e.g., Filippelli 2011). But it is imperative to increase potential supply (i.e., the phosphate reserve) by looking toward phosphate deposits that are currently uneconomic, such as off-shore deposits on continental shelves.

Offshore diamond mining constitutes an important contribution to the Namibian economy and affects a small portion of the Namibian EEZ. The mining industry should continue to cooperate with the fishing industry to avoid trade-offs of mining income for fishing income, which affect and benefit different stakeholders. A blue economy framework is needed to coordinate various actions and initiatives related to the blue economy.

Mining of deposits of heavy mineral sand deposits are necessary to fuel the continued expansion of modern electronics. Yet, mining of these minerals can have major environmental consequences. However, relying only on terrestrial resources has global geopolitical consequences.

The economic and natural resource drivers for mineral extraction should not overwhelm the other two goals of blue economy, environmental and social sustainability. Mining of coastal dunes, beaches, and offshore areas has a variety of negative impacts that must be avoided or mitigated for mining to be considered a contribution to blue economies.

Acknowledgements We take this opportunity to express gratitude to the editors of this book, Drs. Venu Ittekkot and Ed Urban, for extending an invitation to contribute this article for the esteemed Non-Aligned Movement (NAM) Science and Technology Centre, New Delhi India. The outline provided by the editors worked as an excellent roadmap and eased writing of the chapter. PU acknowledges the support received from Alagappa Govt. College (Alagappa University).]

References

Alonso E, Sherman AM, Wallington TJ et al (2012) Evaluating rare earth element availability: a case with revolutionary demand from clean technologies. Environ Sci Technol 46:3406–3414
Anonymous (2010) Guide book for evaluating mining project EIAs. Published by Environment Law Alliance Worldwide (ELAW), University of Nevada, Reno, USA
Anonymous (2019) African mining law changes to look out for. In: Investing in African mining INDABA. www.mining.indaba.com
Ashraf MA, Maah MJ, Yusoff I et al (2011) Sand mining effects, causes and concerns: a case study from Bestari Jaya Selanagar Peninsula, Malaysia. Sci Res Essays 6:1216–1231
Atkinson L, Sink K (2008) User profiles for the South African offshore environment. SANBI Biodiversity Series 10. South African National Biodiversity Institute, Pretoria
Atmanand MA, Jalihal P, Ramanamurthy MV et al (2019) Blue Economy—opportunities for India. IEEE India Info 14:106–115
Blatt H, Tracy RJ (1996) Petrology, 2nd edn. Freeman, New York
Bluck BJ, Ward JD, De Wit MCJ (2005) Diamond mega-placers: southern Africa and the Kaapvaal craton in a global context. Geological Society, London, Special Publications 248:213–245. https://doi.org/10.1144/GSL.SP.2005.248.01.12
Chalov SR (2012) Effect of placer mining on suspended sediment budget; A case study of North Russia's Kamchatka Peninsula. Hydrol Sci J 59:1081–1094
Compton JS, Bergh EW (2016) Phosphorite deposits on the Namibian shelf. Mar Geol 380:290–314
Corbett I, Burrell B (2001) The earliest Pleistocene(?) Orange River fan-delta: an example of successful exploration delivery aided by applied Quaternary research in diamond placer sedimentology and palaeontology. Quatern Int 82:63–73. https://doi.org/10.1016/S1040-6182(01)00009-X
Cordell D, Drangert JO, White S (2009) The story of phosphorus: global food security and food for thought. Global Environ Change 19:292–305
Dillenburg SR, Tomazelli LJ, Barboza EG (2004) Barrier evolution and placer formation at Bujuru, southern Brazil. Mar Geol 203:43–56
Ellis JI, Clark MR, Rouse HL et al (2017) Environmental management frameworks for offshore mining: the New Zealand approach. Mar Policy 84:178–192
Emery KO, Noakes LC (1968) Economic placer deposits of the continental shelf. Technical Bulletin. ECAFE 1:95–111
Fernandes CEG, Malik A, Jineesh VK et al (2015) An appraisal of biological responses and network of environmental interaction in non-mining impacted coastal waters. Environ Sci Pollut Res 22:12,544–12,558

Filippelli GM (2011) Phosphate rock formation and marine phosphorus geochemistry: the deep time perspective. Chemosphere 84(6):759–766. https://doi.org/10.1016/j.chemosphere.2011.02.019

Filippelli GM (2016). The global phosphorus cycle. In Lal (ed) Advances in soil science-soil phosphorus. CRC Press, Francis & Taylor, pp 1–21

Filippelli GM (2018) Balancing the global distribution of phosphorus with a view toward sustainability and equity. Global Biogeochem Cycles 32:904–908. https://doi.org/10.1029/2018GB005923

Fleischer M, Rosenblum S, Woodruff M (1991) The distribution of lanthanides and yttrium in the minerals of the monazite family. U.S. Department of the Interior Geological Survey, File Report 91–580. https://pubs.usgs.gov/of/1991/0580/report.pdf

Foden J, Rogers SI, Jones AP (2009) Recovery rates of UK seabed habitats after cessation of aggregate extraction. Mar Ecol Prog Ser 390:15–26

Gilbert N (2009) Environment: the disappearing nutrient. Nat 461:716–718

Gnandi K, Tobschall HJ (1999) The pollution of marine sediments by trace elements in the coastal region of Togo caused by dumping of cadmium-rich phosphorite tailing into the sea. Environ Geol 38(1):13–24

Gujar AR, Ambre NV, Mislankar PG et al (2010) Ilmenite, magnetite and chromite beach placers from South Maharashtra, Central West Coast of India. Resour Geol 60:71–86. https://doi.org/10.1111/j.1751-3928.2010.00115.x

Hamar J, Sarkany-Kiss A (2000) Biological sequences of the cyanide spill in the affected rivers in Romania and Hungary with respect to the study of molluscs, fish and the Tisza Mayfly. Tisza Club and Liga Pro Europe, p 24, Hungary

Hannington M, Petersen S, Kratschell A (2017) Subsea mining moves closer to shore. Nat Geosci 10(3):158–159. https://doi.org/10.1038/ngeo2897

Hou B, Keeling J, Van Gosen BS (2017) Geological and exploration models of beach placer deposits, integrated from case-studies of Southern Australia. Ore Geol Rev 80:437–459. https://doi.org/10.1016/j.oregeorev.2016.07.016

Hu X., Liu J, Yang H et al (2020) Impacts of potential China's environmental protection tax reforms on provincial air pollution emissions and economy. Earth's Future 8(4):e2019EF001467. https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2019EF001467

Indian Minerals Yearbook, 2019 (2020) Part III: Mineral reviews, 58th ed. Rare Earths. Government of India, Ministry of Mines, Indian Bureau of Mines

IFA (International Fertilizer Industry Association) (1998) Mineral fertilizer use and the environment. IFA, Paris

Iyer SD, Gujar AR, Sanil Kumar V et al (2021) Sedimentological responses to coastal dynamics along the Thane District, North Maharashtra, West Coast of India. Sustainable Water Resources Management 7: Article No. 28. https://doi.org/10.1007/s40899-021-00518-8

Jagannadha Rao M, Raju UPN, Raja Rao G et al (2018) Beach placer deposits of India, their distribution, mineralogy and sustainable mining with reference to placer ilmenite. Int J Sci Res 7:1437–1443. https://www.ijsr.net/archive/v7i5/ART20182614.pdf

Jamasmie C (2018) Brazilian President changes decades old mining laws to lure investment, protect environment. www.mining.com

Kehalley K (2019) United States of America, Chapter 28. International legal guide to mining laws 2019, 6th edition, a practical cross border insight into mining laws. Published and produced by permission of Global Legal Group, London, pp 185–192

Kaikkonen L, Jarvi RV, Hygard H et al (2018) Assessing the impact of seabed mineral extraction in the deep sea and coastal marine environments, current methods and recommendations for environmental risk assessment. Mar Pollut Bull 135:1183–1197

Koehnken L, Rintoul M (2018) Impact of sand mining on ecosystem structure. Processes and biodiversity in rivers. Published by WWF. ISBN: 978-2-94052988-9

Laitos JG (2013) Cyanide, mining and the environment. Pace Environ Law Rev 30:869–948

Mazumdar R, Khurana M (2020) India securing rare earth elements. Working Paper No. 97, India Exim Bank, p 46

Marmorat M (2008) Local momentum for global governance: the management of transboundary pollution. The Baia Mare cyanide spill, Romania 2000. Health and Environment Reports No.1. Published Institute Francois des Relations Internationales, Brussels, Belgium

Miller KA, Thomson KF, Johnson P et al (2018) An overview of seabed mining including current state of development, environmental impact and knowledge gaps. Front Mar Sci 4:1–24. https://doi.org/10.3389/fmars.2017.00418

Mukhopadhyay R, Loveson VJ, Iyer SD et al (2021) Blue economy of the Indian Ocean: resource economics, strategic vision, and ethical governance. CRC Press, Boca Raton, Florida, USA. https://doi.org/10.1201/9780429326004

Nayak S (2019) Report of Blue Economy working group on coastal and deep-sea mining and offshore energy, p 80

Ohde T, Dadou I (2018) Seasonal and annual variability of coastal sulphur plumes in the northern Benguela upwelling system. PLoS One 13(2):e0192140. https://doi.org/10.1371/journal.pone.0192140

Prakash TN, Verghese TI, Prasad R et al (2016) Erosion and heavy mineral depletion of placer mining beach along the south west coast of India, Part II, sedimentological and mineralogical changes. Nat Hazards 83:1–26

Rogers J (1977) Geological report on pelletal Phosphorite form the Outer Shelf off Namibia. SAMICOR Consultancy Report

Rogers J, Li XC (2002) Environmental impact of diamond mining on continental shelf sediments off southern Namibia. Quatern Int 92:101–112

Ruttenberg KC (2003) The global phosphorus cycle. In: Schlesinger WH (ed) Treatise on geochemistry, vol 8. Elsevier, NY, pp 585–643

Ruttinger L, Sarma V (2016) Climatic change and mining: a foreign policy perspective supported by Federal Foreign Office. Adelphi, Berlin, Germany, p 18

Savage C, Field JG, Warwick RM (2001) Comparative meta-analysis of the impact of offshore marine mining on microbenthic communities versus organic pollution studies. Mar Ecol Prog Ser 221:265–275

Schlesinger WH (1997) Biogeochemistry: an analysis of global change. Press, San Diego, Acad

Sengupta D, Van Gosen BS (2016) Placer-type rare earth element deposits (Chapter 4). In: Verplanck, PL, Hitzman MW (eds) Rare earth and critical elements in ore deposits. Revi Econ Geol 18:81–100

Sheela Nair L, Prasad R, Rafeeque MK et al (2018) Coastal morphology and long-term shoreline changes along the southwest coast of India. J Geol Soc India 92:588–595

Sonter LJ, Ali SH, Watson JEM (2018) Mining and biodiversity: key issues and research needs in conservation science. Proc R Soc B 285:20181926. https://doi.org/10.1098/rspb.2018.1926

Spaggiari RI, Bluck BJ, Ward JD (2006) Characteristics of diamondiferous Plio-Pleistocene littoral deposits within the palaeo-Orange River mouth, Namibia. Ore Geol Rev 28:475–492. https://doi.org/10.1016/j.oregeorev.2005.03.011

Steffani N (2011) Environmental impact assessment report on the dredging of marine phosphate enriched sediments from Mining Licence Area No. 170. Steffani Marine Environmental Consultancy Report

Tyler, RM, Minnitt RCA (2004) A review of sub-Saharan heavy mineral sand deposits—Implications for new projects in southern Africa. J S Afr Inst Min Metall 104:89–99. https://www.saimm.co.za/Journal/v104n02p089.pdf

United Nations (2016) Chapter 23: offshore mining industries. https://www.un.org/Depts/los/global_reporting/WOA_RPROC/Chapter_23.pdf

USGS (2009) Mineral commodity summaries: Phosphate rock. United State Geological Survey. Reston, VA

Valsangkar AB, Fernandes D (2008) Impact of offshore placer mining experiment (PLAMEX) on sediment size and heavy minerals. Curr Sci 9:1467–1472 van Aarde RJ, Ferreira SM, Kritzinger JJ et al (1996) An Evaluation of habitat rehabilitation on coastal dune forests in northern KwaZulu-Natal, South Africa. Environ Restor 4(4):334–345, https://doi.org/10.1111/j.1526-100X.1996.tb00186.x

Van Gosen BS, Ellefsen KJ (2018) Titanium mineral resources in heavy-mineral sands in the Atlantic Coastal Plain of the southeastern United States. U.S. Geological Survey Scientific Investigations Report 2018–5045, p 32. https://doi.org/10.3133/sir20185045

Van Gosen BS, Fey DL, Shah AK et al (2014) Deposit model for heavy-mineral sands in coastal environments. U.S. Geological Survey Scientific Investigations Report 2010–5070–L, p 51. https://doi.org/10.3133/sir20105070L

Van Gosen BS, Hou B, Song T (2019) Heavy mineral sands resources in China. Society of Economic Geologists, Special Publication 22:581–593

Wood G, Melanie R (2019) Australia (Chapter 3). In: International Comparative Legal Guide to Mining Laws, 6th ed. A practical cross-border insight into mining law

Xie Y, Hou ZQ, Goldfarb RJ et al (2016) Rare earth element deposits in China. Rev Econ Geol 18:115–136

Yuzhou S, Moony R, Eggert RG (2020) China's public policies towards rare earth, 1975–2018. Miner Econ 33:127–151

Chapter 9
Coastal Pollution

Guizhi Wang, Xiaolin Li, Marc Humphries, Venkatesh Chinni, Khanittha Uthaipan, and Minhan Dai

Abstract Coastal pollution has been one of the most pressing issues at both regional and global levels due to intense pressures from human development, especially in recent decades. This chapter presents general scientific knowledge of classic nutrient-induced coastal eutrophication, heavy metal pollution, organic pollutants such as oil and plastics, and radionuclide pollution, followed by representative cases of coastal pollution from developing countries—China, South Africa, India, and Thailand—to demonstrate how science can improve understanding and tackle the problems and impacts of coastal pollution on blue economies. The case studies of pollution presented here show examples of the blue economy sectors that can be impacted, including human health, fisheries, and tourism. The multiplicity of pollutants, their complex interactions, as well as their impact and potential exacerbation due to climate change pose challenges that can be confronted by blue economic policies based on a better scientific understanding of the issue involved.

Keywords Eutrophication · Metal pollution · Oil spills · Radionuclides · Marine plastics

G. Wang (✉) · X. Li · K. Uthaipan · M. Dai
State Key Laboratory of Marine Environmental Science and College of Ocean and Earth Sciences, Xiamen University, Xiamen, China
e-mail: gzhwang@xmu.edu.cn

X. Li
e-mail: xlli@xmu.edu.cn

M. Dai
e-mail: mdai@xmu.edu.cn

M. Humphries
School of Chemistry, University of the Witwatersrand, Johannesburg, South Africa

V. Chinni
CSIR-National Institute of Oceanography, Dona Paula, Goa, India

E. R. Urban Jr. and V. Ittekkot (eds.), *Blue Economy*,
https://doi.org/10.1007/978-981-19-5065-0_9

9.1 Introduction

As the gateway between the land and ocean, the coastal zone is home to over 50% of the world's human population and produces almost 50% of its gross domestic product (GDP).[1] However, this vital region has undergone intensified pressures from human development ever since the Industrial Revolution. These pressures are further amplified by climate change, loss of biodiversity, and pollution (Winther et al. 2020), which have adversely impacted human society and impaired the coastal ocean's and, by extension, the global ocean's, sustainability. Coastal pollution is one of the most pressing issues at both regional and global levels (Halpern et al. 2008). In the marine environment, pollutants comprise a wide variety of physical, chemical, and biological agents, introduced to the coastal ocean via the following pathways. Pollutants (both point-source and diffuse) from land may be carried into the coastal ocean via surface runoff and rivers, and groundwater, as well as direct discharges of waste waters. Pollutants in the marine environment can also result from human activities at sea and deposition from the atmosphere (Jickells et al. 2017). The origins of pollutants and their distributions are highly spatially and temporally variable around the globe, with megacities at the coast emerging as a major source for pollution (Cabral et al. 2019). This chapter will focus on the general scientific knowledge of classic nutrient-induced coastal eutrophication, heavy metal pollution, organic pollutants (with oil spill and plastics singled out for special attention), and radionuclide pollution. This general information will be followed by representative cases of coastal pollution from China, South Africa, India, and Thailand to demonstrate how science can improve understanding and help tackle the problems and impacts of these coastal pollutants on blue economies.

9.2 Coastal Eutrophication

Eutrophication is a global phenomenon, primarily caused by the excessive addition of nutrients, especially compounds of nitrogen (N) and phosphorus (P) to coastal ecosystems. It results in excess phytoplankton production with undesirable disturbance to the community structure and to water quality (Rabalais et al. 2009; Malone and Newton 2020).

9.2.1 Global Patterns and Trends

In the past few decades, coastal eutrophication has dramatically increased worldwide, especially in the Northern Hemisphere, along the western margins of the Atlantic and Pacific oceans, and in European coastal waters (Steffen et al. 2015). Nitrogen is

[1] Data source: https://www.citypopulation.de/en/world/bymap/Coastlines.html.

seen to be the primary cause of eutrophication in most coastal marine ecosystems, although phosphorus also plays a role in this process (Howarth 2008; Howarth and Paerl 2008). Global anthropogenic N input to the environment is now greater than the natural N-fixation in the ocean (140 teragrams (Tg) N yr^{-1}) by 20 Tg N yr^{-1} (Steffen et al. 2015). Anthropogenic nutrients are mainly sourced from municipal wastewater, fertilizers, the combustion of fossil fuels, and food-related industries, among which the largest source are synthetic fertilizers (Table 9.1).

Most anthropogenic N inputs to the coastal ocean are via river runoff fueled by anthropogenic inputs to coastal watersheds, wet deposition within watersheds, and riverine transport from watersheds and atmospheric deposition derived from both agricultural sources and fossil fuels (Jickells et al. 2017). Direct atmospheric deposition contributes about 14% of the total (Malone and Newton 2020), while the exports of nutrients from submarine groundwater discharge vary greatly from one coastal system to another (Santos et al. 2021), in which the anthropogenic fraction is poorly known.

Table 9.1 Global sources of anthropogenic nutrients (N)

Source	Magnitude (Tg N yr^{-1})	Regional contribution (%)						Reference
Synthetic fertilizer	118	Southern Asia		North America	Europe	South America		Johnson and Harrison (2015), Lu and Tian (2017)
		71		11	7	6		
Combustion of fossil fuels	25–40	Asia		Europe	North America	Sub-Saharan Africa		Lamsal et al. (2011)
		30		20	17	12		
Manure	18	Asia	Africa	South America	Oceania	Europe	North America	Zhang et al. (2017), Malone and Newton (2020)
		34.2	17.6	14.2	13.3	11.6	9.2	
Emission of ammonia from agriculture	10	–						Bouwman et al. (2013)
Sewage	9	–						Malone and Newton (2020)
Finfish aquaculture	2.6	–						

9.2.2 Patterns in Developing Countries

Coastal eutrophication in developing countries is found mainly in East and Southeast Asia, off the Iranian coast of the Caspian Sea, off the coasts of the Red Sea, and on the African and South American coasts (Fig. 9.1). In terms of the major nutrient sources, fertilizer use more than doubled from 2002 to 2012 in Latin America, South Asia, East Asia, and Oceania (Malone et al. 2021), with East Asia, especially China, being the hotspot of fertilizer use in the early Twenty-first Century (Fig. 9.2). China contributed 30.5 Mt synthetic nitrogen in 2016, which was about 30% of the global use (Yu et al. 2019). Consequently, eutrophication has been widely observed along Chinese coasts, with a slow development from the 1970s to the 1990s and a fast increase after 2000 (Wang et al. 2021). Additionally, wastewater discharges may facilitate algal blooms and hypoxia in some regions (Table 9.2). For example, a sharp increase in nutrient concentrations was observed from 2001 to 2019 in Jakarta Bay, Indonesia, related to the increase in human population in the adjacent river basin and direct discharge of 60–80% of untreated domestic wastewater (Prayitno and Afdal 2019; Damar et al. 2020). Moreover, groundwater and atmospheric deposition, as well as shrimp farm and harbor effluents, may also be sources of nutrients. For example, off the coast of Mexico, dissolved inorganic nitrogen (DIN) levels were 35–80 times higher than baseline levels of < 0.2 μM of five decades ago and soluble reactive phosphorus (SRP) levels increased from 0.1 μM in the 1970s to the 2000s by eightfold (González-De Zayas et al. 2020).

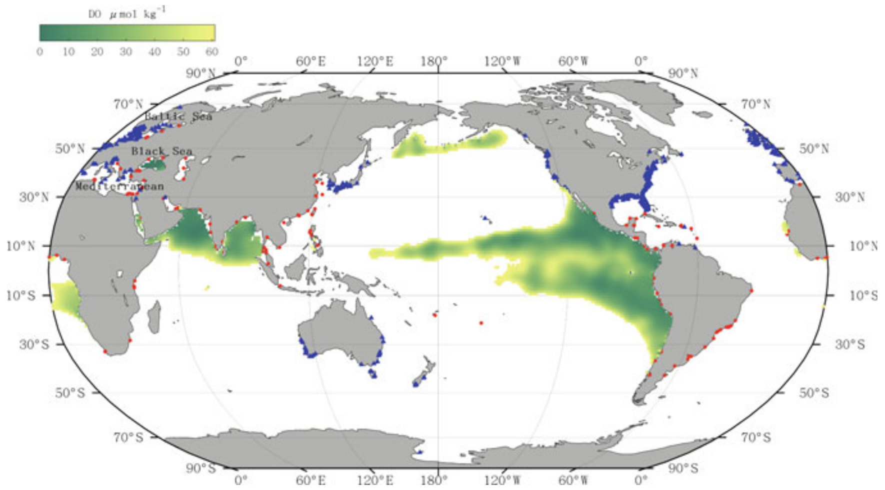


Fig. 9.1 Global sites of observed coastal eutrophication, with those in developing countries in dots and in other countries in triangles (*Data source* Diaz et al. [2011] and references in Table 9.2). The shaded areas have dissolved oxygen (DO) level less than 61 μmol kg^{-1} at the depth of 300 m (*Data source* World Ocean Atlas 2018 [www.ncei.noaa.gov]). Note that countries with more data available may show relatively more eutrophic areas compared to countries with less data

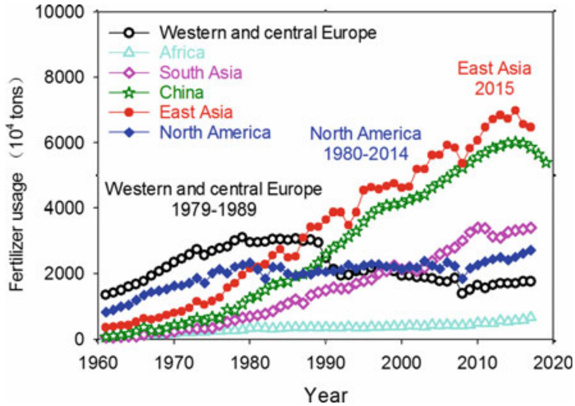


Fig. 9.2 Fertilizer use in different regions around the globe since 1960. Figure revised from Wang (2022) with data available from the International Fertilizer Association (http://ifadata.fertilizer.org/ucSearch.aspx)

9.2.3 Impacts of Eutrophication

The most noticeable consequences of coastal eutrophication include the occurrence and/or expansion of hypoxic (oxygen concentration $\leq 61\ \mu\text{mol kg}^{-1}$), or even anoxic, areas when excess organic matter produced in surface waters sinks below the pycnocline, where its remineralization consumes oxygen, resulting in associated organismal, fisheries, and geochemical effects (Rabalais et al. 2014). Additionally, coastal acidification may be induced by CO_2 produced as a byproduct of aerobic respiration (Wallace et al. 2014). Eutrophication can also increase harmful algal bloom (HAB) occurrence and intensity and may reduce oxygenated habitat and harm biodiversity, ecosystem function, and human well-being. Furthermore, changes in nutrient composition and stoichiometry (nutrient ratios) have been observed in many coastal waters where eutrophication occurs, including increases in the concentration of ammonium and bioavailable organic nitrogen and phosphorus, and increases in elemental ratios of nitrogen to phosphorus and nitrogen to silicate. For example, in the Bohai Sea the ratios of inorganic N:P and N:Si increased from 2–45 and 0.1–1.26, respectively during the 1980s–1990s to 20–87 and 0.68–2.89 in the 2000s (Wang et al. 2021). Globally, coastal eutrophication areas with associated hypoxia coincide with major population centers and watersheds that deliver large amounts of nutrients (Diaz and Rosenberg 2008). Largely as a consequence of land-derived anthropogenic N inputs, surface chlorophyll-a (as a proxy of phytoplankton production) increased by 10% in the coastal ocean in 1998–2003 and the frequency of HABs appears to be increasing, for which eutrophication is at least partially responsible (Malone and Newton 2020).

Since 1950, coastal hypoxic areas have spread exponentially worldwide to over 500 known systems in 2015, with many more systems likely being affected, especially in developing countries, where monitoring may be sparse even in waters with untreated human and agricultural waste (Breitburg et al. 2018). Most marine ecosystem services are likely to be negatively affected by hypoxia, although to varying degrees (Laffoley and Baxter 2019). More than 10% of the worldwide coral reefs are at elevated risks of hypoxia (Altieri et al. 2017). Coral bleaching in the

Table 9.2 Selected coastal eutrophication in developing countries

Country	Site	Phenomenon reported	Sources of nutrients	Reference
China	Chinese coasts	Eutrophication, harmful algal blooms, hypoxia, and acidification	River inputs, atmospheric deposition, sewage discharge, and submarine groundwater discharge	He et al. (2014), Zhao et al. (2020), Wang et al. (2021)
Iran	Iranian coast of the Caspian Sea	Ecosystem shift from oligotrophic to mesotrophic/meso-eutrophic	Terrestrial inputs of N	Basatnia et al. (2018), Saravi et al. (2019)
India	Tapi Estuary	Hypoxia during monsoon and anoxia during post- and pre-monsoon seasons	Agricultural fertilizers and sewage inputs	Ram et al. (2014)
	Coastal margins off west India	Eutrophication	Upwelling, rivers and land drainage	Chauhan et al. (2011), George et al. (2012), Durga Rao et al. (2017), Sivasankar et al. (2018)
Indonesia	Jakarta Bay	Eutrophication, hypoxic water, algal blooms, and mass mortality of aquatic biota	Discharge of untreated domestic wastewater	Prayitno and Afdal (2019), Damar et al. (2020)
	Coastal waters of Bitung, Keunekai, Mimika, and Bintan Island	Eutrophication	–	Baohong et al. (2016), Wisha et al. (2018), Hamuna et al. (2019), Syakti et al. (2019)
Thailand	Southern coastal waters	Nutrient enrichment	River water	Yoshikawa et al. (2017)
Philippines	Bolinao and Anda maricultural areas	Eutrophication	Extensive use of low-quality fish feeds	Ferrera et al. (2016)
	Manila Bay	Eutrophication and hypoxia	Urban wastewater flow	Sotto et al. (2014)
Malaysia	Coastal water of Tioman Island	Eutrophication	Residential wastes discharge	Rahman et al. (2015)
	Semerak River	Eutrophication	Aquaculture activity	Er et al. (2018)

(continued)

Table 9.2 (continued)

Country	Site	Phenomenon reported	Sources of nutrients	Reference
	Klang Estuary	Hypoxia	Elevated river flow	Lee et al. (2020)
Vietnam	Saigon-Dongnai River system	Eutrophication, algal blooms, and hypoxia	Untreated domestic discharges	Nguyen et al. (2019)
United Arab Emirates	Coastal waters of Abu Dhabi in Arabian Gulf	Eutrophication, algal blooms, and hypoxia	Treated sewage discharge, industrial effluents, aeolian dust	Rajan et al. (2020)
South Africa	Algoa Bay	Algal blooms and hypoxia	Wastewater discharge	Lemley et al. (2019)
Nigeria	Coastal lagoons	Hypoxia	Nutrients loading associated from anthropogenic and agricultural activities	Akagha et al. (2020)
Mexico	Coastal areas	Nutrient enrichment	Groundwater, sewage, runoff, atmospheric deposition, and shrimp farm and harbor effluents	Herrera-Silveira et al. (2004), González-De Zayas et al. (2020), Pérez-Gómez et al. (2020)
Brazil	Coastal waters	Hypertrophic, low oxygen level	Waste discharge, agricultural, and aquaculture effluents	de Carvalho Aguiar et al. (2013), Ciotti et al. (2018), Mourão et al. (2020)
Fiji Islands	Laucala Bay	Nutrient enrichment	–	Singh et al. (2009)
Saudi Arabia	Coastal waters	Ammonium enrichment	Sewage effluents	El Sayed et al. (2013), Al-Amri et al. (2020)
Vanuatu	Coastal areas of Port Vila	Nutrient enrichment	Non-treated sewage and stormwater runoff	Devlin et al. (2020)

Great Barrier Reef is promoted by eutrophication (Malone et al. 2021). Land-derived nutrient inputs are one of the main drivers of expanding hypoxia in the Baltic Sea, leading to the creation of the largest man-made hypoxic area in the world, extending almost 70,000 km^2 in 2019 (Carstensen and Conley 2019). The resultant cyanobacteria blooms produce toxins that affect recreation and fisheries in this region. Oyster landings in the Chesapeake Bay (USA) declined by up to sixfold from 1950 to 2000, corresponding with a tripling of the hypoxic water volume (Tian 2020).

In Chinese coastal waters, phytoplankton blooms have appeared with increasing spatial extent and frequency in the Bohai Sea, the Yellow Sea, the inner shelf of the East China Sea, and the northern shelf of the South China Sea. Persistent summer hypoxia appeared as early as the late 1950s on the inner shelf of the East China Sea off the Yangtze River estuary and the spatial extent expanded from about 1,800 km^2 in 1959 to $> 15{,}400$ km^2 in 2006, which has been attributed to elevated nutrient input due to fertilizers used in the Yangtze watershed (Malone and Newton 2020). Reported toxic algal blooms along the coast increased from none in the 1950s to more than a total of 100 in the 1990s due to an increase in the nutrient input from the Yangtze River (Yan et al. 2002), which adversely impacted local aquaculture and other marine services. In Algoa Bay, South Africa, wastewater discharges are the dominant source of inorganic nutrients to the nearshore environment, representing 71% of total DIN and 62% of dissolved inorganic phosphorus (DIP) loads, which has yielded, in part, increased algal blooms and hypoxia (Lemley et al. 2019).

9.3 Heavy Metal Pollution

Heavy metals are a group of naturally occurring elements with a density greater than 4 g cm^{-3}, including metals and metalloids such as arsenic (Duffus 2002). Heavy metal pollution is a serious issue because of the toxicity, persistence, and non-biodegradable nature of these metals. Such pollution is usually most severe in coastal areas adjacent to highly industrialized and urbanized regions. Anthropogenic activities have dramatically increased concentrations of metals in coastal zones, with zinc, copper, chromium, lead, nickel, mercury, and cadmium being of most concern.

9.3.1 Global Patterns

Heavy metals in coastal environments originate from natural and anthropogenic sources. The lowest metal concentrations are observed in North America and the Arctic. The most metal-polluted region is observed along the Egyptian Mediterranean coast due to metals from industries, sewage, irrigation, and urban runoff. The concentrations of heavy metals vary greatly in coastal systems around the globe (Lu et al. 2018). Unlike eutrophication, however, a consistent temporal trend of metal contamination on a global scale is lacking, although metal concentrations show a decrease for lead in surface waters by nearly an order of magnitude compared to ~ 200 picomol kg^{-1} during the 1970s (Boyle et al. 2014) and a slight increase for mercury in higher trophic level organisms (Ebinghaus et al. 2021).

Natural sources of heavy metals include weathering of rocks and volcanic activities. For example, in the Red Sea-Gulf of Aqaba coast of Saudi Arabia, iron, manganese, cadmium, copper, zinc, and chromium are mostly of terrestrial origin, derived from weathering of nearby pre-Cambrian basement rocks, and Tertiary and Quaternary sedimentary rocks (El-Sorogy et al. 2020). The major anthropogenic sources of heavy metals include reclamation and dredging (which mobilize heavy metals to elevated levels relative to sediment quality guidelines), traffic emissions, agricultural and sewage discharges, and industrial effluents in countries with rapid industrial growth. In particular, lead pollution arises from aerosol deposition and ship moorings, and lead levels may be maintained because of semi-closed characteristics and circulation pattern of coastal embayments (Gao and Chen 2012; Zhuang and Gao 2014). In the Arabian Gulf countries, heavy metals mainly derive from activities related to oil refining and petrochemical industries, desalination plants, coal combustion, and oil pollution due to oil spills from cargo ships and oil tankers, as well as from drilling platforms (Pekey 2006; Naser 2013; El-Sorogy et al. 2020). Fishing trawler and shipping activities, such as repairing, fueling, greasing and painting of ships, may aggravate metal contamination in coastal areas (Jilani 2015). Each individual metal may enter the environment from various sources in different regions and some may have the same sources in the same region (Lu et al. 2018).

As metals in coastal waters tend to be bound by suspended particles and sink to the seafloor, coastal sediments are generally the major reservoirs of heavy metals and overlying seawater may have low levels of dissolved heavy metals (Liu et al. 2021). For the same reason, estuaries serve as sink locations of past metal contamination (Ridgway and Shimmield 2002). In downstream areas, however, estuarine dynamics such as waves and tidal currents may promote re-suspension of bottom sediments, leading to desorption and release of heavy metals in the suspended particles from sediments into the water column. Sediments comprised of fine particles tend to have relatively high metal concentrations due to their high specific surface area in surface adsorption and ionic attraction (Zhuang and Gao 2014).

9.3.2 Patterns in Developing Countries

In various countries, different regions may be dominated by different metals. For example, iron is the most abundant heavy metal in surface sediments of the Red Sea-Gulf of Aqaba coast of Saudi Arabia, along the coast of Pakistan, and in the coastal waters of Nigeria with a range from 1,413–3,374 μg g^{-1}, although still about an order of magnitude lower than in the Brisbane River, Australia (Olaifa 2005; Saher and Siddiqui 2016; El-Sorogy et al. 2020). In the surface sediments of Ulsan Bay, Korea, zinc is the most abundant metal, with a mean concentration of 362 μg g^{-1}, higher near industrial complexes; however, mercury and cadmium with mean concentrations of 0.16 and 0.40 μg g^{-1}, respectively are the metals posing a very high potential ecological risk (Ra et al. 2014). The Bay of Bengal, Bangladesh is highly polluted by cadmium, chromium, copper, mercury, nickel, lead, and uranium, mainly due to agricultural, domestic and industrial wastes directly discharged into the waterways (Kibria et al. 2016). In the surface sediments in Mejillones Bay, Chile, cadmium is the only metal whose values are high relative to the average concentration in Earth's crust (Valdes et al. 2005).

The metal hotspots in China are usually located in estuaries and nearshore regions where industrial and domestic sewage discharge and the metal concentrations decrease sharply with the distance offshore or away from the estuary (Gao and Chen 2012; Rui et al. 2013; Liu et al. 2021). Metal pollution of copper, nickel, lead, and zinc in the Bohai Sea, surrounded by highly industrialized regions, is more serious than in the South Yellow Sea and the Changjiang River Estuary, while less severe than in the Pearl River Estuary. The metal concentrations in the Bohai Sea are comparable to those in heavily polluted coastal areas in European countries (Lu et al. 2018). Likely related to industrial wastes, cadmium pollution is the most serious in coastal areas of the Bohai Sea. In southern China, the coastal sediments of Guangdong province are enriched in lead, zinc, and cadmium, due to development of nearby industrial sectors and rapid urbanization in these areas, while metal levels in the coastal sediments of Guangxi and Hainan provinces are relatively low (Wang et al. 2013).

9.3.3 Impacts of Heavy Metals on Coastal Ecosystems

Some metals (such as iron, copper, zinc, manganese, nickel) are essential for organisms, but are toxic when their concentrations are above certain thresholds. A few other metals—such as mercury, lead, silver, and cadmium—are toxic to marine organisms even when present in minute amounts. For example, in the Baltic Sea the established threshold concentration of mercury is 20 μg kg^{-1} in fish muscle, of lead is 26 μg kg^{-1} in fish liver, and of cadmium is 137.3 μg kg^{-1} in mussel tissues (Ebinghaus et al. 2021). Heavy metals have diverse negative effects on marine organisms including, but not limited to, increased energy demand and impaired development and reproduction, which depend on metal concentration, speciation, interactions with receptor sites, uptake into the organisms, and other factors (Cabral et al. 2019). Since metals are not degradable during biological uptake and release, they tend to accumulate through food webs in higher trophic levels, especially in top predators (Vareda et al. 2019). For example, in the coastal sediments near Santa Rosalía, Mexico, metal pollution due to copper mining and smelting over the past century has caused accumulation of metals in a local seaweed (Rodríguez-Figueroa et al. 2009). In the Persian Gulf, concentrations of arsenic, cadmium, lead, and mercury exceeded the maximum allowable levels in international commerce in fish muscles (Cunningham et al. 2019). Thus, metal contamination in coastal systems may render water and sediments unsuitable for marine aquaculture, which potentially reduces seafood stocks and affects the blue economy of the region, and bioaccumulation of metals through the trophic chain poses risks to human health.

9.4 Oil Spills

Oil spill pollution results from the leaking of crude oil or oil products from work sites or reservoirs to natural environments due to the accidents or regular operations during petroleum exploration, development, refining, storage and transportation (Ramseur 2017).

9.4.1 Global Patterns

The major sources of oil spill pollution include oil tanker accidents, offshore oil exploration leaks and blowout accidents. Long-term input sources include oily sewage discharge from port and ship operations, natural seabed leakage, and erosion of oily sedimentary rocks (Guo 2004). From the 1970s to 2020, statistics from oil transportation activities show that there were 1,847 oil spills (more than 7 tons) from oil tankers, and the total amount of oil spills reached 5.86 million tons.[2] Among them, there were 11 oil spills with more than 100,000 tons leakage in each incident, including the oil spill of Atlantic Express off Tobago, West Indies, which leaked 287,000 tons in 1979; the oil spill of ABT Summer at 700 nautical miles off Angola, which leaked 260,000 tons in 1991; and the oil spill of Castillo De Bellver off Saldanha Bay, South Africa, which leaked 252,000 tons in 1983. The statistics also demonstrate that the frequency of spills greater than 7 tons from tankers has decreased over the past 50 years. As the region with the highest oil production in the world, oil spills occur frequently in the Middle East. From 1967 to 2010, accidental oil spills in the Arabian Sea amounted to about 1 million tons of oil, which is about 10 times as much as the annual long-term oil spills of the entire Persian Gulf region (Danish 2010).

In addition, crude oil spills caused by drilling platform accidents are also an important source of marine oil spill pollution. In 1979, an outburst occurred in the exploratory well of Kestock 1 in the Gulf of Mexico, and approximately 140 million gallons of crude oil was discharged into the sea. In 2010, about 300 barrels of crude oil leaked from a drilling platform of the American Mobil Oil Company in Nigeria. On April 20, 2010, due to the explosion of BPs Deepwater Horizon drilling rig in the Gulf of Mexico, a large amount of oil spilled over a period of nearly three months. The maximum daily oil spill volume reached 126,000 tons, covering 2,500 square

[2] Data source: www.itopf.org/fileadmin/data/Documents/Company_Lit/Oil_Spill_Stats_publication_2020.pdf.

kilometers of seawater, making it the most serious oil spill in American history (Beyer et al. 2016).

9.4.2 Pattern in Developing Countries

The developing countries of South and West Asia are adjacent to the Indian Ocean, which is the main route connecting the Pacific Ocean, the Middle East and the Mediterranean Sea. Oil spills occur frequently in this region. The following were large oil spills in the Indian Ocean from 2017 to 2018: Chennai oil spill, Sharjah oil spill, Al Khiran oil spill, and Mubarak village oil spill (Naz et al. 2021). Nigeria is the 11th largest oil producer in the world, and the extraction and processing of oil in this area have caused significant oil spill pollution (Sam et al. 2016). In the past 50 years, approximately 10–13 million tons of oil have been spilled into the Niger Delta due to oil spills, of which only 33% have been recovered (Nwilo and Badejo 2006; Kadafa 2012). In China, from 1990 to 2010, about 22,035 tons of oil flowed into Chinese waters due to oil tanker accidents. The average annual loss is 1,049 tons, and more than 70 accidents have leaked more than 50 tons of oil each (Xiong et al. 2015). In 2018, there was a major oil spill from the oil tanker of Sanchi offshore Shanghai due to a ship collision and 111,510 tons of condensate oil leaked (Pan et al. 2021).

9.4.3 Impacts of Oil Spills

Marine oil spills are mainly composed of crude oil and its derivatives in a flammable, explosive, and complex toxic chemical mixture. These pollutants released to the environment on a short-term and limited spatial scale may cause adverse impacts on marine and coastal environments such as beach contamination and a wide range of biological effects, for example, habitat destruction, reduced growth, disease, impaired reproduction, impaired physiological health, and mortality of fish, invertebrates, birds, and sea mammals (Beyer et al. 2016), so that beach tourism and ecological resources are adversely affected. Thus, such pollution is regarded as an essential environmental concern by marine scientists and relevant government agencies. Oil spills require days to years to clean up, and can stay in marine waters for decades, becoming a long-term pollutant. Due to its intensity, temporal and spatial scales, the damage caused by an oil spill may have a very long-term impact on coastal marine ecosystems.

9.5 Plastics Pollution

Plastics are synthetic organic polymers made by polymerization of monomers extracted from petroleum or natural gas (Derraik 2002).

9.5.1 Global Patterns

Plastics were invented more than 100 years ago and are widely used in daily life and industrial production. In the past half century, the global total plastic production increased by nearly 250 times, from 1.5 million tons in 1950 to 368 million tons in 2019 (PlasticsEurope 2020). Due to special physical and chemical properties of plastics, plastic fragments can disperse in the natural water environment and be transported long distances by ocean currents. Now plastics are the main component of marine litter (Galgani et al. 2021). It may take hundreds of years before they are finally deposited in seafloor sediments (Ryan 1987; Hansen 1990; Goldberg 1995, 1997).

Riverine input is the main source of plastics to the ocean, transporting 1.15 million to 2.41 million tons of plastic wastes each year (Lebreton et al. 2017), although some plastics originate from various marine activities, for example, commerce, recreation, fisheries and aquaculture (Haward 2018). It is estimated that 640,000 tons of fishing gear is discarded in the ocean every year, accounting for about 10% of the total marine debris (Li et al. 2016). Plastics, like other organic materials, eventually degrade, but at a very slow rate (Andrady 2015). Some natural processes accelerate the degradation process, such as UV-induced photodegradation, thermal reactions, polymer hydrolysis, and microbial degradation.

Plastic fragments found in the marine environment vary in size, with a continuous distribution of particle sizes from nanometers to meters. According to their sizes and forms, plastic particles (fragments, fibers or plastic beads) with a diameter of less than 5 mm are usually defined as microplastics. These small plastic particles come from the decomposition of large plastic fragments, fabrics and polymer materials on clothes, and small plastic beads used in cosmetics and other consumer products (Browne et al. 2011; Ladewig et al. 2015; Napper and Thompson 2016; Cesa et al. 2017). Microplastics are mainly distributed by ocean currents, wind and river outflows (Ng and Obbard 2006; Barnes et al. 2009; Martinez et al. 2009) and are transported to remote locations, including islands in the middle of the ocean (Ivar do Sul et al. 2009), polar regions (Barnes et al. 2010), and the deep ocean (Lozano and Mouat 2009; Reineccius et al. 2020). Deep ocean troughs and trenches may be one of the largest microplastic sinks on the planet.

9.5.2 Patterns in Developing Countries

The rivers from the Asian continent are one of the most important sources of plastics into the ocean; the 20 rivers from which most plastic pollution enters the ocean are mainly located in Asia (Lebreton et al. 2017). The top 20 countries for waste discharge of mismanaged plastic in 2010 include 13 Asian countries; China, Indonesia, and the Philippines are the top three, emitting 8.82, 3.22, and 1.88 million metric tons of plastics per year, respectively. Microplastic pollution has been widely detected in the natural aqueous environment of developing countries, for example, China, India and South Africa (Chae and An 2017; Dahms et al. 2020; Singh et al. 2021).

9.5.3 Impacts of Plastics Pollution

The hazards of microplastics to aquatic organisms can be divided into three types: physical, chemical, and biological hazards. Microplastics can be ingested and accumulated by low-trophic level plankton, causing physical internal wear and blockage, which can lead to reduced feeding efficiency, energy deficiency, and injury or death (Browne et al. 2008; Murray and Cowie 2011; Wright et al. 2013). Components leached from microplastics can be toxic, such as some persistent organic pollutants, carcinogenic and endocrine-disrupting compounds (Mato et al. 2001; Oehlmann et al. 2009; Talsness et al. 2009). Microplastics can cause diseases in organisms that ingest them through pathogens adsorbed to the surface of the microplastics (Zettler et al. 2013; Kiessling et al. 2015). Because of their potential to compromise food security, food safety, and consequently human health, microplastic pollution is of growing concern as the presence of microplastics in marine animals used for human food is an emergent global phenomenon (Galgani et al. 2021). Due to their special physical and chemical properties, microplastics can also be a carrier of other environmental pollutants, and have a significant impact on environmental behaviors of heavy metals and some hydrophobic organic compounds (Ashton et al. 2010; Law and Thompson 2014; Alimi et al. 2018).

9.6 Radionuclide Pollution

Radionuclide pollution refers to the introduction of radioactive materials into the ocean by human activities, leading to elevated radioactivity relative to natural baselines, causing harm to organisms.

9.6.1 Global Patterns

Much of the radioactivity in the waters, biota and sediments of the ocean is from natural sources. Significant inputs from human activities since the 1940s, however, have resulted in additional radioactivity in the ocean above natural background levels (Ebinghaus et al. 2021). Anthropogenic radionuclides in the coastal ocean mainly originate from three sources: (a) products from nuclear explosions (e.g., ^{90}Sr, ^{131}I, and ^{35}S), transported into the ocean via atmospheric deposition; (b) discharges from nuclear power plants and nuclear submersibles (e.g., ^{137}Cs, ^{90}Sr, ^{66}Mn, and ^{60}Co), in cooling water and wastes; and (c) radionuclides generated from medical radiation applications and nuclear research, including ^{131}I, ^{32}P, ^{3}H, ^{14}C, etc., and discharged in aqueous form. In recent years, nuclear leakage due to nuclear accidents has become another source of radionuclide pollution. For example, after the Fukushima Dai-ichi Nuclear Power Plant incident, the activities of ^{134}Cs and ^{137}Cs measured three months later in seawaters off Japan increased 10–1,000 times over prior levels off Japan (Buesseler et al. 2017). Radioactive discharges from nuclear power reactors to the ocean were orders of magnitude less than those from weapons testing, reprocessing plants and major accidents and most of such discharges tend to decrease over time with improved technology, even though the number and scale of nuclear power plants have increased (Ebinghaus et al. 2021).

The level of radionuclide pollution of the ocean is higher in the Northern Hemisphere than in the Southern Hemisphere due to nuclear tests mostly carried out in the Northern Hemisphere, for example, 2.9 ± 0.8 Bq m^{-3} of ^{137}Cs in 45-50ºN, while 1.5 ± 0.2 Bq m^{-3} in 45–50ºS (Duran et al. 2004). For the same reason, the Pacific Ocean is more contaminated than the Atlantic Ocean and radionuclide pollution is much less seen in developing countries than in developed countries. Enclosed and semi-enclosed seas, as well as coastal areas, have higher radionuclide concentrations than the open ocean. Radioactivity in surface waters is usually greater than in the intermediate and bottom layers of the ocean (Ma 1981). Due to its persistence caused by radionuclide pollutants being relatively long-lived (e.g., the half-life of ^{239}Pu is 2.4×10^4 years), radionuclide pollution usually lasts relatively long in the marine environment (Yang et al. 2015).

9.6.2 Patterns in Developing Countries

Along the entire coast of China in regions where nuclear power plants are located, one or more of the three anthropogenic radionuclides, ^{3}H, ^{90}Sr, and ^{137}Cs, are detectable at environmental baseline levels of 0.2–11 Bq L^{-1}, 0.3–2.4 mBq L^{-1}, and 0.5–3.5 mBq L^{-1}, respectively in the seawater and sediments. ^{54}Mn, ^{58}Co, ^{60}Co, ^{65}Zn, ^{95}Zr, ^{110m}Ag, ^{124}Sb, ^{134}Cs, and ^{144}Ce are not detected in the seawater and ^{54}Mn, ^{58}Co, ^{60}Co, ^{95}Zr,

^{110m}Ag, ^{134}Cs, and ^{144}Ce are not detected in the sediments.[3] The activities of these radionuclides indicate little radionuclide pollution due to nuclear power plants in Chinese coastal zones. The overall level of anthropogenic radionuclides in marine organisms in Chinese seas decreased from late 1970s to the late 1990s (Tang and Shang 2005). For example, the activity of ^{137}Cs in fish flesh was in the range of 128–1340 Bq kg^{-1} in 1976–1981 and decreased to 0.03–0.08 Bq kg^{-1} in 1997–1998 in Chinese coastal waters. In 2015, the activity of ^{137}Cs was almost identical before and after the Fukushima incident, indicating that the impact of the incident on Chinese seas was minor (Wu et al. 2012). Most of ^{239,240}Pu in the East China Sea and Yellow Sea are retained in the continental shelf sediments, and 50–80% of ^{137}Cs is contained in sediments (Nagaya and Nakanura 1992). The activity of ^{137}Cs in the surface seawater decreases in the order: the South China Sea, the Sulu and Indonesian Seas, and the Bay of Bengal and the Andaman Sea, while the Sulu and Indonesian Seas have the highest ^{239,240}Pu activity in these regions (Yamada et al. 2006).

9.6.3 Impacts of Radionuclide Pollution

Exposure to large amounts of radioactivity is life threatening to humans and other organisms. According to the World Health Organization, the dose threshold for acute radiation syndrome for humans is about 1000 millisieverts. Marine organisms can take up and accumulate radionuclides through seawater, sediments, feeding, and uptake by the body surface, serving as carriers and transporters of marine nuclear pollutants (Benitez-Nelson et al. 2018). Accumulation of radioisotopes inside organisms via the food chain results in much higher radioactivity levels than in the ambient environments, which severely damages the health of organisms.

9.7 Mitigations Against Coastal Pollution

After the impacts of coastal pollution on humans became better known, strategies for mitigating these pollutants have been adopted, based on ever-growing scientific understanding of their sources to coastal waters and the fates of these pollutants. For example, based on the scientific knowledge of the role of nutrient inputs on coastal eutrophication, many European and North American countries began to limit the use of chemical fertilizers and initiated steps to reduce nutrient loadings to the coastal ocean in the 1970s. Consequently, nutrient discharges in these areas peaked in the 1980s and 1990s (Reusch et al. 2018). Most of the nutrient reductions have come from improvements in wastewater treatment plants, for example, for the Baltic

[3] Available from National Nuclear Safety Administration of China at http://nnsa.mee.gov.cn/ztzl/haqnb.

Sea (Boesch 2019). Management of nutrients, both N and P, and carbon inputs has reduced coastal hypoxia in a few systems, such as the Hudson River and Chesapeake Bay in the United States and the Mersey Estuary in England (Parker and Oreilly 1991; Jones 2006; Boesch 2019). However, in most cases these practices fail to reduce eutrophication. Associated eutrophication, hypoxia, and other environmental problems such as algal blooms and coastal acidification have persisted both at regional and global scales.

As for heavy metal pollution, after the hazardous effects of heavy metals became well recognized, particularly on human well-being, the use of heavy metals has been constrained and their emission is monitored worldwide. Bans on leaded fuels and antifouling paints, and mercury regulations, have been implemented in European countries and the United States (Lu et al. 2018). In addition, wastewater has been treated to remove heavy metals before being discharged, using strategies based on the scientific knowledge of these metals. Following these mitigations, levels of metals have significantly decreased in coastal waters and surface sediments in most areas, although the decrease in surface sediments is relatively slow. However, there are observed increases in concentrations of metals in higher trophic-level fish species in spite of some decreases in emissions (Ebinghaus et al. 2021).

In terms of oil spills, improved safety measures regarding the phaseout of single-hull tankers came into effect in 2003 and at the same time maritime inspections started as a measure for cargo owners to demand higher safety standards for oil tankers, which likely has resulted in a decreasing global trend in terms of shipping accidents leading to oil spills (Ebinghaus et al. 2021). Moreover, significant improvements have been achieved in oil spill forecasting and response, and understanding of oil spill impacts has been aided by advances in modeling, the use of satellites, and other techniques such as ultrasound and artificial intelligence (NOAA 2020).

The remediation of the microplastic waste has been proposed as part of both upstream (e.g., wastewater treatment plant, waste management and bioplastics) and downstream (e.g., physico-chemical and biological remediation) solutions (Wong et al. 2020). More than 60 countries have introduced bans and levies to curb single-use plastic waste (UNEP 2018). A variety of measures have been implemented including, but not limited to, gear marking, onshore collection, disposal and recycling, and alternatives to single-use plastics (Food and Agriculture Organization of the United Nations 2016).

9.8 Cases of Coastal Pollution in Developing Countries

Typical cases of pollution in the Pearl River Delta in China and the iSimangaliso Marine Protected Area in South Africa, and along the coasts of India and Thailand, are presented below (Fig. 9.3a). These regions experience pollution with different substances and levels, and with different degrees of scientific understanding, which makes them good models to show how science can help us understand and tackle pollution problems.

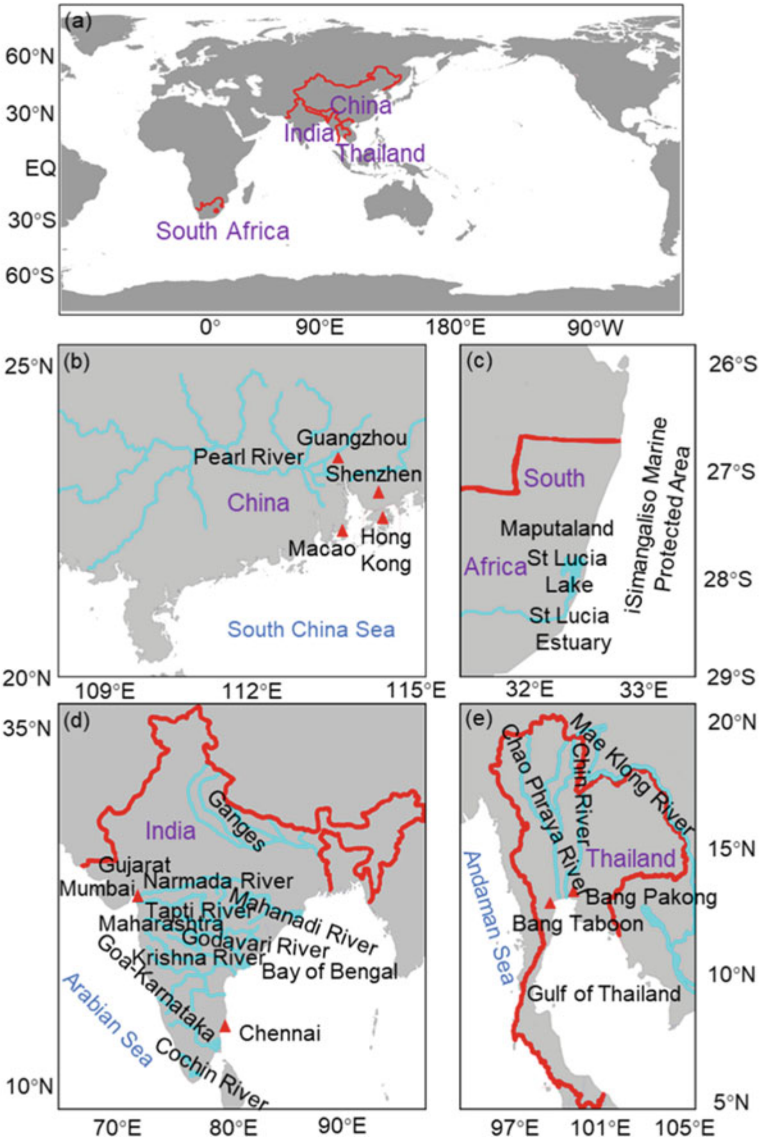


Fig. 9.3 Sites of cases of coastal pollution. **a** locations of the developing countries where these sites are located, **b** the Pearl River Delta in China, **c** the iSimangaliso Marine Protected Area in South Africa, **d** India, and **e** Thailand

9.8.1 The Pearl River Delta in China

The Pearl River Delta (PRD) is located on the northern shelf of the South China Sea and covers about 4,000 km^2 marine area and 56,000 km^2 land area, including the large cities of Hong Kong, Macao, Shenzhen, and Guangzhou (Fig. 9.3b). The Pearl River, with an annual water discharge of ~ 3.26×10^{11} m^3 and a drainage area of 4.5 $\times 10^5$ km^2, is the 17th largest river in the world in terms of freshwater discharge (Dai et al. 2014). The ocean and humans are inextricably linked in the PRD via various key social and economic activities.

Coastal eutrophication and associated issues: Since the 1980s, rapid industrial and agricultural development and urbanization have input large amounts of anthropogenic nutrients into the Pearl River Estuary and onto the adjacent continental shelf (Huang et al. 2003; Callahan et al. 2004; Harrison et al. 2008). Sewage discharge in the PRD increased more than seven fold from 2100 Mt in the 1980s to 15,100 Mt in the 2000s (Ma et al. 2009). As a result, the coastal waters in the PRD, especially around Hong Kong, are affected by persistent and increasing eutrophication. This deteriorating situation may increase the frequency of HABs, expand the area of hypoxic zones and lead to other ecosystem disruptions such as loss of habitat for bottom-dwelling fish.

In the last decade, summer hypoxia was frequently observed off the Pearl River Estuary, with an increasing area and intensity (e.g., Su et al. 2017; Zhao et al. 2020). In 2014, the area of bottom hypoxia was about 3,000 km^2 southwest of Hong Kong (Su et al. 2017). A decreasing trend of ~ 2 ± 0.9 $\mu mol\ kg^{-1}\ yr^{-1}$ was shown in the annual minimum DO concentration in the bottom water adjacent to Hong Kong over the period 1990–2014 (Qian et al. 2018). Associated with the decrease in DO was an increase in the annual maximum surface concentration of DIN at a rate of ~ 1.4 $\pm$ 0.3 $\mu mol\ kg^{-1}\ yr^{-1}$ under almost constant bottom temperatures, suggesting that eutrophication is the most plausible driver of oxygen deficiency in this region.

In contrast, before the 1990s only small-scale and short-lived hypoxia events were recorded in this area (Yin et al. 2004), but since then, these events have been increasing in intensity, frequency, and geographic extent. Hypoxia has been growing and has reached an alarming level in the Pearl River Estuary. If the current trend continues, large-scale hypoxia could spread and may eventually offset the progress made by the costly sewage treatment and cause severe ecological and environmental damage.

Eutrophication/hypoxia in the PRD is primarily caused by the ecosystem's responses to the increasing nutrient discharge from the Pearl River and local sewage effluents. As direct waste products from human activities and the most reactive nitrogen species, ammonium discharge resulted from domestic sewage (67%), agricultural wastes (25%), and industrial wastes (8%) in 2017 (National Bureau of Statistics and Ministry of Ecology and Environment 2018). Meanwhile, increasing discharge of organic pollutants also modulates biogeochemical pathways and ecological consequences, and further increases the severity of eutrophication/hypoxia in the PRD. Cyclonic vortices and centers of convergence in the coastal transition zone between the Pearl River Estuary and the adjacent continental shelf create a stable water column with weak mixing and long residence time, and accumulate nutrients and organic matter that result in eutrophication and hypoxia development (Li et al. 2020). In addition, passages of typhoons can cause stirring up of bottom waters so that hypoxia is disrupted, while nutrients stirred up from the bottom foster primary production and subsequent hypoxia reinstatement in 6–12 days (Kuss et al. 2021; Zhao et al. 2021). Ocean acidification in coastal waters is further greatly aggravated with the development of bottom water hypoxia due to a reduction in the acid–base buffering capacity of seawater.

Heavy metal pollution: Besides eutrophication, hypoxia and coastal acidification, other factors also contribute to the deterioration of the coastal ecosystem in the PRD. Coastal sediments in the offshore waters of Hong Kong are the most polluted by heavy metals in southern China, with high levels of copper, lead, zinc, cadmium, and mercury. There were significantly high heavy metal concentrations, especially zinc (200 mg kg^{-1}) and chromium (130 mg kg^{-1}), in sediments deposited in 1975–1985, consistent with the rapid development in coastal areas in China, particularly the PRD, and increasing discharges of contaminants from local industrial, agriculture and urban activities due to China's reform and opening-up policy (Ye et al. 2020). Over the period 1986–1992, heavy metal concentrations displayed a downward trend, likely related to economic adjustment. The high heavy metal concentrations after 1992 were related to a new economic reform driven by economic transition in 1992 with the concentrations in surface sediments of 91 mg kg^{-1} for chromium and 145 mg kg^{-1} for zinc. Heavy metals in waters of the Pearl River Estuary mainly come from wastewater of the metallurgical industry, electroplate industry and corrosion of metal equipment in ports, boats and ships, and overland runoff of mining areas upstream (Huang and Onyx 2004).

Ecological and economic impacts and science and technology applied to deal with the environmental issues: Eutrophication/hypoxia and metal pollution affect local fisheries in the PRD. In terms of food resources, fish and crustaceans are less tolerant to reduced oxygen levels than gastropods and bivalves, so that for resource use sectors and communities reliant on fish and crustaceans, greater impacts are expected from hypoxia on productivity and size of stocks. Metal contamination may render water and sediments unsuitable for marine aquaculture, which potentially reduces seafood stocks in the PRD, and subsequently may reduce the benefits of marine aquaculture to the blue economy of the region.

To deal with deteriorating water quality in the PRD, regular monitoring of water quality has been carried out by the Hong Kong Environmental Protection Department and by local environmental agencies on the mainland China since the 1990s. Environmental measures such as wastewater treatment in the large cities of the PRD before wastewater is discharged have been implemented. These measures have been effective in reducing nutrient point-source inputs to the Pearl River Estuary; consequently the upper Estuary has become relatively clean since the beginning of the Twenty-first Century. However, large amounts of anthropogenic nutrient inputs and resultant eutrophication have tipped the lower Estuary and adjacent shelf areas into seasonal hypoxia, despite intermittent summertime mixing of coastal waters by tropical cyclones (Qian et al. 2018). The risk of eutrophication and hypoxia is rapidly increasing around Hong Kong despite the massive sewage treatment project (Qian et al. 2018).

Due to strengthening of pollution controls by local government and relocation of industries to mainland China, heavy metals in coastal sediments of Hong Kong increased before the early 1990s and dropped afterward (Wang et al. 2013). The strengthening of environmental controls imposed by local governments, such as the construction of sewage interception pipe networks at the upstream and establishment of wastewater treatment plant in the PRD and industrial transformation and upgrading, likely explain the lower concentrations of chromium, nickel, copper, and zinc in the top sediment layers in this region (Gao et al. 2017). However, the average chromium, nickel, copper, and lead concentrations in surface sediments still exceed the threshold effect level values of 52.3, 15.9, 18.7, and 30.2 mg kg^{-1}, respectively, but lower than the probable effect level values of 160.4, 42.8, 108.2, and 112.2, indicating some degree of potential adverse ecological effects.

9.8.2 The iSimangaliso Marine Protected Area in South Africa

The iSimangaliso Wetland Park (10,700 km^2) located in Maputaland on the east coast of South Africa (Fig. 9.3c), encompasses a diverse variety of terrestrial, coastal and marine environments. Declared a UNESCO World Heritage Site in 1999, iSimangaliso is the single largest formally protected area along the South African coastline. Limited sediment exchange with the ocean occurs and the absence of any major riverine inputs north of St. Lucia Estuary results in remarkably clear offshore waters.

Pesticide pollution: Despite their protected status, seemingly pristine coastal and marine habitats are threatened by pollution, originating largely from activities occurring within catchment areas external to the Wetland Park. Maputaland has a long history of pesticide use and pesticide pollution is probably the single most serious contamination threat to the region. Beginning in the mid-1940s, organochlorine pesticides (OCPs) were widely used on agricultural crops and to control the spread of insect-borne diseases. Large quantities of insecticides—including hexachlorocyclohexanes (HCHs), aldrin, heptachlor, and endosulfan—were used on commercial sugarcane and citrus fruit farmlands, while aerial spraying with DDT was employed to combat tsetse fly that spread African trypanosomiasis and mosquitos that spread malaria. As in many other developing countries impacted by malaria, use of DDT in South Africa is permitted for indoor residual spraying (IRS) purposes and DDT is typically applied annually during the late summer months to the inside of dwellings as the primary method of malaria control (Maharaj et al. 2019).

Due to their environmental persistence and susceptibility to long-range transport, the intensive use of OCPs in Maputaland led not only to widespread contamination in the areas where they were applied, but also in the neighboring ecosystems of iSimangaliso. Transport of sediment from contaminated catchment areas remain an importance source of legacy OCPs, particularly for large fluvially dominated systems such as Lake St. Lucia (Buah-Kwofie and Humphries 2021). While the majority of this contamination is attributable to past use, the illegal and continued use of obsolete OCP stocks on farmlands surrounding iSimangaliso has been suspected (Buah-Kwofie and Humphries 2017, 2021). Furthermore, while malaria control operations permit the limited use of DDT, thousands of homesteads across large areas of Maputaland that border conservation areas are routinely sprayed. Today, iSimangaliso's lake and wetland systems represent vast contaminated sinks in the landscape, harboring substantial quantities of sediment-bound pesticides that originated from catchment areas outside of the park boundary (Humphries 2013; Buah-Kwofie and Humphries 2017). The continued presence of significant DDT concentrations detected within sediments (74–510 ng g^{-1}) and biological tissues (390–5,000 ng g^{-1}) (Buah-Kwofie and Humphries 2021) suggest that ongoing IRS practices remain an important source of environmental contamination in the region, indicating a conflict between the need to protect human health against malaria and protection of coastal ecosystems from DDT pollution.

Ecological impacts and science and technology applied to deal with the environmental issues: While offering a highly effective and low-cost approach to pest control, the release of OCPs into the environment is accompanied by significant ecological and human health concerns. Because of their high toxicity and tendency to bioaccumulate through the food web, many OCPs have been linked with several adverse toxicological responses in both humans (Bornman and Bouwman 2012; Ferguson et al. 2013) and wildlife populations (Delong et al. 1973; De Guise et al. 1995; Tubbs and McDonough 2017). The accumulation of OCPs in local fish species is prevalent, with tissue analyses revealing the presence of particularly high concentrations of HCHs, DDTs, endrin, and methoxychlor (Buah-Kwofie et al. 2018). While a variety of teratogenic, reproductive, and neurotoxic effects have been reported in fish exposed to environmentally significant levels of OCPs (Martyniuk et al. 2020), such effects remain largely understudied in local fish species.

Pesticides also impact adjacent coral reef systems, diminishing their value as blue economy resources. The proximity of coral reef communities found along the Maputaland coastline exposes a diverse variety of marine organisms to the long-term effects of pesticide pollution. Remarkably high OCP concentrations (450–3000 ng g^{-1} wet weight) have been detected in soft corals and sponges from several shallow reefs along the coastline (Porter et al. 2018), rivalling some of the highest pesticide levels reported in marine organisms globally. Although the toxicological impacts of OCP pollution on Maputaland reefs are yet to be studied, monitoring studies have indicated a steady decline in soft coral cover of almost 1% per year over the past 25 years (Porter and Schleyer 2017). It is speculated that the observed decline in cover of soft coral (54% in 1993 to 36% in 2014) may be associated with prolonged exposure to OCPs (Porter and Schleyer 2017; Porter et al. 2018). Moreover, it is likely that OCPs bioaccumulate in other reef-associated fauna (e.g., crustaceans, fish and turtles), potentially affecting coral reef ecosystems in the region more broadly.

To deal with the pesticide pollution, use of most OCPs in South Africa was banned in the early 2000s, with the exception of DDT, which continues to be used for disease vector control in the northeastern malaria-endemic regions of the country. Despite the widespread occurrence of pesticide pollution in Maputaland, little is known about the specific long-term toxicological impacts of these contaminants on ecosystems and biological communities. So far, there have been no meaningful attempts from management authorities to assess or mitigate the effects of pesticide contamination. Of particular relevance is the continued use of DDT in areas surrounding iSimangaliso. While promoted by the World Health Organization and South African Department of Health, evaluating the trade-off between disease control and related adverse effects on human and ecosystem health is severely constrained by inadequate data.

9.8.3 India

India is the 7th largest country by area and second largest by population (~1.3 billion) in the world, with over 25% of its population residing in the coastal areas (Fig. 9.3d). The coastal zone of India is the location of many cities (such as Mumbai, Chennai, Kolkata, Visakhapatnam, Kochi, Mangalore etc.). In addition, 14 major rivers drain into the Bay of Bengal and the Arabian Sea from India's east and west coasts, respectively (Rao 1979). Due to urbanization, coastal areas have become hotspots for pollution. Apart from industrial and agricultural effluents, there have been growing concerns over pollution associated with heavy metals, microplastics, and oil pollution in recent years.

Microplastic pollution: India is one of the leading consumers of plastics in the world, with an annual consumption of nearly 5.6 million tons (Toxics link 2014), which is a significant portion of global consumption. The River Ganges is the second largest plastic polluter to the global ocean (Lebreton et al. 2017). The highest concentrations of microplastics are found in metropolitan cities such as Mumbai (west coast of India; Maharana et al. 2020), Chennai (east coast of India; Sathish et al. 2019), and the River Ganges (Goswami et al. 2020). However, sediments found along the east coast of India are relatively less polluted with microplastics than sediments of the west coast of India (Ranjani et al. 2021).

Eighty percent of the plastic debris in India is derived from land-based sources such as rivers and by the human population, mainly at coastal places (Lebreton et al. 2017). The most frequently identified polymer types of microplastic materials in sediments along the east coast and west coast of India are polyethylene (47%) and polypropylene (18.8%); other polymer types are polystyrene, polyethylene terephthalate, and polyamide (Ranjani et al. 2021). India produces nearly 2.5 MTPA (million tons per annum) of polypropylene, where demand is 2.1 MTPA; the rest is exported to other southeast Asian countries (Veerasingam et al. 2017).

Oil spills and tarballs: In India, oil pollution is another concern due to the existence of several oil rigs and significant transport of oil by ship, as international shipping routes traverse the Arabian Sea and Bay of Bengal. Oil spills were more frequent in the offshore waters off Gujarat (41.6%), Maharashtra (34.8%), and Goa-Karnataka (23.5%) based on data in 2017 (Suneel et al. 2019). Oil residues in the form of tarballs are observed along the west coast of India, especially along the coasts of Goa and Gujarat (Suneel et al. 2016). Tarballs were first reported in the peer-reviewed literature on Indian beaches by Nair et al. (1972). The main sources of tarballs are emergent oil spills from ships and oil platforms along international ship transport routes and in areas of offshore production. Due to the monsoon circulation patterns in the northern Indian Ocean, these floating tarbars reach the coasts of India.

Ecological and economic impacts and science and technology applied to deal with the environmental issues: Plastics and oil pollution affect fisheries and beach tourism in India, negatively impacting the country's blue economy. Ingestion of plastic materials has been reported in lower trophic levels of the food chain, such as fish, mollusk, crab, and shrimp, which eventually may affect humans (Kumar et al. 2018; Naidu 2019; Piarulli et al. 2019; Daniel et al. 2020). In addition, due to the existence of a long coastline around India, beaches are another hotspot for microplastic accumulation introduced due to tourism and recreational activities. Oil spills cannot dissolve in water and form a thick sludge that can suffocate marine life such as fish, mammals, and seabirds, and can hamper photosynthetic activity by blocking sunlight (Dicks 1998) so as to damage marine ecosystems such as coral reefs. The science on oil spills is limited in terms of their fate, origin, and transport along the east and west coasts of India.

The Indian government is committed to reduce plastic usage by encouraging reducing, recycling, and reuse of plastics. As a result, 10 beaches in India have won blue flags by 2021 (https://www.blueflag.global/all-bf-sites), an eco-label certificate awarded by the Foundation for Environmental Education to beaches and sustainable beach tourism operators that meet a comprehensive set of requirements.

9.8.4 Thailand

Thailand is located between the Gulf of Thailand and the Andaman Sea (Fig. 9.3e), with a coastline of 3,219 km (DMCR 2015) and a population of about 69 million in 2020 (UN Data 2020).

Water pollution: The first major water pollution event in Thailand occurred in 1970, named the "molasses incident", caused by a spill of molasses into the Mae Klong River, which resulted in elimination of fish in the river and massive cockle mortality, covering several thousand acres in the coastal zone (Ludwig 1976). Water pollution has increased due to deterioration of watersheds caused by agricultural development, industrialization, and rapidly growing population since 1965 and sharply since 1985 (World Bank 2020). Eutrophication is increasing in frequency as well. Between 2007 and 2020, 86 algal blooms were reported along the Thai coastal zone. DO concentrations below 122 μmol kg^{-1} have occurred in the upper Gulf of Thailand, predominantly caused by domestic wastes, with ammonia the main contributor from agriculture and aquaculture sources (PCD 2000).

Water pollution in the Gulf of Thailand has two sources: (a) primary untreated metropolitan, urban and industrial wastewater; and (b) water contamination by agricultural nutrients, which contributes to coastal eutrophication and oxygen depletion events, killing organisms in the upper Gulf of Thailand. Domestic sewage, industrial effluents, and agricultural runoff each year are estimated to be 9.6, 9.9, and 178 × 10^6 m^3 d^{-1}, respectively (Dumrongthai 2019; ONREPP 2020).

Additionally, oil pollution has degraded water resources in the estuarine and coastal environments since the 1950s due to oil spill accidents, industrial activities, and shipping along the coast (Boonyatumanond et al. 2007). Moreover, emerging organic pollutants such as cosmetics, pharmaceutical drugs (including acetylsalicylic acid, caffeine, and ibuprofen), and skincare products (such as synthetic musk and UV filters) in wastewaters may pose a high risk to aquatic organisms in Thailand's estuaries and coastal zones (Juksu et al. 2020). Heavy metals have high concentrations in the sediments of the Chao Phraya estuary and the Gulf of Thailand, e.g., 1.04 mg kg^{-1} for cadmium, 213 mg kg^{-1} for copper, 50.7 mg kg^{-1} for chromium, 98.1 mg kg^{-1} for lead, and 643 mg kg^{-1} for zinc (Wijaya et al. 2013).

Ecological and economic impacts and science and technology applied to deal with the environmental issues: Water pollution affects fisheries and tourism in Thailand. Contaminated waters have resulted in habitat degradation, human health vulnerability, and marine ecosystem damage in the Gulf of Thailand and Andaman Sea (Wattayakorn 2006). Mass shellfish death occurred more frequently after 2006 in shellfish farms in the upper Gulf of Thailand (DMCR 2020). Microplastic fibers were found in 82.76% of demersal fish and 57.14% of pelagic fish in Thai waters (Klangnurak and Chunniyom 2020). The decline of *Rastrelliger brachysoma,* a commercially exploited fish species, due to poor reproduction, may be caused by pollutants such as heavy metals and oil (Senarat et al. 2017). Increasing plastic waste accumulation in Thai marine ecosystems has become an additional acute stress to an already overstressed fisheries (overfishing) and marine wildlife, and impacts tourist destination images.

To address the water pollution problem in Thailand, untreated metropolitan, urban and industrial wastewater is the top priority concern of government management that intends to support the master plan of SDG 14 in Thailand (ONREPP 2020). Currently, the industrial sector is reducing pollutant loads due to the wastewater outflow control, required by the Pollution Control Department in Thailand (PCD). The master plan for water quality management in Thailand (2018–2037) is as follows: (a) improve and maintain surface water quality, and (b) improve and maintain coastal marine quality (NESDC 2018). The PCD has taken actions on marine debris on beaches and in coastal seas to limit the ever-growing consumption and disposal of plastics under the government and private sectors, and to increase society's engagement (PCD 2020).

9.9 Knowledge and Capacity-Building Gaps

In terms of scientific understanding, given the vast diversity of coastal contaminants, coupled with climate change and associated processes, it is extremely challenging to have a complete understanding of the distribution of contaminants in coastal water, sediments, and biota, their interactions, and synergistic short- and long-term effects on coastal ecosystems on regional and global scales. Further studies are needed at the community and population levels to improve knowledge of the ecotoxicity of coastal pollutants. Socio-economic impacts of coastal pollution are rarely quantitatively assessed. Research needs to be advanced in how to transfer the best available science acquired into actionable strategies and schemes.

In terms of observations, insufficient or non-existent monitoring of coastal pollutants, especially in developing countries, results in a significant gap in understanding of the impacts of anthropogenic pollutants on coastal waters. There is a need for more coordinated spatial and temporal sampling of pollutants, within a global strategy. A long-term monitoring of essential indicators and processes is required (see Chap. 14).

In terms of capacity building, standardized measurement techniques and protocols need to be applied at an optimized resolution to detect temporal trends and for ease of comparisons between researchers and geographic regions. There is a need to develop laboratory and in-situ facilities that can improve knowledge and monitoring of pollutants. There are major gaps in the capacities of most developing countries to monitor concentrations of pollutants in coastal areas. There are inadequate infrastructures for effective waste collection and managements. A database of pollutants in coastal areas as well as a scientist network would be desirable. An integrated modelling and forecasting framework is proposed to serve cross-scale and interdisciplinary synthesis, diagnosis and simulations of key processes, allowing prediction of future changes. Improving awareness, information and education and communicating scientific findings to management and policy makers are crucial steps in helping advance monitoring strategies and measures to effectively preserve the marine environment and to sustainably utilize coastal resources. Joint efforts are sought from academia, industry, and government agencies to understand physical, chemical, and biological factors, socio-economic drivers, and governance affecting coastal pollution in order to identify the sources and mediate existing coastal pollution around the globe and adapt to climate change for future healthy developments of coastal systems.

9.10 Implications for Blue Economy

Several sectors of blue economy are affected or have the potential to be affected by the wide variety of organic and inorganic pollutants reaching coastal seas. They disrupt coastal water quality, and the biogeochemical and ecological functions of such interconnected ecosystems as mangroves, seagrasses, and corals reefs (see Chaps. 2–3). As a consequence, such pollution has an impact on ecosystem health, products and services, and the aesthetic value of coastal habitats. Our cases of pollution from selected developing countries show examples of the blue economic sectors that can be impacted: human health, fisheries, and tourism. The multiplicity of pollutants, their complex interactions, as well as their impact and potential exacerbation due to climate change pose challenges that can be confronted by blue economic policies based on a better scientific understanding of the issues involved.

Acknowledgements We are thankful to Weizhen Jiang, Guiyuan Dai, Yafei Sun, and Fei Zhang for their help in literature searching. We appreciate the thorough editing and constructive comments from Ed Urban, Venu Ittekkot, and an anonymous reviewer. Guiyuan Dai plotted Fig. 9.1 and Weizhen Jiang drafted Fig. 9.3. The work by Guizhi Wang was supported by Natural Science Foundation of Fujian Province (#2019J01020).

References

Akagha SC, Nwankwo DI, Yin K (2020) Dynamics of nutrient and phytoplankton in Epe Lagoon, Nigeria: possible causes and consequences of reoccurring cyanobacterial blooms. Appl Water Sci 10(5):109

Al-Amri AA, Qari HA, El-Sherbiny MM (2020) Distribution and community structure of micro-phytoplankton in relation to increasing anthropogenic impact along coastal waters of Jeddah, the central Red Sea. Oceanol Hydrobiol St 49(2):193–205

Alimi OS, Budarz JF, Hernandez LM et al (2018) Microplastics and nanoplastics in aquatic environments: aggregation, deposition, and enhanced contaminant transport. Environ Sci Technol 52(4):1704–1724

Altieri AH, Harrison SB, Seemann J et al (2017) Tropical dead zones and mass mortalities on coral reefs. Proc Natl Acad Sci USA 114(14):3660–3665

Andrady AL (2015) Persistence of plastic litter in the oceans. In: Gutow L, Klages M (eds) Bergmann M. Marine anthropogenic litter. Springer, pp 57–72

Ashton K, Holmes L, Turner A (2010) Association of metals with plastic production pellets in the marine environment. Mar Pollut Bull 60(11):2050–2055

Baohong C, Muchtar M, Tingting F et al (2016) A baseline study of coastal water quality in the Lembeh Strait of North Sulawesi, Indonesia, in 2013. Mar Pollut Bull 104:364–370

Barnes D, Galgani F, Thompson RC et al (2009) Accumulation and fragmentation of plastic debris in global environments. Philos T R Soc B Biol Sci 364(1526):1985–1998

Barnes DKA, Walters A, Goncalves L (2010) Macroplastics at sea around Antarctica. Mar Environ Res 70(2):250–252

Basatnia N, Hossein SA, Rodrigo-Comino J et al (2018) Assessment of temporal and spatial water quality in international Gomishan Lagoon, Iran, using multivariate analysis. Environ Monit Assess 190(5):314

Benitez-Nelson CR, Charmasson S, Buesseler K et al (2018) Radioactivity in the marine environment: understanding the basics of radioecology. Limnol Oceanogr e-Lectures, 8(1):170–228. https://aslopubs.onlinelibrary.wiley.com/doi/abs/10.1002/loe2.10007

Beyer J, Trannum HC, Bakke T et al (2016) Environmental effects of the Deepwater Horizon oil spill: A review. Mar Pollut Bull 110(1):28–51

Boesch DF (2019) Barriers and bridges in abating coastal eutrophication. Front Mar Sci 6:25

Boonyatumanond R, Wattayakorn G, Amano A et al (2007) Reconstruction of pollution history of organic contaminants in the upper Gulf of Thailand by using sediment cores: first report from Tropical Asia Core (TACO) project. Mar Pollut Bull 54(5):554–565

Bornman MS, Bouwman H (2012) Environmental pollutants and diseases of sexual development in humans and wildlife in South Africa: harbingers of impact on overall health? Reprod Domest Anim 47:327–332

Bouwman L, Goldewijk K K, Van Der Hoek KW et al (2013) Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900–2050 period. Proc Natl Acad Sci USA 110:20882–20887.

Boyle EA, Lee JM, Echegoyen Y et al (2014) Anthropogenic lead emission in the ocean the evolving global experiment. Oceanography 27(1):69–75

Breitburg D, Levin LA, Oschlies A et al (2018) Declining oxygen in the global ocean and coastal waters. Science 359(6371). https://doi.org/10.1126/science.aam7240

Browne MA, Crump P, Niven SJ et al (2011) Accumulation of microplastic on shorelines worldwide: sources and sinks. Environ Sci Technol 45(21):9175–9179

Browne MA, Dissanayake A, Galloway TS et al (2008) Ingested microscopic plastic translocates to the circulatory system of the mussel, *Mytilus edulis* (L). Environ Sci Technol 42(13):5026–5031

Buah-Kwofie A, Humphries MS (2017) The distribution of organochlorine pesticides in sediments from iSimangaliso Wetland Park: ecological risks and implications for conservation in a biodiversity hotspot. Environ Pollut 229:715–723

Buah-Kwofie A, Humphries MS (2021) Organochlorine pesticide accumulation in fish and catchment sediments of Lake St. Lucia: risks for Africa's largest estuary. Chemosphere 274:129712

Buah-Kwofie A, Humphries MS, Pillay L (2018) Bioaccumulation and risk assessment of organochlorine pesticides in fish from a global biodiversity hotspot: iSimangaliso Wetland Park, South Africa. Sci Total Environ 621:273–281

Buesseler K, Dai MH, Aoyama M et al (2017) Fukushima Daiichi-derived radionuclides in the ocean: transport, fate, and impacts. Ann Rev Mar Sci 9:173–203

Cabral H, Fonseca V, Sousa T et al (2019) Synergistic effects of climate change and marine pollution: an overlooked interaction in coastal and estuarine areas. Intern J Environ Res Pub Health 16(15):17

Callahan J, Dai MH, Chen RF et al (2004) Distribution of dissolved organic matter in the Pearl River estuary, China. Mar Chem 89(1–4):211–224

Carstensen J, Conley DJ (2019) Baltic Sea hypoxia takes many shapes and sizes. Limnol Oceanogr Bull 28(4):125–129

Cesa FS, Turra A, Baruque-Ramos J (2017) Synthetic fibers as microplastics in the marine environment: a review from textile perspective with a focus on domestic washings. Sci Total Environ 598(15):1116–1129

Chae Y, An YJ (2017) Effects of micro- and nanoplastics on aquatic ecosystems: current research trends and perspectives. Mar Pollut Bull 124(2):624–632

Chauhan OS, Raghavan BR, Singh K et al (2011) Influence of orographically enhanced SW monsoon flux on coastal processes along the SE Arabian Sea. J Geophys Res-Oceans 116:C12037. https://doi.org/10.1029/2011JC007454

Ciotti ÁM, Ferreira A, Giannini MFC (2018) Seasonal and event-driven changes in the phytoplankton communities in the Araçá Bay and adjacent waters. Ocean Coast Manage 164:14–31

Cunningham PA, Sullivan EE, Everett KH et al (2019) Assessment of metal contamination in Arabian/Persian Gulf fish: a review. Mar Pollut Bull 143:264–283

Dahms H, Rensburg G, Greenfield R (2020) The microplastic profile of an urban African stream. Sci Total Environ 731:138893

Dai M, Gan JP, Han A et al (2014) Physical dynamics and biogeochemistry of the Pearl River plume. In: Bianchi T, Allison M, Cai WJ (eds.) Biogeochemical dynamics at major river-coastal interfaces: linkages with global change. Cambridge University Press, pp 321–352

Damar A, Colijn F, Hesse KJ et al (2020) Phytoplankton biomass dynamics in tropical coastal waters of Jakarta Bay, Indonesia in the period between 2001 and 2019. J Mar Sci Eng 8

Daniel DB, Ashraf PM, Thomas SN (2020) Abundance, characteristics and seasonal variation of microplastics in Indian white shrimps (*Fenneropenaeus indicus*) from coastal waters off Cochin, Kerala, India. Sci Total Environ 737:139839

Danish EY (2010) Ecological impact from chemicals in the Arabian Gulf due to Gulf oil spill. Water Environ J 24(1):65–73

de Carvalho Aguiar VM, Abuchacra PFF, Neto JAB (2013) Biogeochemistry of Jurujuba sound concerning phosphorus dynamics, Rio de Janeiro, Brazil. J Coast Res 65:1–6

De Guise S, Martineau D, Beland P et al (1995) Possible mechanisms of action of environmental contaminants on St. Lawrence beluga whales (*Delphinapterus leucas*). Environ Health Perspect 103:73–77

DeLong R, Gilmartin WG, Simpson JG (1973) Premature births in California sea-lions: association with high organochlorine pollutant levels. Sci 181:1168–1170

Department of Marine and Coastal Resources (DMCR) (2020) Plankton bloom. https://km.dmcr.go.th/th/c_261/d_2419. Accessed 20 Dec 2020

Derraik J (2002) The pollution of the marine environment by plastic debris: a review. Mar Pollut Bull 44(9):842–852

Devlin M, Smith A, Graves CA et al (2020) Baseline assessment of coastal water quality, in Vanuatu, South Pacific: insights gained from in-situ sampling. Mar Pollut Bull 160:111651

Diaz RJ, Rosenberg R (2008) Spreading dead zones and consequences for marine ecosystems. Science 321(5891):926–929

Diaz RJ, Selman. M, Chique C (2011) Global eutrophic and hypoxic coastal systems. World Resources Institute. Eutrophication and hypoxia: nutrient pollution in coastal waters. http://docs.wri.org/wri_eutrophic_hypoxic_dataset_2011-03.xls

Dicks B (1998) The environmental impact of marine oil spills—effects, recovery and compensation. International seminar on tanker safety, pollution prevention, spill response and compensation, Rio de Janeiro, Brazil

DMCR (2015) Marine and Coastal Resources of Thailand. Ministry of Natural Resources and Environment, Bangkok. p. 246 (in Thai)

Duffus JH (2002) "Heavy metals" a meaningless term? (IUPAC technical report). Pure Appl Chem 74(5):793–807

Dumrongthai P (2019) Progress of water environment governance in Thailand. Paper presented at the 14th WEPA Annual Meeting, Tokyo, 22 Feb 2019

Duran EB, Povinec PP, Fowler SW et al (2004) Cs-137 and Pu239+240 levels in the Asia-Pacific regional seas. J Environ Radioact 76(1–2):139–160

Durga Rao G, Kanuri VV, Kumaraswami M et al (2017) Dissolved nutrient dynamics along the southwest coastal waters of India during northeast monsoon: a case study. Chem Ecol 33:229–246

Ebinghaus R, Grøsvik BE, Hassellöv I-M et al (2021) Changes in liquid and atmospheric inputs to the marine environment from land (including through groundwater), ships and offshore installations. In The Second World Ocean Assessment, vol II. United Nations, New York

El Sayed MA, Al Farawati RK, El Maradny AA et al (2013) Environmental status and nutrients and dissolved organic carbon budget of two Saudi Arabian Red Sea coastal inlets: a snapshot statement. Environ Earth Sci 74(12):7755–7767

El-Sorogy AS, Youssef M, Al-Kahtany K et al (2020) Distribution, source, contamination, and ecological risk status of heavy metals in the Red Sea-Gulf of Aqaba coastal sediments. Saudi Arabia. Mar Pollut Bull 158:111411

Er HH, Lee LK, Lim ZF et al (2018) Responses of phytoplankton community to eutrophication in Semerak Lagoon (Malaysia). Environ Sci Pollut Res Int 25(23):22944–22962

Ferguson KK, O'Neill MS, Meeker JD (2013) Environmental contaminant exposures and preterm birth: a comprehensive review. J Toxicol Environ Health B Crit Rev 16:69–113

Ferrera CM, Watanabe A, Miyajima T et al (2016) Phosphorus as a driver of nitrogen limitation and sustained eutrophic conditions in Bolinao and Anda, Philippines, a mariculture-impacted tropical coastal area. Mar Pollut Bull 105(1):237–248

Food and Agriculture Organization of the United Nations (2016) The State of World Fisheries and Aquaculture 2016: contributing to Food Security and Nutrition for All. Rome
Galgani F, Stöfen-O'Brien A, Ambulkar A et al (2021) Changes in inputs and distribution of solid waste, other than dredged material, in the marine environment. In the Second World Ocean Assessment, vol II. United Nations, New York
Gao L, Wang Z, Shan J et al (2017) Aquatic environmental changes and anthropogenic activities reflected by the sedimentary records of the Shima River, Southern China. Environ Pollut 224:70–81
Gao X, Chen CJWR (2012) Heavy metal pollution status in surface sediments of the coastal Bohai Bay. Water Res 46:1901–1911
George R, Muraleedharan KR, Martin GD et al (2012) Nutrient biogeochemistry of the eastern Arabian Sea during the southwest monsoon retreat. Environ Earth Sci 68:703–718
Goldberg ED (1995) The health of the oceans—a 1994 update. Chem Ecol 10(1–2):3–8
Goldberg ED (1997) Plasticizing the seafloor: an overview. Environ Technol 18(2):195–201
González-De Zayas R, Rossi S, Hernández-Fernández L et al (2020) Stable isotopes used to assess pollution impacts on coastal and marine ecosystems of Cuba and México. Reg Stud Mar Sci 39:101413
Goswami P, Vinithkumar NV, Dharani G (2020) First evidence of microplastics bioaccumulation by marine organisms in the Port Blair Bay. Andaman Islands. Mar Pollut Bull 155:111163
Guo Z (2004) The prevention and control of oil pollution off Chinese coastal waters. J Zhejiang Ocean Uni 23(3):269–273
Halpern BS, Walbridge S, Selkoe KA et al (2008) A global map of human impact on marine ecosystems. Science 319(5865):948–952
Hamuna B, Tanjung R, Alianto A (2019) Assessment of water quality and pollution index in coastal waters of Mimika, Indonesia. J Ecol Eng 20:87–94
Hansen J (1990) Draft position statement on plastic debris in marine environments. Fish 15(3):16–17
Harrison PJ, Yin KD, Lee JHW et al (2008) Physical-biological coupling in the Pearl River estuary. Cont Shelf Res 28(12):1405–1415
Haward M (2018) Plastic pollution of the world's seas and oceans as a contemporary challenge in ocean governance. Nat Commun 9(1):667
He BY, Dai MH, Zhai WD et al (2014) Hypoxia in the upper reaches of the Pearl River Estuary and its maintenance mechanisms: a synthesis based on multiple year observations during 2000–2008. Mar Chem 167:13–24
Herrera-Silveira JA, Comin FA, Aranda-Cirerol N et al (2004) Coastal water quality assessment in the Yucatan Peninsula: management implications. Ocean Coast Manage 47(11–12):625–639
Howarth RW (2008) Coastal nitrogen pollution: a review of sources and trends globally and regionally. Harmful Algae 8(1):14–20
Howarth R, Paerl HW (2008) Coastal marine eutrophication: control of both nitrogen and phosphorus is necessary. Proc Natl Acad Sci USA 105(49):E103–E103
Huang SL, Onyx WHW (2004) A review of heavy metal pollution in the pearl river estuary. J Hydrodyn 16(4):367–378
Huang XP, Huang LM, Yue WZ (2003) The characteristics of nutrients and eutrophication in the Pearl River estuary. South China. Mar Pollut Bull 47(1–6):30–36
Humphries MS (2013) DDT residue contamination in sediments from Lake Sibaya in northern KwaZulu-Natal, South Africa: Implications for conservation in a World Heritage Site. Chemosphere 93:1494–1499
Ivar do Sul JA, Spengler A, Costa M (2009) Here, there and everywhere. Small plastic fragments and pellets on beaches of Fernando de Noronha (Equatorial Western Atlantic). Mar Pollut Bull 58(8):1236–1238
Jickells TD, Buitenhuis E, Altieri K et al (2017) A reevaluation of the magnitude and impacts of anthropogenic atmospheric nitrogen inputs on the ocean. Glob Biogeochem Cycles 31(2):289–305

Jilani S (2015) Assessment of heavy metal pollution in Lyari river and adjoining coastal areas of Karachi. J Biodivers Environ Sci 6(2):208–214
Johnson A, Harrison M (2015) The increasing problem of nutrient runoff on the coast. Am Sci 1003:98
Jones PD (2006) Water quality and fisheries in the Mersey estuary, England: a historical perspective. Mar Pollut Bull 53(1–4):144–154
Juksu K, Liu YS, Zhao JL et al (2020) Emerging contaminants in aquatic environments and coastal waters affected by urban wastewater discharge in Thailand: an ecological risk perspective. Ecotoxicol Environ Saf 204:110952
Kadafa AA (2012) Oil exploration and spillage in the Niger Delta of Nigeria. Civil Environ Res 22(1):45–50
Kibria G, Hossain MM, Mallick D et al (2016) Trace/heavy metal pollution monitoring in estuary and coastal area of Bay of Bengal, Bangladesh and implicated impacts. Mar Pollut Bull 105(1):393–402
Kiessling T, Gutow L, Thiel M (2015) Marine litter as habitat and dispersal vector. In: Bergmann M, Gutow L, Klages M (eds) Marine anthropogenic litter. Springer, pp 141–181
Klangnurak W, Chunniyom S (2020) Screening for microplastics in marine fish of Thailand: the accumulation of microplastics in the gastrointestinal tract of different foraging preferences. Environ Sci Pollut Res 27:27161–27168. https://doi.org/10.1007/s11356-020-09147-8
Kumar VE, Ravikumar G, Jeyasanta KI (2018) Occurrence of microplastics in fishes from two landing sites in Tuticorin, South east coast of India. Mar Pollut Bull 135:889–894
Kuss J, Frazão HC, Schulz-Bull, DE et al (2021) The impact of typhoon "Mangkhut" on surface water nutrient and chlorophyll inventories of the South China Sea in September 2018. J Geophys Res: Biogeosci 126:e2021JG006546
Ladewig SM, Bao S, Chow AT (2015) Natural fibers: a missing link to chemical pollution dispersion in aquatic environments. Environ Sci Technol 49(21):12609–12610
Laffoley D, Baxter JM (2019) Ocean deoxygenation: everyone's problem: causes, impacts, consequences and solutions. IUCN, Gland, Switzerland
Lamsal LN, Martin RV, Padmanabhan A et al (2011) Application of satellite observations for timely updates to global anthropogenic NOx emission inventories. Geophys Res Lett 38:L05810
Law KL, Thompson RC (2014) Microplastics in the seas. Science 345(6193):144–145
Lebreton LC, Van Der Zwet J, Damsteeg JW et al (2017) River plastic emissions to the world's oceans. Nat Commun 8(1):1–10
Lee CW, Lim JH, Heng PL et al (2020) Influence of elevated river flow on hypoxia occurrence, nutrient concentration and microbial dynamics in a tropical estuary. Environ Monitor Assess 192(10):1–12
Lemley DA, Adams JB, Bornman TG et al (2019) Land-derived inorganic nutrient loading to coastal waters and potential implications for nearshore plankton dynamics. Cont Shelf Res 174:1–11
Li D, Gan J, Hui R et al (2020) Vortex and biogeochemical dynamics for the hypoxia formation within the coastal transition zone off the Pearl River Estuary. J Geophys Res 125(8) e2020JC016178. https://doi.org/10.1029/2020jc016178
Li WC, Tse HF, Fok L (2016) Plastic waste in the marine environment: a review of sources, occurrence and effects. Sci Total Environ 566–567:333–349
Liu R, Jiang W, Li F et al (2021) Occurrence, partition, and risk of seven heavy metals in sediments, seawater, and organisms from the eastern sea area of Shandong Peninsula, Yellow Sea. China. J Environ Manage 279:111771
Lozano RL, Mouat J (2009) Marine litter in the North-East Atlantic Region: assessment and priorities for response. KIMO International
Lu C, Tian H (2017) Global nitrogen and phosphorus fertilizer use for agriculture production in the past half century: shifted hot spots and nutrient imbalance. Earth Syst Sci Data 9:181–192
Lu Y, Yuan J, Lu X et al (2018) Major threats of pollution and climate change to global coastal ecosystems and enhanced management for sustainability. Environ Pollut 239:670–680

Ludwig HF (1976) Environmental guidelines for coastal zone management in Thailand: inner Gulf Zone. Environmental Impact Evaluation Division National Environmental Board, Office of the National Environment Board
Ma S (1981) Introduction to marine radionuclide pollution. Mar Sci Bull 2:78–88
Ma Y, Wei W, Xia HY et al (2009) History change and influence factor of nutrient in Lingdinyang Sea area of Zhujiang River Estuary. Acta Oceanol Sin 31(2):69–77
Maharaj R, Seocharan I, Qwabe B et al (2019) Decadal epidemiology of malaria in KwaZulu-Natal, a province in South Africa targeting elimination. Malar J 18:368
Maharana D, Saha M, Dar JY et al (2020) Assessment of micro and macroplastics along the west coast of India: abundance, distribution, polymer type and toxicity. Chemosphere 246:125708
Malone TC, Newton A (2020) The globalization of cultural eutrophication in the coastal ocean: causes and consequences. Front Mar Sci 7:30
Malone TC, Ambulker A, Bebianno MJ et al (2021) Changes in nutrient inputs to the marine environment. In the Second World Ocean Assessment, vol II. United Nations, New York
Martinez E, Maamaatuaiahutapu K, Taillandier V (2009) Floating marine debris surface drift: convergence and accumulation toward the South Pacific subtropical gyre. Mar Pollut Bull 58(9):1347–1355
Martyniuk CJ, Mehinto AC, Denslow ND (2020) Organochlorine pesticides: agrochemicals with potent endocrine-disrupting properties in fish. Mol Cell Endocrinol 507:110764
Mato Y, Isobe T, Takada H et al (2001) Plastic resin pellets as a transport medium for toxic chemicals in the marine environment. Environ Sci Technol 35(2):318–324
Mourão FV, de Sousa ACSR, da Luz Mendes RM et al (2020) Water quality and eutrophication in the Curuçá estuary in northern Brazil. Reg St Mar Sci 39
Murray F, Cowie PR (2011) Plastic contamination in the decapod crustacean *Nephrops norvegicus* (Linnaeus, 1758). Mar Pollut Bull 62(6):1207–1217
Nagaya Y, Nakamura K (1992) ^{239,240}Pu and ^{137}Cs in the East China and the Yellow Seas. J Oceanogr 48(1):23–35
Naidu SA (2019) Preliminary study and first evidence of presence of microplastics and colorants in green mussel, *Perna viridis* (Linnaeus, 1758), from southeast coast of India. Mar Pollut Bull 140:416–422
Nair A, Devassy VP, Dwivedi SN et al (1972) Tar ball pollution in Central west coast of India. Curr Sci 41:766–767
Napper IE, Thompson RC (2016) Release of synthetic microplastic plastic fibres from domestic washing machines: effects of fabric type and washing conditions. Mar Pollut Bull 112(1–2):39–45
Naser HA (2013) Assessment and management of heavy metal pollution in the marine environment of the Arabian Gulf: a review. Mar Pollut Bull 72(1):6–13
National Bureau of Statistics and Ministry of Ecology and Environment (ed) (2018) China Statistical Yearbook on Environment. China Statistical Press. https://www.yearbookchina.com/navibooklist-n3019041927-1.html
National Oceanic and Atmospheric Administration (NOAA) (2020) Advances in oil spill science in the decade since *Deepwater Horizon*. Office of Response and Restoration. https://blog.response.restoration.noaa.gov/8-advances-oil-spill-science-decade-deepwater-horizon
National Strategy Secretariat Office (NESDC) (2018) National Strategy 2018–2037 (Royal Thai Government Gazette). National Strategy Secretariat Office, Office of the National Economic and Social Development Council (NESDC), Bangkok
Naz S, Iqbal MF, Mahmood I et al (2021) Marine oil spill detection using synthetic aperture radar over Indian Ocean. Mar Pollut Bull 162:111921
Ng KL, Obbard JP (2006) Prevalence of microplastics in Singapore's coastal marine environment. Mar Pollut Bull 52(7):761–767
Nguyen TT, Némery J, Gratiot N et al (2019) Nutrient dynamics and eutrophication assessment in the tropical river system of Saigon-Dongnai (southern Vietnam). Sci Total Environ 653:370–383
Nwilo PC, Badejo OT (2006) Impacts and management of oil spill pollution along the Nigerian Coastal Areas. Administering Marine Spaces: International Issues 119

Oehlmann J, Schulte-Oehlmann U, Kloas W et al (2009) A critical analysis of the biological impacts of plasticizers on wildlife. Philos Trans R Soc B364(1526):2047–2062
Olaifa FE (2005) Hydrocarbon and heavy metal pollution of water and sediments of cross river and Akwa Ibom coastal waters, Nigeria. J Environ Syst 32(1, SI)27–36
ONREPP (2020) State of the Environmental 2019. Office of Natural Resources and Environmental Policy and Planning (ONREPP), Ministry of Natural Resources and Environment, Bangkok, Thailand
Pan Q, Zhu X, Wan L et al (2021) Operational forecasting for Sanchi oil spill. Appl Ocean Res 108
Parker CA, Oreilly JE (1991) Oxygen depletion in Long Island sound—a historical perspective. Estuaries 14(3):248–264
Pekey H (2006) Heavy metal pollution assessment in sediments of the Izmit Bay, Turkey. Environ Monitor Assess 123(1–3):219–231
Pérez-Gómez JA, García-Mendoza E, Olivos-Ortiz A et al (2020) Indicators of nutrient enrichment in coastal ecosystems of the northern Mexican Caribbean. Ecol Indic 118:106756
Piarulli S, Scapinello S, Comandini P et al (2019) Microplastic in wild populations of the omnivorous crab *Carcinus aestuarii*: a review and a regional-scale test of extraction methods, including microfibres. Environ Pollut 251:117–127
PlasticsEurope (2020) Plastics—the facts 2020: an analysis of European plastic production, demand and waste data
Pollution Control Department (PCD) (2000) Thailand State of Environment: the decade of 1990s. Pollution Control Department, Ministry of Natural Resources and Environment
Pollution Control Department (PCD) (2020) State of the Environment 2019. Office of Natural Resources and Environmental Policy and Planning, Ministry of Natural Resources and Environment
Porter SN, Schleyer MH (2017) Long-term dynamics of a high-latitude coral reef community at Sodwana Bay, South Africa. Coral Reefs 36:369–382
Porter SN, Humphries MS, Buah-Kwofie A et al (2018) Accumulation of organochlorine pesticides in reef organisms from marginal coral reefs in South Africa and links with coastal groundwater. Mar Pollut Bull 137:295–305
Prayitno HB, Afdal (2019) Spatial distributions of nutrients and chlorophyll-a: a possible occurrence of phosphorus as a eutrophication determinant of the Jakarta Bay. J Ilmu dan Teknologi Kelautan Tropis 11:1–12
Qian W, Gan J, Liu J et al (2018) Current status of emerging hypoxia in a eutrophic estuary: the lower reach of the Pearl River Estuary, China. Estuar Coast Shelf Sci 205:58–67
Ra K, Kim J.-K, Hong SH et al (2014) Assessment of pollution and ecological risk of heavy metals in the surface sediments of Ulsan Bay, Korea. Ocean Sci J 49(3):279–289
Rabalais NN, Cai WJ, Carstensen J et al (2014) Eutrophication-driven deoxygenation in the coastal ocean. Oceanography 27(1):172–183
Rabalais NN, Turner RE, Diaz RJ et al (2009) Global change and eutrophication of coastal waters. ICES J Mar Sci 66(7):1528–1537
Rahman MM, Noor NM, Saad S et al (2015) Coastal water quality of Tioman Island: effects of human activity and the distance from shoreline. Desalin Water Treat 1–5
Rajan A, Al Raisi A, Thankamony R et al (2020) Eutrophication sources, impacts and management: a case study from Abu Dhabi. Aquat Ecosyst Health 23(2):175–186
Ram A, Jaiswar JRM, Rokade MA et al (2014) Nutrients, hypoxia and mass fishkill events in Tapi Estuary, India. Estuar. Coast Shelf Sci 148:48–58
Ramseur JL (2017) Oil spills: background and governance. Congressional Research Service
Ranjani M, Veerasingam S, Venkatachalapathy R et al (2021) Assessment of potential ecological risk of microplastics in the coastal sediments of India: a meta-analysis. Mar Pollut Bull 163:111969
Rao KL (1979) India's water wealth. Orient Blackswan
Reineccius J, Appelt J-S, Hinrichs T et al (2020) Abundance and characteristics of microfibers detected in sediment trap material from the deep subtropical North Atlantic Ocean. Sci Tot Environ 738:140354. https://doi.org/10.1016/j.scitotenv.2020.140354

Reusch TBH, Dierking J, Andersson HC et al (2018) The Baltic Sea as a time machine for the future coastal ocean. Sci Adv 4(5):eaar8195

Ridgway J, Shimmield G (2002) Estuaries as repositories of historical contamination and their impact on shelf seas. Estuar Coast Shelf Sci 55(6):903–928

Rodríguez-Figueroa GM, Shumilin E, Sánchez-Rodríguez I (2009) Heavy metal pollution monitoring using the brown seaweed *Padina durvillaei* in the coastal zone of the Santa Rosalía mining region, Baja California Peninsula, Mexico. J Appl Phycol 21(1):19–26

Rui Z, Li Z, Fan Z et al (2013) Heavy metal pollution and assessment in the tidal flat sediments of Haizhou Bay, China. Mar Pollut Bull 74(1):403–412

Ryan PG (1987) The origin and fate of artefacts stranded on islands in the African sector of the Southern Ocean. Environ Conserv 14(4):341–346

Saher NU, Siddiqui AS (2016) Comparison of heavy metal contamination during the last decade along the coastal sediment of Pakistan: multiple pollution indices approach. Mar Pollut Bull 105(1):403–410

Sam K, Coulon F, Prpich G (2016) Working towards an integrated land contamination management framework for Nigeria. Sci Total Environ 571:916–925

Santos IR, Chen X, Lecher AL et al (2021) Submarine groundwater discharge impacts on coastal nutrient biogeochemistry. Nat Rev Earth Environ Environment 2(5):307–323

Saravi HN, Pourang N, Foong SY et al (2019) Eutrophication and trophic status using different indices: a study in the Iranian coastal waters of the Caspian Sea. Iranian J Fish Sci 18(3):531–546

Sathish N, Jeyasanta KI, Patterson J (2019) Abundance, characteristics and surface degradation features of microplastics in beach sediments of five coastal areas in Tamil Nadu, India. Mar Pollut Bull 142:112–118

Senarat S, Jiraungkoorskul W, Kettratad J (2017) Ovarian histology and reproductive health of short mackerel, *Rastrelliger brachysoma* (Bleeker, 1851), as threatened marine fish in Thailand. Songklanakarin J Sci Technol 39(2):225–235

Singh N, Mondal A, Bagri A et al (2021) Characteristics and spatial distribution of microplastics in the lower Ganga River water and sediment. Mar Pollut Bull 163:111960

Singh S, Aalbersberg WGL, Morrison RJ (2009) Nutrient pollution in Laucala Bay, Fiji Islands. Water Air Soil Poll 204(1–4):363–372

Sivasankar R, Ezhilarasan P, Sathish Kumar P et al (2018) Loricate ciliates as an indicator of eutrophication status in the estuarine and coastal waters. Mar Pollut Bull 129:207–211

Sotto LPA, Jacinto GS, Villanoy CL (2014) Spatiotemporal variability of hypoxia and eutrophication in Manila Bay, Philippines during the northeast and southwest monsoons. Mar Pollut Bull 85(2):446–454

Steffen W, Richardson K, Rockstrom J et al (2015) Planetary boundaries: guiding human development on a changing planet. Science 347(6223):11

Su J, Dai MH, He BY et al (2017) Tracing the origin of the oxygen-consuming organic matter in the hypoxic zone in a large eutrophic estuary: the lower reach of the Pearl River Estuary, China. Biogeosciences 14:4085–4099

Suneel V, Ciappa A, Vethamony P (2016) Backtrack modeling to locate the origin of tar balls depositing along the west coast of India. Sci Total Environ 569:31–39

Suneel V, Rao VT, Suresh G et al (2019) Oil pollution in the Eastern Arabian Sea from invisible sources: a multi-technique approach. Mar Pollut Bull 146:683–695

Syakti AD, Idris F, Koenawan CJ et al (2019) Biological pollution potential in the water of Bintan-Riau Islands Province, Indonesia: first appearance of harmful algal bloom species. Egypt J Aquat Res 45:117–122

Talsness CE, Andrade A, Kuriyama SN et al (2009) Components of plastic: experimental studies in animals and relevance for human health. Philos Trans R Soc 364:2079–2096

Tang S, Shang Z (2005) Investigating environmental radioactivity in the coastal zone of China. Nucl Saf 2:25–34

Tian R (2020) Factors controlling hypoxia occurrence in estuaries, Chester River, Chesapeake Bay. Water 12(7):1961

Toxics link (2014) Plastics and the environment assessing the impact of the complete ban on plastic carry bag. Central Pollution Control Board (CPCB New Delhi India)
Tubbs CW, McDonough CE (2017) Reproductive impacts of endocrine-disrupting chemicals on wildlife species: implications for conservation of endangered species. Annu Rev Anim Biosci 6:287–304
United Nations Environment Programme (UNEP) (2018) Single-Use Plastics: a roadmap for sustainability. Nairobi
UN Data (2020) Thailand, UN Data: A world of information, accessed 10 Jan 2021, http://data.un.org/en/iso/th.html
Valdes J, Vargas G, Sifeddine A et al (2005) Distribution and enrichment evaluation of heavy metals in Mejillones Bay (23 degrees S), Northern Chile: geochemical and statistical approach. Mar Pollut Bull 50(12):1558–1568
Vareda JP, Valente AJM, Durães L (2019) Assessment of heavy metal pollution from anthropogenic activities and remediation strategies: a review. J Environ Manage 246:101–118
Veerasingam S, Saha M, Suneel V et al (2017) Microplastic pollution: a serious threat to the marine ecosystem. Blue Waters: Newsletter on Marine Environment Protection 18:6–9
Wallace RB, Baumann H, Grear JS et al (2014) Coastal ocean acidification: the other eutrophication problem. Estuar Coast Shelf Sci 148:1–13
Wang G (2022) Why coastal zones become eutrophic. Front Sci 15(4):62–66
Wang SL, Xu XR, Sun YX et al (2013) Heavy metal pollution in coastal areas of South China: a review. Mar Pollut Bull 76:7–15
Wang Y, Liu D, Xiao W et al (2021) Coastal eutrophication in China: trend, sources, and ecological effects. Harmful Algae 107:102058
Wattayakorn G (2006) Environmental issues in the Gulf of Thailand. In: Wolanski E (ed) The environmental in Asia Pacific harbours. Springer, pp 249–259
Wijaya AR, Ouchi AK, Tanaka K et al (2013) Evaluation of heavy metal contents and Pb isotopic compositions in the Chao Phraya River sediments: implication for anthropogenic inputs from urbanized areas, Bangkok. J Geochem Explor 126–127:45–54
Winther JG, Dai M, Douvere F et al (2020) Integrated ocean management. World Resources Institute, Washington, DC. Available online at www.oceanpanel.org/blue-papers/integrated-ocean-management
Wisha UJ, Ondara K, Ilham (2018) The influence of nutrient (N and P) enrichment and ratios on phytoplankton abundance in Keunekai Waters, Weh Island, Indonesia. Makara J Sci 22:187–197
Wong J, Lee K, Tang K et al (2020) Microplastics in the freshwater and terrestrial environments: prevalence, fates, impacts and sustainable solutions. Sci Total Environ 719:137512
World Bank (2020) Thailand Population. https://datacommons.org/place/country/THA. Accessed 27 Dec 2020
Wright SL, Thompson RC, Galloway TS (2013) The physical impacts of microplastics on marine organisms: a review. Environ Pollut 178:483–492
Wu JW, Zhou KB, Dai MH (2012) Impacts of the Fukushima nuclear accident on the China Seas: evaluation based on anthropogenic radionuclide ^{137}Cs. Chin Sci Bull 58(4–5):552–558
Xiong S, Long H, Tang G et al (2015) The management in response to marine oil spill from ships in China: a systematic review. Mar Pollut Bull 96(1–2):7–17
Yamada M, Zheng J, Wang ZL (2006) Cs-137, Pu239+240 and Pu-240/Pu-239 atom ratios in the surface waters of the western North Pacific Ocean, eastern Indian Ocean and their adjacent seas. Sci Total Environ 366(1):242–252
Yan T, Zhou M, Zou J (2002) A national report on harmful algal blooms in China. Harmful Algal Blooms in the PICES Region of the North Pacific, vol. 21. F.J.R. “Max” Taylor and Vera L. Trainer, (eds.) PICES Scientific Report, No. 23. Sidney, British Columbia, Canada: North Pacific Marine Science Organization (PICES)
Yang X, Li S, Wei P et al (2015) Radionuclide pollution in the environment and its harmfulness. Front Sci 1(9):4–15

Ye ZP, Chen JY, Gao L et al (2020) Pb-210 dating to investigate the historical variations and identification of different sources of heavy metal pollution in sediments of the Pearl River Estuary. Southern China. Mar Pollut Bull 150:110670

Yin K, Lin Z, Ke Z (2004) Temporal and spatial distribution of dissolved oxygen in the Pearl River Estuary and adjacent coastal waters. Cont Shelf Res 24(16):1935–1948

Yin K, Harrison PJ (2008) Nitrogen over enrichment in subtropical Pearl River estuarine coastal waters: possible causes and consequences. Cont Shelf Res 28(12):1435–1442

Yoshikawa T, Tomizawa K, Okamoto Y et al (2017) Nutrients, light and phytoplankton production in the shallow, tropical coastal waters of Bandon Bay, Southern Thailand. Mar Ecol 38(6):e12475

Yu CQ, Huang X, Chen H et al (2019) Managing nitrogen to restore water quality in China. Nature 567:516–520

Zettler ER, Mincer TJ, Amaral-Zettler LA (2013) Life in the "Plastisphere": microbial communities on plastic marine debris. Environ Sci Technol 47(13):7137–7146

Zhang B, Tian H, Lu C et al (2017) Global manure nitrogen production and application in cropland during 1860–2014: A 5 arcmin gridded global dataset for Earth system modeling. Earth Syst Sci Data 9:667–678

Zhao Y, Liu J, Uthaipan K et al (2020) Dynamics of inorganic carbon and pH in a large subtropical continental shelf system: interaction between eutrophication, hypoxia, and ocean acidification. Limnol Oceanogr 65(6):1359–1379

Zhao Y, Uthaipan K, Lu Z et al (2021) Destruction and reinstatement of coastal hypoxia in the South China Sea off the Pearl River estuary. Biogeosciences 18:2755–2775

Zhuang W, Gao X (2014) Integrated assessment of heavy metal pollution in the surface sediments of the Laizhou Bay and the coastal waters of the Zhangzi Island, China: comparison among typical marine sediment quality indices. PLoS ONE 9(4):e94145

Chapter 10
Harmful Algae

Catharina Alves de Souza, Jorge I. Mardones, Aletta T. Yñiguez, Véronique Le Bihan, Patrice Guillotreau, Clemence M. I. Gatti, Mindy L. Richlen, Jacob Larsen, and Elisa Berdalet

Abstract This chapter provides the first overview of the disruptive impacts of HABs on the blue economy, with a particular focus on the application of science and technology in their management and mitigation. We present case studies of HABs in five different locations as examples of their effects on different sectors of the blue

---

C. Alves de Souza (✉)
Algal Resources Collection, Center for Marine Science, University of North Carolina Wilmington, Wilmington, NC, USA
e-mail: desouzac@uncw.edu

J. I. Mardones
Centro de Estudios de Algas Nocivas, Instituto de Fomento Pesquero, Puerto Montt, Chile
e-mail: jorge.mardones@ifop.cl

Centro FONDAP de Investigación en Dinámica de Ecosistemas Marinos de Altas Latitudes (IDEAL), Valdivia, Chile

CAICAI Foundation, Puerto Varas, Chile

A. T. Yñiguez
Marine Science Institute,
University of the Philippines Diliman, Quezon City, Philippines
e-mail: atyniguez@msi.upd.edu.ph

V. Le Bihan
Laboratory of Economics and Management Nantes-Atlantique (LEMNA), University of Nantes, Nantes, France
e-mail: veronique.lebihan@univ-nantes.fr

P. Guillotreau
MARBEC, University of Montpellier, CNRS, Ifremer, IRD, Sète, France
e-mail: patrice.guillotreau@ird.fr

LEMNA, University of Nantes, Nantes, France

C. M. I. Gatti
Laboratoire des Biotoxines Marines, Institut Louis Malardé, UMR 241 EIO (Ifremer, ILM, IRD, UPF), Papeete, Tahiti, French Polynesia
e-mail: cgatti@ilm.pf

M. L. Richlen
Woods Hole Oceanographic Institution, Woods Hole, MA, USA

E. R. Urban Jr. and V. Ittekkot (eds.), *Blue Economy*,
https://doi.org/10.1007/978-981-19-5065-0_10

economy. We also review the main technological advances in recent decades, and current needs for improved understanding of HAB dynamics, monitoring, and forecasting. An evident gap in dealing with HABs in the frame of the blue economy is the inequity in resources available for monitoring worldwide. While developed countries count on advanced (and even impressive) tools for monitoring and early warning (e.g., automated tools, oceanographic moored instruments, forecast models), efficient monitoring in most developing countries is still missing and, when performed, mainly focused on seafood products intended for export. Basic research on HABs in these countries is also frequently deficient, with modeling capabilities for early warning virtually non-existent. Considering that many (truly) sustainable blue economy activities are developed precisely in vulnerable areas with low economic power, the need for the development of affordable and sustainable technologies becomes critical, allowing for the efficient monitoring of HABs.

Keywords HAB · Fisheries · Aquaculture · Human health · Early warning systems · Observations · Monitoring · Impact on Blue Economy

10.1 Introduction

The blue economy concept is increasingly becoming the new paradigm for exploitation of the ocean and coastal areas. Based on the three dimensions of sustainable development (i.e., economic, social, and environmental), it "*seeks to promote economic growth, social inclusion, and the preservation or improvement of livelihoods while at the same time ensuring environmental sustainability of the oceans and coastal areas*" (World Bank and United Nations Department of Economic Social Affairs 2017). The blue economy idea encompasses many established ocean industries, such as fisheries, aquaculture, tourism, maritime transport, as well as emerging activities, including offshore renewable energy, seabed extractive activities, and marine biotechnology. It also comprises ecosystem attributes lacking tangible monetary value but with many socio-economical impacts on human activities such as biodiversity, natural coastal habitat, and carbon sequestration.

The term harmful algal bloom (HAB) applies to the proliferation of micro- or macroalgae perceived as harmful by humans (Kudela et al. 2017). Given that there is no consensus on what a harmful bloom is, the best definition would be a sufficiently high concentration of an algal species causing adverse effects, either from

e-mail: mrichlen@whoi.edu

J. Larsen
IOC Science and Communication Centre on Harmful Algae, Marine Biological Section, Department of Biology, University of Copenhagen, Copenhagen Ø, Denmark
e-mail: jacobl@bio.ku.dk

E. Berdalet
Institute of Marine Sciences (ICM-CSIC), Barcelona, Spain
e-mail: berdalet@icm.csic.es

microalgal-derived toxins (i.e., phycotoxins) or due to adverse effects caused by high algal biomass (Smayda 1997a). HABs are broadly considered as natural events known from historic times, with many examples reported between the 1200s and the 1700s (Anderson 1776; Vancouver 1798; Fukuyo et al. 2002), with a perceived global increase in their frequency and geographical distribution in recent decades linked to the effects of human activities such as eutrophication, ballast waters, coastal urbanization, ocean acidification and global warming (Glibert et al. 2010; Anderson et al. 2015; Griffith and Gobler 2020; Wells et al. 2020). While a recent analysis of the global Harmful Algal Event Database (HAEDAT) (http://haedat.iode.org) suggested that intensified monitoring efforts associated with increased aquaculture production are responsible for the perceived worldwide increase of HABs (Hallegraeff et al. 2021), there are documented increases in some HABs regionally (Anderson et al. 2021), frequently linked to different pressures, such as excessive nutrient loading (Bricker et al. 2008; Heisler et al. 2008; Davidson et al. 2014; Glibert 2017). Similarly, the analysis of long-term regional time series shows an increasing number of extraordinary HAB events associated with extreme weather conditions (Moore et al. 2009; McKibben et al. 2017; Griffith et al. 2019; Mardones et al. 2020a). A general consensus thus exists that HABs will continue to expand and/or intensify in at least some regions due to global climate change induced by both natural and anthropogenic forcing (Griffith and Gobler 2020; Trainer et al. 2020b).

Much scientific effort has been exerted in recent decades to estimate the socio-economic impact of HABs (e.g., Adams et al. 2018; Trainer 2020). Most of these studies have been mainly focused, however, on sectors of society for which the economic losses are relatively more evident, such as fisheries, aquaculture, and human health, with very few assessments so far accounting for possible interactions across these sectors and how they can affect and be affected by the well-being of coastal communities and/or ecosystem services (e.g., Willis et al. 2018; Moore et al. 2019, 2020). Although HABs are broadly identified as one of the major threats to the ocean and human health, as well as to the development of sustainable activities (Wenhai et al. 2019; Borja et al. 2020; Sandifer et al. 2021), up to now, no review has been entirely focused on HABs as deterring agents of the blue economy. This chapter aims to provide the first overview of the disruptive impact of HABs on sustainable development, with a particular focus on the application of science and technology advancements in the management and mitigation of HABs to facilitate the implementation of blue economy goals.

10.2 Impacts of HABs on the Blue Economy: Case Studies

The number of potentially harmful algal species is remarkable: about 200 species (from the several thousand described phytoplankton species) belonging to different phylogenetic groups and exhibiting diverse physiological and ecological characteristics (Lassus et al. 2016; Moestrup et al. 2021). The diversity of hazardous impacts they have on the social, economic, and environmental dimensions of the blue economy is also notable (Fig. 10.1). The successful management and mitigation of HAB threats and, in some cases, the efforts to prevent their occurrence are thus fundamental for achieving several indicators related to the Sustainable Development Goals (SDGs) of Agenda 2030 (related to the 2021–2030 United Nations Decade of Ocean Science For Sustainable Development) that are closely related to the blue economy (Lee et al. 2020), such as food security (SDG 2), human health (SDG 3), water supply (SDG 6), sustainability (SDG 11), climate change (SDG 13), and aquatic ecosystems (SDG 14).

Thirty-four major phycotoxin groups have been described to date (Hess 2018), with about 600 toxins produced by marine microalgae estimated so far (P. Hess, pers, comm.). Toxic microalgae have severe adverse effects, varying from fish kills and wildlife deaths to human syndromes caused by consumption of seafood contaminated with phycotoxins accumulated throughout the food web, as well as by direct contact with phycotoxins in the water or aerosol in the air (see Berdalet et al. 2016 for a summary of the main human syndromes caused by phycotoxins and their symptoms). Proliferations of non-toxic algal species can cause fish kills by mechanical damage of gills or the production of reactive oxygen species (Dorantes-Aranda et al. 2015). Blooms of non-toxic algae also can harm other aquatic organisms by decreasing sunlight penetration in the water column or causing anoxic conditions as a result of the degradation of high algal biomass (Smayda 1997b; GEOHAB 2001). HABs also impair ecosystem services by decreasing species diversity, resulting in reduced

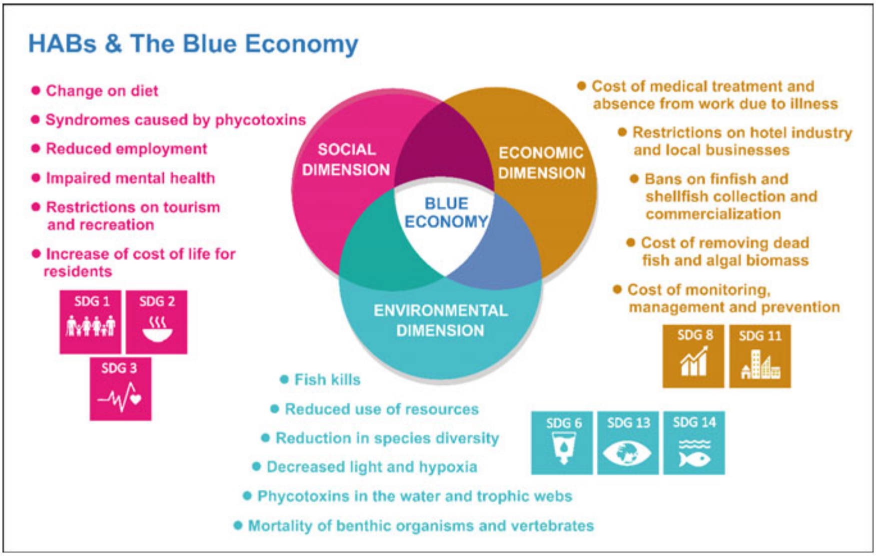


Fig. 10.1 Negative effects of harmful algal blooms (HABs) on the economic, social, and environmental dimensions of the blue economy and their interactions with some indicators of the Sustainable Development Goals (SDGs) of the United Nations Agenda 2030

operationally defined resource use efficiency (defined as the ratio of phytoplankton biomass to total phosphorus) in coastal plankton assemblages (Chai et al. 2020).

Adverse effects of HAB organisms have significant socio-cultural and economic consequences resulting from bans on finfish and shellfish collection and commercialization, restriction of tourism and leisure activities due to the closure of beaches, as well as additional costs related to medical treatment of the human syndromes caused by phycotoxins and increased monitoring activities (Sanseverino et al. 2016). The proliferation of certain macroalgae has emerged as a problem for tourism, maritime activities, aquaculture, and artisanal fisheries in the last two decades. Examples are the massive proliferations of green algae (*Ulva prolifera*) in the Yellow Sea (Liu and Zhou 2018), mainly related to coastal eutrophication, and the influx of *Sargassum* spp. in the Caribbean Sea and Atlantic coasts of Africa (Smetacek and Zingone 2013). In the open ocean, pelagic *Sargassum* species (*S. natans* and *S. fluitans*) serve as critical habitats for numerous species of fishes and invertebrates. However, since 2011, massive proliferations of *Sargassum* species have occurred in the Atlantic basin, from the Gulf of Guinea, throughout the North Equatorial Recirculation Region (NERR), including the Caribbean Sea and the Gulf of Mexico (Wang et al. 2019). These "brown tides" accumulate in bays, shallow waters and beaches, causing extensive near-shore "dead zones," wildlife mortalities, economic losses to coastal fisheries and tourism, and human health impacts associated with hydrogen sulfide toxicity (van Tussenbroek et al. 2017; Wang et al. 2019). Some uses of *Sargassum* biomass have been proposed, from fertilizers to paper, bioplastics, and cosmetics (Desrochers et al. 2020).

In addition to economic losses, fishery bans reduce employment opportunities and impair cultural identity as well as the physical and mental health of individuals (Ritzman et al. 2018). Adverse effects of HABs on desalination plants may also potentially have severe socio-economic impacts, particularly in many arid and island countries, where desalination of seawater makes a significant contribution to the drinking water supply (Anderson et al. 2017).

The nature of blue economy activities and the magnitude of HAB impacts have one thing in common: they depend strongly on the local environmental and socio-cultural context. As a consequence, the negative effects of HABs on the blue economy must be assessed locally (Fig. 10.2), as they depend on the interplay of several factors defined on a regional scale, such as the characteristics of the individual HAB species, oceanographic features, economic activities, and socio-cultural practices. The next sections present some case studies to illustrate the effects of HABs on the blue economy.

10.2.1 Chilean Fjords

Shellfish and finfish farming are the main aquaculture activities in Chile traditionally threatened by HABs (Díaz et al. 2019). In the case of shellfish aquaculture, total mussel production reached ~ 370,000 t in 2018, equivalent to USD $7,000 M in

Fig. 10.2 Examples of local blue economy activities affected by harmful algal blooms (HABs): **a** Bloom and **b** salmon mortality caused by *Heterosigma akashiwo* in a fjord in Southern Chile, **c** Bloom of *Ostreopsis* covering benthic organisms in the Mediterranean Sea, **d** Fisherman communities affected by HABs in the French Polynesia and **e** Philippines (Photo credits **a** Fundación Huinay, **b** Álvaro Vidal, **c** Elisa Berdalet and Magda Vila, **d** Clémence Gatti, **e** Rodrigo Eco)

exports (GLOBEFISH 2018). Thus, phycotoxins that are potentially bioaccumulated in the seafood not only pose human health risks, but also result in important economic losses for the industry due to commercialization bans. Patagonian fjords are a hotspot for salmon aquaculture, positioning Chile as the world's second-largest producer of farmed salmon, after Norway (Bjørndal 2002), a condition that highlights the need to develop strategies for sustainable aquaculture improvement and management. This productive activity has greatly suffered from the effects of recurrent and intense HAB events in Chilean fjords in recent decades, with annual losses running into millions of dollars (Mardones et al. 2020b).

Four known and monitored human health syndromes related to phycotoxin ingestion are found in Chile: diarrhetic shellfish poisoning (DSP), amnesic shellfish poisoning (ASP), azaspiracid shellfish poisoning (AZP), and paralytic shellfish poisoning (PSP) (Mardones et al. 2020b). The latter, caused by blooms of the dinoflagellate *Alexandrium catenella*, has caused 35 fatal cases and about three hundred human intoxications since its first detection in 1972 in southern Chilean Patagonia. The length of shellfish farm closures due to PSP toxins has varied with the intensity of HAB outbreaks. These events have negatively affected the value of these aquaculture products in several ways (Mardones et al. 2020b): (1) reduced demand by consumers due to fears about seafood safety, (2) delay of the harvest to a point where shellfish are larger than their optimal marketable size, (3) inability to supply during peak demand periods, and (4) effects on the ability to use gear and space to begin growing new cohorts.

Although HABs have been recorded in the Chilean fjords since the 1970s, an apparent increase in the intensity and distribution of some HAB species has been observed in the last decade. Eutrophication resulting from aquaculture has been proposed as the principal causative factor of this increase. Intensive aquaculture activities (i.e., salmon cage-farming) may produce an inevitable rise in nutrient loading (and changes in nutrient ratios) through the addition of food and salmon excretions. The overall effect of high nutrient loads can be made worse by global warming, which has triggered a dramatic decrease in precipitation and streamflow in Southern Chile during the last decade (Garreaud 2018; Aguayo et al. 2019). Drastic and sustained reductions in precipitation and river discharges alter the nutrient stoichiometry by reducing surface silica loading into the fjords, which have been proposed as a cause of increased HAB species occurrence in Chilean fjords (León-Muñoz et al. 2018; Aguayo et al. 2019; Navedo and Vargas-Chacoff 2021). Of significant concern for the scientific community is the fact that several of the recent HAB events occurred in sounds and fjords with longer retention times (121–200 days), where nutrients and phycotoxins can persist for more extended periods (Mardones et al. 2020b).

Exceptional conditions in the coast and open ocean produced by the positive phase of the Southern Annular Mode (SAM) and an extreme El Niño event coincided with the 2016 "Godzilla-Red tide events" that included several successive HAB events, resulting in the most extensive fish farm mortality ever recorded worldwide and creating a vast socio-environmental impact in the region by affecting artisanal fisheries (blue mussels, oysters, clams) (Trainer et al. 2020a, b). The first HAB caused by the dictyochophyte *Pseudochattonella verruculosa* killed farmed salmon, with losses for the Chilean salmon industry amounting to USD $800 M (Mardones et al. 2020a, b, c). Subsequently, an *A. catenella* bloom affected 600 km of benthic artisanal fisheries due to a 4-month closure of 200 shellfish farms (~15% reduction in harvest compared to 2015) (Díaz et al. 2019). Two years later, in summer 2018, a new outbreak of *A. catenella* producing an intense PSP event occurred, which resulted in world record PSP shellfish toxicity (143,130 μg STXeq. 100 g^{-1} shellfish) (Mardones et al. 2020b). Moreover, the end of the La Niña event and a positive phase of SAM during summer-fall 2021 produced the second driest season in the last 70 years, which coincided with a massive *Heterosigma akashiwo* bloom (>70,000 cells mL^{-1}) in the Comau fjord (Fig. 10.2a–b) that caused the mortality of more than 8,000 t of salmon (Flores-Leñero et al. 2022).

Climatic anomalies have also triggered "super blooms" of opportunistic toxic dinoflagellates of the genera *Karenia* and *Karlodinium* in outer waters off Patagonia. Unlike known phycotoxins (e.g., PSP, ASP, and DSP toxins), the potent cytotoxins produced by these dinoflagellates affect the gill and other sensitive tissues of marine organisms (Mardones et al. 2020c) and can kill a wide variety of marine organisms, ranging from marine mammals (i.e., baleen whales) to small invertebrates (Häussermann et al. 2017; Mardones et al. 2020c). Blooms of cytotoxic HAB species may produce severe effects on the recruitment and growth of juvenile and adult wild species, negatively affecting artisanal fisheries. No studies have measured the impact of these types of HABs on non-cultured marine wildlife.

10.2.2 *Ostreopsis* spp. in the Mediterranean Sea

Since the end of the 1990s, blooms of benthic dinoflagellates of the genus *Ostreopsis* have become recurrent in several Mediterranean beaches (Fig. 10.2c). Initially reported in tropical areas, *Ostreopsis* species have expanded their biogeographic distribution to temperate latitudes (recently reviewed by Tester et al. 2020). Blooms of these benthic dinoflagellates threaten human health and the environment. In the context of the blue economy, these blooms have direct costs related to human health assistance and can cause economic losses related to tourism activities.

Ostreopsis blooms have been associated with mild acute respiratory illness, and skin and mucosa irritation in humans (Pavaux et al. 2020). Palytoxin-analogues produced by this dinoflagellate have been proposed as the causative agent of these problems, although their direct implication is yet to be demonstrated (Tubaro et al. 2011). Previously, in the tropics, *Ostreopsis* toxins had been associated with rare, but dramatic, seafood poisonings. In the Mediterranean, respiratory irritations occurred massively in Genoa (Italy) when 200 people were reported to the hospital with symptoms of rhinorrhea, cough, wheezing, and fever (Gallitelli et al. 2005; Brescianini et al. 2006). Epidemiology studies (Vila et al. 2016; Berdalet et al. 2022), and the experience of researchers during sampling (e.g., Pfannkuchen et al. 2012), indicate that direct exposure to high *Ostreopsis* cell concentrations in seawater or aerosols during blooms of these dinoflagellates can result in mild acute symptoms. The effects of chronic exposure to toxic *Ostreopsis* blooms are still unknown. The potential health risks posed by blooms of *Ostreopsis* species stimulated the regular monitoring of these events in some areas, leading to occasional beach closures (Lemée et al. 2012; Funari et al. 2015). Some blooms have also been linked to massive mortalities of benthic fauna (Sansoni et al. 2003; Vila et al. 2016).

The available evidence indicates that people experienced *Ostreopsis*-related symptoms mainly during a particular stage of the bloom period, suggesting that toxicity is related to specific physiological conditions of the blooming algal cells (Vila et al. 2016; Berdalet et al. 2022). Based on that, alert thresholds of *Ostreopsis* abundances corresponding to high risk of impacts on human health have been established (5×10^5 cells g^{-1} of FW macroalgae and 3×10^4 cells L^{-1}, in the benthos and plankton, respectively) and used by French and Italian authorities. These numbers should be combined with other environmental conditions, such as wind direction and seawater temperature, as discussed by Funari et al. (2015) and Giussani et al. (2017) and with health symptoms (Berdalet et al. 2022) in Catalonia, Spain. However, symptoms were also noticed with cell concentrations below these alert values, and thus, more studies are required on this aspect.

Although the implementation of beach monitoring and surveillance systems in summer constitutes an effective strategy to prevent *Ostreopsis* impacts on human health, it requires optimal coordination between health and environmental authorities and researchers. In France, the National *Ostreopsis* Surveillance Network established in 2006 aims to prevent human health problems by detecting and responding to *Ostreopsis* bloom events in recreational waters along the French Mediterranean coast

(Kermarec et al. 2008). This network operates on an active basis during the blooming period from early summer to early fall (June to September) in coordination with other environmental and health surveillance agencies to ensure appropriate recommendations regarding control and management. It encompasses a health surveillance system with clinical toxicologists and experts on natural toxins and environmental *Ostreopsis* monitoring. Since beaches on the French coasts are strictly supervised and closed during *Ostreopsis* blooms, poisoning of the general public is less frequent nowadays. This prevents collapsing hospital or primary health care emergency facilities from massive admittances, as observed in the past in Italy and Algeria.

In order to ascertain the socio-economic impacts that a potential increasing frequency and biogeographic expansion of *Ostreopsis* blooms might cause in the future, the first step consists of knowing the behavior of tourists and residents concerning their recreational use of the affected beaches and localities. A recent survey conducted in Monaco (Berdalet et al. 2022) by the University of Nantes, within the European funded project CoCliME ("Co-development of Climate Services for adaptation to changing Marine Ecosystems", part of the ERANET for Climate Services; https://www.coclime.eu) and the RAMOGE Agreement (among France, Monaco, and Italy; https://ramoge.org), indicated that, the occurrence of *Ostreopsis* blooms and their effects seem to be still poorly known by the general public. In the hypothetical scenarios of future increases of *Ostreopsis* blooms, many people would stop or decrease beach use, resulting in impairment of a significant portion of coastal recreational and tourist activities. However, a substantial part of the tourist and resident populations would continue to go to the beaches and thus could be exposed to health risks, resulting in increased health care costs. Efficient communication with the public thus becomes essential, with warning signs informing beach users about the presence of *Ostreopsis*. However, the messages should not be alarmistic and should avoid unnecessary panic. Overall, it is presently challenging to precisely ascertain the economic impacts that a potential increasing frequency and biogeographic expansion of *Ostreopsis* blooms might cause in the future.

An open question is why *Ostreopsis* species seem to have expanded their biogeographic distribution from tropical to temperate waters and why the species are increasingly blooming. The answer seems to be partly found in global warming and species tolerance to highly urbanized and deteriorated coastal habitats, characterized by turf algal formations and eutrophic conditions (Meroni et al. 2018). However, the assessment of this issue requires further clarification on the species resolution in this genus. While the recent detection of *Ostreopsis* cf. *siamensis* in the Bay of Biscay in the Northeast Atlantic Ocean (Drouet et al. 2021) seems to confirm this apparent expansion from tropical to temperate areas, a recent taxonomic study found that *O. siamensis* is a tropical species while *O.* cf. *siamensis* is a separate and almost certainly undescribed species (Nguyen-Ngoc et al. 2021).

10.2.3 Northeast Atlantic Ocean

European Union countries face regular occurrences of several toxic microalgal species in the northeast Atlantic Ocean region. More than any other industry, including tourism, shellfish farming is by far the most affected one (Guillotreau et al. 2021). The European Union food law imposes specific obligations resulting in trade bans and area closures when acceptable biotoxin concentrations are exceeded (O'Mahony 2018). The shutdowns of shellfish farming and harvesting can last for a few days up to several weeks and occasionally even months (e.g., Rodríguez et al. 2011; O'Mahony 2018; Chenouf et al. 2020; Martino et al. 2020; Theodorou et al. 2020).

The French Institute of Marine Research (Ifremer), in close collaboration with the French government and other stakeholders, has implemented the French monitoring program for phycotoxins in marine organisms (REPHYTOX), a rapid alert system that transmits the results of toxic phytoplankton and phycotoxins in shellfish weekly. Special emphasis is given to the dinoflagellates *Dinophysis acuminata* and *A. catenella*, and the diatoms *Pseudo-nitzschia* spp., the toxin producers associated with the DSP, ASP, and PSP syndromes in this area, respectively. In France, toxic outbreaks are more prevalent in the northern Atlantic coastline, when compared to the south. *Dinophysis* outbreaks in the northern region are recurrent and cyclical, while only one toxic event caused by *Pseudo-nitzschia* has been observed in 40 years all along the Atlantic French coastline. More recently, in the last decade, blooms of the dinoflagellate *Lepidodinium chlorophorum* caused significant events of shellfish mortality every summer (July–August), particularly in the Pen-Bé area. The exposure to risk for shellfish farmers and harvesters can also be recurrent in other countries on the northeast Atlantic coast. Alert systems have been implemented through the ASIMUTH project ("Applied Simulations and Integrated Modelling for the Understanding of Harmful Algal Blooms") (Maguire et al. 2016) and applied to alert shellfish harvesters in Portugal, where blooms of *Pseudo-nitzschia* and dinoflagellates of the genera *Dinophysis*, *Gymnodinium*, and recently *Karenia*, are more frequently observed. From July 2013 to March 2014, this system performed 85% of correct one-week forecasts, with accuracy depending on specific areas (i.e., coastal, estuaries, and lagoons (Silva et al. 2016).

The economic impact of HABs due to the closures of mussel farms was studied in Galicia (Spain) between 1990 and 2008, with an incidence rate (i.e., the proportion of closing days per annum) varying between 2 and 47% (Rodríguez et al. 2011). This survey demonstrated that administrative closures can be anticipated by farmers to mitigate the economic losses by harvesting prior to the shutdown and marketing mussels when the measure is repealed. The economic impact of these HAB events is therefore limited, except when the incident rate is exceptionally high, as observed in 2005, or if the event takes place during the last months of the year corresponding to the peak of demand (Rodríguez et al. 2011). A similar trend was observed in Greece, where public authorities may prohibit harvesting mussels for periods that may vary from one to six months during HAB events, with profit reduction ranging between 4 and 38% when HAB-related events last between 6 weeks and half a year, respectively (Konstantinou et al. 2012). Additional costs are incurred by farmers when the closure takes place in August (e.g., storage, meshbags, loss of seeds), but the usual spring occurrence of HAB events can be anticipated by mussel producers and cause limited impacts. When closures last less than 30 days, which represents the great majority of cases, there is no economic loss at all (Konstantinou et al. 2012). Alternatively, it has been proposed that the timing of trade restrictions during peak market seasons matters more than the length of the ban. For instance, a 3-week closure in the peak season in Greece (May to August) was observed to have greater consequences than a trade ban occurring in springtime for periods of more than six weeks (Theodorou et al. 2020).

HABs may represent a loss of turnover in the short term during the closure period. Although the losses are not irretrievable, they induce short-term cash flow problems related to the shift in the timing of sales. For instance, the economic consequences of trade bans and closures in France proved to be reasonably limited. Between 2004 and 2018, in the regions of south Britanny and Pays de la Loire, 432 prefectural bylaws of closures were promulgated, with an average length of 30 days and more than two-thirds concerning DSP outbreaks (Guillotreau et al. 2021). Because 82% of trade bans concerned the spring months between April and June, they were anticipated by shellfish farmers. For some producers, the management of HAB events is done by purchasing mussels not contaminated with phycotoxins from stocks harvested by other professionals. Other practices include the management of human resources, such as the assignment of staff to maintenance tasks during blooms or by requesting employees to take their annual leave during the blooms. These strategies allow producers to avoid overall economic losses. Nonetheless, the impact can be higher if HAB frequency and intensity increase over time, as in the case of Scottish shellfish farmers. An economic study based on a Cobb–Douglas function found that a 1% change in diarrhetic shellfish toxins would reduce sales by 0.66% (Martino et al. 2020). The annual loss from *Dinophysis*-generated biotoxins was estimated at 15% of total output (equivalent to GBP 1.37 M per year in 2015).

10.2.4 Ciguatera in the Caribbean and French Polynesia

Ciguatera Poisoning (CP) is caused by the consumption of marine fish and invertebrates contaminated with a suite of compounds, collectively known as ciguatoxins, produced by benthic dinoflagellates of the genera *Gambierdiscus* and *Fukuyoa* (Chinain et al. 2020). Ciguatoxins accumulate in coral reef food webs after herbivorous fish inadvertently ingest cells of these toxic dinoflagellates growing attached to their food source (e.g., macroalgae) or when invertebrates filter cells free-floating in the water column (Anderson and Lobel 1987). Poisoning includes various gastrointestinal, cardiovascular, and neurological symptoms, the latter of which may last from days to years and can be highly debilitating, complicated by the absence of a permanent cure (Friedman et al. 2017). While restricted to tropical and subtropical areas, CP is currently considered the most prevalent phycotoxin syndrome worldwide, estimated to affect between 10,000 and 500,000 people each year, although the real number of cases is not known, mainly due to misdiagnosis and underreporting (Friedman et al. 2017).

The Pacific and the Greater Caribbean are endemic regions, hosting the highest incidence rates of CP cases (Chinain et al. 2020). This status results from the combination of favorable habitat and growth conditions for ciguatera-causative dinoflagellates and the high dependence of local populations on marine food resources. CP represents 96% of seafood poisonings in French Polynesia, responsible for ~ 150 to over 700 cases every year since 2000 (Gatti et al. 2008; Chinain et al. 2020). CP distribution in French Polynesia shows no significant evolution over time, but variability is apparent between the archipelagoes or islands from year to year. In the Greater Caribbean region, CP has been reported from most islands, with the highest incidence rates reported in Montserrat, Antigua and Barbuda and the British Virgin Islands (from 1996 to 2006, as reported by Tester et al. 2010), and lower prevalence occurring along continental margins (e.g., Colombia, Central America). Over the past decade, the geographic extent of CP appears to be expanding to some adjacent areas (e.g., northern Gulf of Mexico), while some endemic locations such as St. Thomas exhibited declines in incidence (Radke et al. 2013).

The full scope of CP impact on coastal communities is challenging to understand and quantify due to the high degree of underreporting and lack of tools and approaches needed to diagnose and treat this illness accurately. Indeed, only 10–20% of CP cases are estimated to be reported (Friedman et al. 2008), which challenges the assessment of the true evolution of this illness in the Pacific and the Caribbean Sea. In both regions, CP is considered an almost inevitable risk associated with local fish consumption, and many affected by this poisoning do not seek medical help unless symptoms are critical, with only 0.1% or fewer intoxicated persons consulting a physician (Chinain et al. 2020 and references therein).

Although still a recent concept in both French Polynesia and the Caribbean, the blue economy is a substantial part of the economic and social web of their communities, as fishing and marine ecotourism are key sectors, with strong cultural and historical roots (Fig. 10.2d). For example, a survey conducted on Moorea island in French Polynesia found that over 50% of households interviewed consumed fish six to seven times each week, with 76% of them having at least one member of the household actively involved in local reef fishing activity (Morin et al. 2016). This heavy dependence on fish resources for subsistence explains why these communities are at such high risk of exposure to ciguatoxins, with fishermen being the first to suffer from the economic consequences of CP as the sale of toxic fish may decrease their income and export opportunities. In addition to the risk of losing customer confidence, fishermen are forced to avoid certain fish species and fishing areas known to be risky, leading to additional time and expenses (e.g., additional fuel cost) associated with accessing safer fishing areas.

The financial losses caused by decreased harvests associated with these bans were estimated to be USD $1.1 M per year in French Polynesia and USD $10 M in the Caribbean (Chinain et al. 2020). In French Polynesia, hotels and restaurants are reluctant to serve reef fish to their customers, preferring to offer offshore products. Local restaurants in the U.S. Virgin Islands frequently choose to import fish rather than serving those caught locally due to the threat of lawsuits and risk of bad publicity (Olsen 1988), which may tarnish the destination image and desirability for a particular location. Some professionals also turn away from at-risk species to avoid insurance costs to cover potential ciguatera-caused damages (Anderson et al. 2000). This shift from locally caught to imported fish increases costs to restaurants and hotels, resulting in the loss of revenue, and also represents a loss of an important source of income for all businesses in the seafood supply chain. At the global level, CP may discourage hotelkeepers, restaurants, and consumers from purchasing marine products generally due to the perception of risk (Gillet 2016).

Beyond these economic consequences, CP may also have social and cultural impacts on coastal communities, including lifestyle, local food trade, dietary shifts, and loss of fishing as an occupation, as the local population may abandon the consumption of locally caught seafood in favor of imported and processed food (Rongo and van Woesik 2011). In the long term, this situation may contribute to the increased occurrence of non-communicable diseases such as obesity, diabetes, and arterial hypertension, already prevalent in the Pacific region. In communities to which local fishing is culturally important, CP may also lead to a progressive loss of transmission of knowledge related to lagoon fishing techniques, and more globally, loss of local ecological knowledge to younger generations (Rongo and van Woesik 2012). Finally, lawsuits brought by fish consumers who have suffered CP can affect fishers, restaurants, hotels, and other markets that comprise the supply chain/dealers. Such an example of litigation has already been described after a massive poisoning in Australia in 1997 (Ng and Gregory 2000).

The effects of CP on human health and well-being pose a severe limitation on the development of blue economy activities in the Caribbean Sea and the Pacific, which are largely based on food supply from the sea and tourism revenue. However, it is critical to understand the factors favoring CP. Although this syndrome has been known in these areas for centuries, habitat destruction caused by both natural (e.g., tsunamis, cyclones) and anthropogenic sources (excessive building and ports)—as well as coral bleaching from ocean acidification and ocean heatwaves—seems to be fostering ecosystem disturbances favoring macroalgal communities where benthic *Gambierdiscus* thrive, therefore increasing the risk of CP. In addition, global warming also seems to be involved in the increase of biogeographical distribution of these species and their toxins (Tester et al. 2020).

10.2.5 PSP Outbreaks and Fish Kills in the Philippines

Aquaculture production in Asia constitutes 89% of global production and has outpaced capture fisheries. Within this region, the Philippines was ranked 11th in the world in 2018 in terms of aquaculture production of fish, crustaceans, and mollusks (BFAR 2019). Aquaculture now contributes 53% of the total fish harvest in this country. As the Philippines' population keeps growing, there is a push to increase aquaculture of marine species (mariculture) activities across its many coastlines as a source of food and livelihood.

Beyond mariculture, the ocean-based blue economy significantly contributes to the country's economy (Fig. 10.2e) and has the potential to contribute more, despite historically being relatively marginalized (Azanza 2017). Embayments are the prime sites for shellfish mariculture, as well as wild harvest. Mussels and oysters are cultured through different methods, such as stakes and long lines. These cultures tend to be based on small farms set up by one to several fisherfolks (e.g., through cooperatives). Gleaners in surrounding communities also harvest wild shellfish. Unfortunately, many of these embayments are affected by PSP outbreaks due mainly to the dinoflagellate *Pyrodinium bahamense*, while a few are caused by *Alexandrium minutum* or *Alexandrium tamiyavanichii* (Azanza and Benico 2013; Yñiguez et al. 2021). These embayments are typically characterized by high residence times at their head, with river run-off contributing to stratified conditions during rainy periods and increasing nutrient loading (Villanoy et al. 2006; Yñiguez et al. 2018). These conditions allow for the retention of dinoflagellate cysts within the bays, which contributes to recurrent HAB events when cysts germinate and cell densities increase, depending on the environmental conditions (Villanoy et al. 2006; Azanza et al. 2018; Yñiguez et al. 2018).

The Philippines currently has the highest worldwide number of PSP outbreaks, with 2,555 poisonings recorded between 1985 and 2018 (Azanza and Taylor 2001; Arcamo et al. 2014), with 165 of these ending in deaths. Apart from health impacts, these HAB events have had substantial socio-economic implications. Shellfish farmers and gleaners, who are already the poorest in the country, are the most affected through the loss of their food source and livelihood due to shellfish harvest bans, with their annual net income decrease due to PSP outbreaks estimated to be on average 33% and 55%, respectively (Azanza 2017). A more negligible impact (9% decline) is also felt by other industries, such as restaurants, that use shellfish as ingredients. Shrimp and krill are also included in harvest bans and would have further socio-economic impacts that have not been analyzed. In some sites, these shellfish harvest bans have extended for more than one year, thus amplifying the impacts of HABs.

Although PSP is by far the dominant HAB-related concern in the country, other toxic algal species have been observed in Philippine waters. The diatom *Nitzschia navis-varingica* (a domoic acid producer) has been reported in different areas (Kotaki et al. 2005, 2006), and high levels of domoic acid have been observed in the bivalve *Spondylus*, which are commonly consumed by people (Takata et al. 2009). During a bloom of *Dinophysis caudata* and *Dinophysis miles* in the central Philippines, high levels of diarrhetic shellfish toxins were measured in the mussel *Perna viridis* (Marasigan et al. 2001). So far, only one confirmed ASP case had been documented, and no DSP cases. The toxins for these syndromes are tested much less frequently compared to paralytic toxins in the national monitoring program. Only four CP events due to the consumption of reef fishes contaminated with ciguatera toxins have been confirmed, though there are several other suspected cases (Yñiguez et al. 2021). Thus, the occurrence and impacts of other toxic microalgae in the Philippines strongly need to be further assessed.

The expansion of mariculture parks is being promoted in the country as a means to enhance production, especially from fish farms. These fish-farming areas again tend to be located in embayments or channels, where they can overlap with other coastal habitats and uses such as capture fisheries and tourism. These sites can be vulnerable to HABs in addition to anthropogenic impacts (David et al. 2009). Fish kill events in the Philippines occur sporadically in some areas and almost yearly in others (Yñiguez et al. 2021). A variety of algal species have been associated with these fish kill events. The first major fish kill occurred in 2002 due to a bloom of *Prorocentrum cordatum* in Bolinao-Anda, Pangasinan, at the northwestern portion of the country (Azanza et al. 2005; San Diego-McGlone et al. 2008). This led to the death of thousands of kilos of milkfish in fish pens and cages, and approximately USD $9 M in losses. As with most fish kill estimates in the country, this monetary figure does not include impacts on livelihoods revolving around the industry and is likely a conservative estimate of the actual impact. Other HAB species associated with fish kills in this same area are diatoms of the genera *Skeletonema* and *Rhizosolenia*, the raphidophyte *Chatonella subsalsa*, and the dinoflagellate *Takayama* sp.

HABs compromise the existing and potential blue economy in the Philippines. Although these events do not appear to be increasing in frequency and duration, more sites are being affected, and new harmful species are detected (Yñiguez et al. 2021). The occurrence of toxic HAB species in shellfish farms around the country, along with other considerations (e.g., water quality, sanitation, and management), limit the potential capacity of the country to supply its burgeoning population and also export these fisheries products. HABs leading to fish kills increase the uncertainties in fish farming and again restrict potential production. These aspects affect the sustainability of the different mariculture and fisheries activities and tend to have negative and inequitable impacts among the stakeholders.

10.3 Role of Science and Technology in Facing HAB-Related Challenges

The vast diversity of harmful algal species and phycotoxins, combined with the unpredictable nature of HABs due to complex biotic and abiotic ecological drivers, makes the complete prevention of these events an unrealistic goal. While some preventive measures, such as the limitation of anthropogenic nutrient input in water bodies (Glibert 2020) and international ballast water regulation (Anderson 2014), may contribute to alleviating the problem in some areas, our ability to manage and mitigate the adverse effects of HABs still depends largely on the early detection of the causative species and their toxins (Kudela et al. 2015). The case studies described in the previous sections gave tangible examples of how both basic and applied research and monitoring have improved our understanding of HAB dynamics and risks, whereas Doucette et al. (2018) and Stauffer et al. (2019) provided comprehensive reviews of the methods and technological tools currently available for the monitoring of HABs. We will next discuss some of the main technical challenges faced by scientific and local community stakeholders in dealing with harmful algae from a sustainable perspective.

10.3.1 Increasing Diversity of HAB Species

The importance of correct species identification in HAB monitoring has already been addressed by Pitcher (2012), and this issue has been further accentuated by the discovery of several cryptic species, strongly suggesting that some species may have been misidentified in the past. Proper identification at the species level is mandatory, as several genera include complexes of both toxic and non-toxic species, as well as species with populations from different geographic areas with different toxin profiles. Some representative examples of such HAB species complexes are found in the "*Alexandrium tamarense*-complex" (John et al. 2014), *Prymnesium parvum* (Binzer et al. 2019), and *Pseudo-nitzchia* spp. (Lundholm et al. 2003; Chen et al. 2021), in which the species appear to be genetically distinct, but distinguished by only minor and sometimes subtle ultrastructural details. To further complicate species' identifications, several nanoplanktonic HAB species (of difficult detection in routine monitoring analysis) have been described during the last few decades, including species of the dinoflagellate genera *Azadinium* (Tillmann et al. 2009) and *Karlodinium* (Daugbjerg et al. 2000).

Experience from training courses run by UNESCO's Intergovernmental Oceanographic Commission (IOC) for the identification of HAB species from 1995 to 2020 shows that species identification in most monitoring programs is carried out on preserved material. It is estimated that only one-third (36%) of the species included in the IOC Taxonomic Reference List (Moestrup et al. 2021) can be reliably identified in preserved samples using light microscopy (LM). Species that cannot be identified using LM (Fig. 10.3) present a challenge for monitoring personnel, who do not generally have time or facilities to examine species in scanning or transmission electron microscopy (SEM/TEM) or carry out molecular analyses. Such species include:

- Naked or nano-flagellates, many of which cannot be identified correctly in preserved samples (in particular if fixed with Lugol's solution), for example, raphidophytes and dictyochophytes (Eckford-Soper and Daugbjerg 2016);
- Nanoplanktonic HAB species where morphological differences, albeit distinct, between species cannot be observed in LM due to their small size;
- Benthic dinoflagellates, mainly belonging to the genera *Gambierdiscus*, *Fukuyoa* and *Ostreopsis*, for which molecular analyses are needed for proper identification of most species (Berdalet et al. 2017);
- Diatoms of the genus *Pseudo-nitzschia*, where most diagnostic morphological differences between species can be observed only by SEM/TEM.

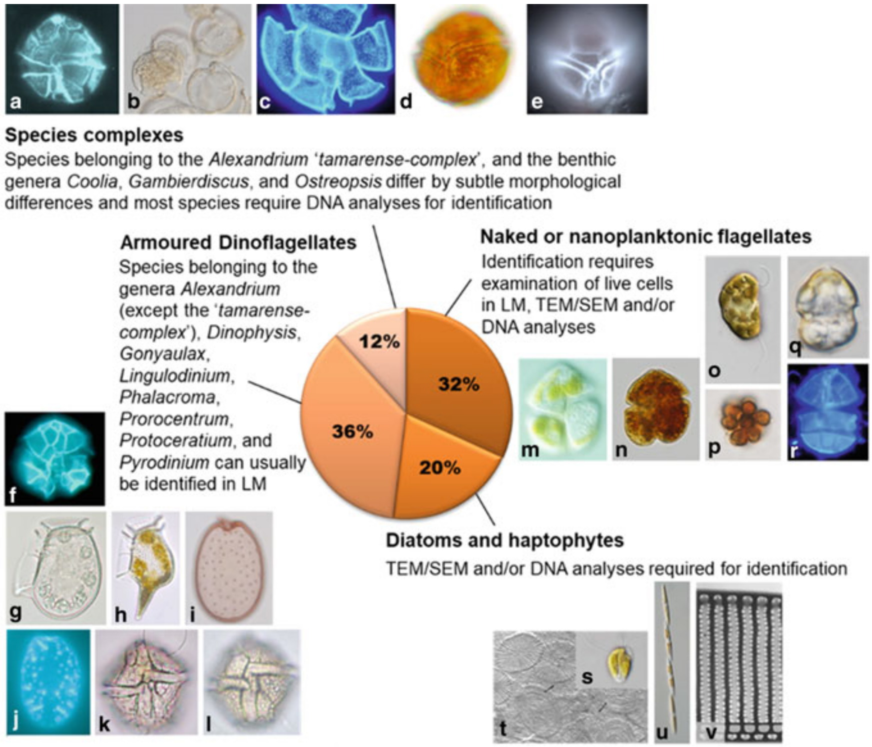


Fig. 10.3 Various types of potentially toxic, eukaryotic microalgae, grouped according to methodological requirements for identification to the species level. Percentages indicated of the total number of species (154) in the IOC Taxonomic Reference List (Moestrup et al. 2021). **a** *Alexandrium tamarense*, **b–c** *Gambierdiscus australes*, **d–e** *Coolia tropicalis*, **f** *Alexandrium minutum*, **g** *Dinophysis fortii*, **h** *Dinophysis caudata*, **i** *Prorocentrum lima*, **j** *Prorocentrum rhathymum*, **k** *Protoceratium reticulatum*, **l** *Lingulodinium polyedrum*, **m–n** *Karenia mikimotoi*, **o–p** *Heterosigma akashiwo*, **q–r** *Azadinium spinosum*, **s–t** *Prymnesium parvum*, **u–v** *Pseudo-nitzshcia* spp. Specimens documented under LM, except **t** and **v** for which SEM and TEM were used, respectively. Photos not to scale (Photo credits: J. Larsen, except by G. Hansen **g** and N. Lundholm **u–v**)

Molecular methods based on oligonucleotide probes (e.g., qPCR and DNA microarrays) have been successfully used in some developed countries to monitor HABs (e.g., Scholin et al. 2009; Penna and Galluzi 2013; Dittami et al. 2013; McNamee et al. 2016). However, this strategy only works well in locations where blooms of target species are recurrent and ignores the presence of putative emergent HAB species (Medlin and Orozco 2017). Massively parallel sequencing (MPS; also known as "metabarcoding") constitutes a powerful alternative that enables the simultaneous detection of many HAB species in monitoring programs (Nagai et al. 2019; Esenkulova et al. 2020). While these molecular-based technologies are promising, most HAB monitoring activities still rely on the opportune detection of HAB organisms solely through LM. This is particularly true for developing countries where LM is sometimes the only available tool. Consequently, species requiring examination beyond observation in LM may be adequately identified only when they form blooms with severe impacts on human health or the marine environment. This means that occurrences of certain taxa (e.g., raphidophytes, *Prymnesium* spp., *Pseudo-nitzschia* spp.) without associated adverse effects can be assumed to remain unreported or reported only at the generic level, impeding further insight into the geographical distribution and seasonal occurrence of these species. Under a scenario of increasing frequency of emerging HAB events, this issue is expected to get worse with the future discovery of cryptic species, and increasing sea surface temperature may cause a shift in phytoplankton assemblages towards smaller species (Morán et al. 2010).

10.3.2 Toxin Detection

While the detection of potential HAB organisms is critical for the early warning of bloom development, the toxicity of algal species can vary markedly due to the interplay between their genetic makeup and physiological responses to multiple environmental factors (Granéli and Flynn 2006). This frequently results in potential uncoupling of cell and toxin concentration, with under- or overestimation of the adverse effects of a bloom event (Doucette et al. 2018). The simultaneous detection of HAB organisms and phycotoxins in seafood is thus required to protect consumers from poisoning without causing losses due to unnecessary fisheries closures (Kudela et al. 2015). While shellfish phycotoxin monitoring is implemented by public and private resources in many countries, international coordination for the establishment of standard analytical procedures and regulations is still an urgent need (Berdalet et al. 2016). A critical aspect concerns the maximum amount of toxins in shellfish intended for human consumption, that is, the toxicity equivalence factors that apply to commercialized products (FAO/WHO 2016).

The overwhelming diversity of algal toxins and toxic mechanisms involved in their harmful effects on humans and marine organisms pose a challenge for monitoring agencies and managers. Liquid chromatography with tandem mass spectrometry (LC–MS/MS) is currently considered the most reliable method for the precise determination of phycotoxins. However, this tool is mainly used for basic research and is rarely used in monitoring programs due to elevated equipment cost, required high professional expertise, and lack of toxin analytical standards (McNamee et al. 2016). Routine detection of phycotoxins in many countries is still based on mouse bioassay (Berdalet et al. 2016), the latter presenting several drawbacks such as its qualitative nature, delays for results, and high incidence of false positives, in addition to ethical issues (Hess 2018). Thus, much effort has been made in recent years to develop functional and structural assays that would also be low-cost, user-friendly, and provide high-throughput analyses (reviewed by Reverté et al. 2014). Although these methods still have some limitations (e.g., lack of sensitivity or specificity and poor understanding of toxic mechanisms), they represent promising alternatives for the sustainable monitoring of HAB toxins. ELISA kits (nowadays available for many phycotoxins) have been used in monitoring programs and by fishermen to test shellfish and other commercial products themselves, resulting in the more efficient management of shellfish harvest (Anderson 2014). Still, the main gap in this regard is the lack of a reliable kit-based assay for ciguatoxins, as CP remains the most serious of all phycotoxin-related human poisoning syndromes worldwide.

10.3.3 Observing Systems

The early detection of HAB events depends on obtaining timely information about the presence of harmful algal species and the environmental conditions favoring their growth. HABs are complex oceanographic phenomena affected by a broad range of physical processes (e.g., turbulence, upwelling, local retention) and characterized by episodic occurrence over a broad range of temporal and spatial scales varying from days to months and meters to kilometers, respectively (Glibert et al. 2018a). However, the collection of samples for phytoplankton counting and phycotoxin analysis in monitoring programs rarely takes place more than weekly (frequently monthly in developing countries, if performed at all) and/or with proper spatial resolution, with undersampling becoming even more critical in remote areas (Berdalet et al. 2016). Thus, much effort has been applied in recent decades to integrate these routine monitoring activities with complementary oceanographic approaches and predictive models in coordination with key stakeholders such as local communities, fishers, managers, and scientists (e.g., Cusack et al. 2016; Maguire et al. 2016).

Available ocean observational technologies for real-time (or nearly real-time) detection of HABs include remote satellite detection (IOCCG 2021), as well as automated instruments that can be deployed on moored, ship-based, or autonomous mobile platforms (see Stauffer et al. 2019 for a review). Examples of such automated approaches are PhycoProbeTM and Optical Phytoplankton Discriminator (OPD; also know as BreveBuster). The former leverages multichannel excitation and fluorescence to discriminate among different pigment signatures to detect main microalgal groups (Stauffer et al. 2019), while the latter focuses on the optical pigment signature of the dinoflagellate *Karenia brevis* (Shapiro et al. 2015). Recent development in imaging flow cytometry also allows the implementation of this observing capability in deployable instruments such as Imaging Flow Cytobot (IFCB: Brosnahan et al. 2017; Shultz et al. 2019) and Cytobuoy (Pomati et al. 2011), while the Environmental Sample Processor (ESP; Scholin et al. 2017) uses molecular and enzymatic assays to detect the presence of toxic cells and toxins in the water, respectively. Although these instruments are still viewed mainly as research tools, they are useful for understanding HAB dynamics and are increasingly becoming incorporated into monitoring programs.

Anderson et al. (2019) provided meaningful examples of HAB observing systems that integrate routine monitoring of harmful algal species and phycotoxins with complementary oceanographic approaches. One of the main conclusions presented by these authors is that there is no universal solution that fits the needs of monitoring programs in all regions. As a matter of fact, while automated instruments play significant roles in some regional programs on the West Coast of the United States (Trainer et al. 2020a) and France (Serre-Fredj et al. 2021), good results have been obtained with satellite remote sensing in China (He et al. 2021), Korea (Kim et al. 2017), the Iberian Peninsula (Caballero et al. 2020), Scotland (Davidson et al. 2021), Ecuador (Borbor-Cordova et al. 2019), and Chile (Rodríguez-Benito et al. 2020). Citizen science programs are also increasingly becoming critical to improving the spatial and temporal coverage of regional HAB monitoring programs, as observed in some areas in the United States (e.g., Alaska and Gulf of Mexico) (Hardison et al. 2019; Harley et al. 2020) and France (Siano et al. 2020).

The improved resolution obtained with these HAB observing systems has supported predictive models in some regional programs allowing for short-term early warning (days to months). Examples of such forecast approaches based on cell/cyst counts coupled with remote satellite data and hydrodynamic models are carried out in the Gulf of Maine (McGillicuddy et al. 2011) and California (Anderson et al. 2016) to predict cell concentration and spatial distribution of toxic blooms. More recently, the ASIMUTH project (mentioned previously in Sect. 10.2.3) developed a prototype HAB alert system allowing for the forecast of phytoplankton and biotoxin data using satellite remote sensing and other information on current, past recent, or future modeled oceanographic conditions (Davidson et al. 2021 and references therein). The potential of these models to increase our forecast capacity for risk assessment depends on obtaining a better ecophysiological understanding of the growth dynamics of toxic algal species such as loss processes, life cycle (e.g., encystment and excystment), and species-specific environmental conditions promoting toxicity (Flynn and McGillicuddy 2018).

10.4 Concluding Remarks and Perspectives

The main sectors of the blue economy affected by the negative impacts of HABs and examples of their economic losses are shown in Fig. 10.4 and Table 10.1, respectively, whereas the case studies presented in the previous sections provide examples of these effects. Aquaculture is by far the blue economy sector most affected worldwide by phycotoxins and fish kills caused by high microalgal biomass/ichtyotoxins (Flynn and McGillicuddy 2018; Brown et al. 2020). Indeed, it was the most impaired sector in three of the five regions described in this chapter (i.e., Chile, North Atlantic, and the Philippines). However, effects on other sectors—such as fisheries, tourism, local businesses, and coastal resilience—are also illustrated by the case studies describing *Ostreopsis* blooms in the Mediterranean Sea and CP in French Polynesia and the Caribbean Sea. In all of these areas, HABs also affect the well-being of local communities either by directly impairing their health (e.g., consumption of phycotoxins in shellfish and/or aerosols) or the way they economically support themselves. In this regard, a better epidemiological assessment of the effects of HABs on human health is desperately needed as chronic impacts due to the repeated exposure to low toxin levels are still largely unknown (Young et al. 2020). Some sectors of the blue economy can, in turn, also favor the prevalence of HABs (Fig. 10.4). One example of that is the introduction of harmful algal species in new areas through oceanic transportation (e.g., ballast water) and/or aquaculture activities (Trottet et al. 2021). Another important aspect to consider is that the frequency and magnitude of HABs will likely increase in response to other blue economy environmental threats such as eutrophication, global warming, and ocean acidification. As a matter of fact, changes in the amount and stoichiometry of nutrients in incoming freshwater to estuaries are expected to promote HABs in the future (Glibert et al. 2018b). See also Chapter 5.

Significant progress has been achieved in the last four decades in understanding HAB dynamics, improved taxonomy, toxin detection, monitoring, and forecasting. At this point, it is important to consider that the blue economy "seeks to promote economic growth, social inclusion, and the preservation or improvement of livelihoods while at the same time ensuring environmental sustainability of the oceans and coastal areas" (World Bank and United Nations Department of Economic Social Affairs 2017). The blue economy is based on fisheries and aquaculture to provide food for humans, but also tourism and leisure, transport of goods and people, generation of clean and renewable energy and minerals, drinking water, and new drugs. However, conducting the activities to obtain these benefits entrains risks for the environment

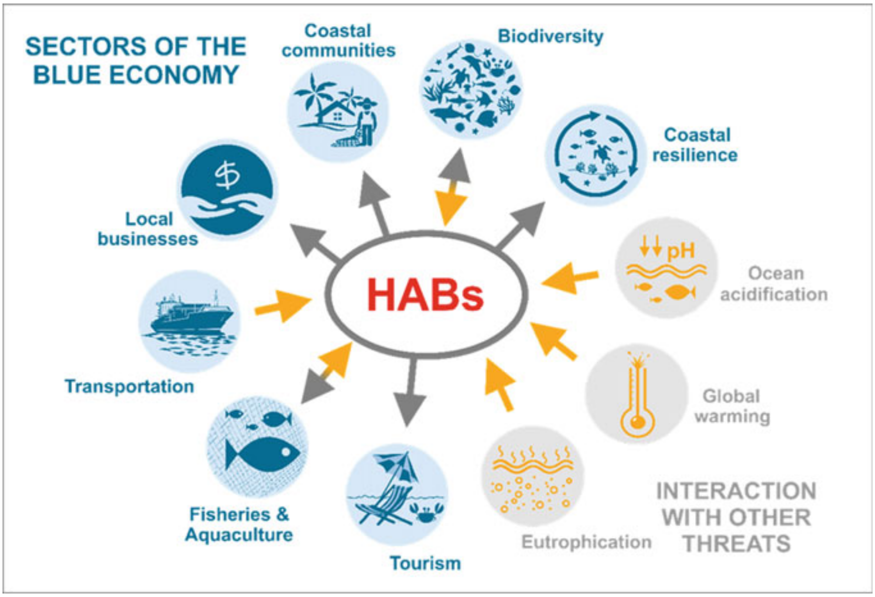


Fig. 10.4 Interactions of harmful algal blooms (HABs) with different sectors of the blue economy and other environmental threats. Sectors negatively affected by HABs are indicated by grey arrows, whereas orange arrows indicate factors promoting these events

Table 10.1 Examples of financial losses and costs caused by harmful algal blooms (HABs) on different economic sectors

Economic Sector	Country	Period	Annual loss/cost (USD $)	Source
Commercial fisheries	Maine (US East Coast)	2008–2011	~ 3.47–10.4 M	Trainer (2020)
	U.S. West Coast	2015	43.7 M	Trainer (2020)
	Korea	2010–2018	0 –126,900	Trainer (2020)
	Southern Chile	2016	2 M	Trainer (2020)
Recreational fisheries	Korea	2010–2018	0–37.7 M	Trainer (2020)
	U.S. West Coast	non-specified	10.6 M	Trainer (2020)
Aquaculture	Scotland	2009–2018	~ 1.31 M	Trainer (2020)
	Korea	2010–2018	0–20.8 M	Trainer (2020)
	Southern Chile	2016	800 M	Trainer (2020)
Tourism	Korea	2010–2018	0–19 M	Trainer (2020)
Human Health	U.S. Southeast	non-specified	60,000–700,000	Trainer (2020)
	Moorea Island (French Polynesia)	2007–2013	6,452–51,616	Morin et al. (2016)
	Southern Chile	2014–2018	6,621–93,119	Trainer (2020)
Monitorig	Southern Chile	2019	6.91 M	Trainer (2020)
	Korea	2010–2018	0.9–6.2 M	Trainer (2020)
R&D	Korea	2013–2018	0.83–4 M	Trainer (2020)

that, in some cases, are also direct or indirect factors fostering HABs (Griffith and Gobler 2020):

- Eutrophication caused by intensive aquaculture, agriculture, or urban run-off;
- Excessive use of the coastal zones favoring water retention and thus the accumulation of a high number of HAB organisms;
- Ballast water, plastics, and transport of aquaculture organisms facilitating the spread of harmful species to new habitats;
- Fisheries exploitation causes biodiversity loss and food web disruptions.

An evident gap in dealing with HABs is the difference in the resources available for monitoring in the different areas of the world. While developed countries count on automated tools, oceanographic moored instruments, and forecast models based on hydrographic conditions to provide early warning, robust monitoring in most developing countries is still missing and, when performed, mostly focused on seafood products aimed for export to developed countries (Berdalet et al. 2016). Most developing countries still rely solely on microscopic analysis and, depending on the type of harmful algae, occasionally on remote satellite data, with toxin analysis seldom performed. As basic research on HABs in these countries is frequently also deficient, modeling capabilities for early warning are virtually non-existent.

There is an urgent need to implement blue economy practices, sustainable by definition, everywhere, as a tool to cope with the environmental threats and to achieve a more equitable planet. Indeed, many successful (truly sustainable) blue economy activities are precisely developed in vulnerable areas with low economic power (e.g., UNDP 2018; Chen et al. 2020). Thus, it becomes critical that affordable and sustainable technologies be developed to allow efficient monitoring of HABs. This need is reinforced by the fact that some HAB-related health issues (ciguatera being the most emblematic among those) occur mostly in developing countries in the tropical and subtropical areas, which poses constraints to the implementation of sustainable fisheries, aquaculture, and tourism in these areas. Scientific knowledge can undoubtedly support that by facilitating the development of low-cost and reliable monitoring tools for HABs. Minimizing the anthropogenic forcings that favor HABs occurrence, especially in the most vulnerable habitats and human communities, is one efficient way to protect the environment while promoting economic growth and social inclusion, and thus moving towards a blue economy-based system.

Acknowledgements We thank Beatriz Reguera (IOC, Spain) for a meaningful discussion on the status of monitoring activities in developing countries and Philipp Hess (Ifremer, France) for providing an estimate of the number of known marine phycotoxins. We also thank Gene Felice (Dept of Art and Art History, University of North Carolina Wilmington) for the final art of Fig. 10.1. This document contributes to the implementation of the scientific plan of the international IOC of UNESCO and SCOR program GlobalHAB (https://www.globalhab.info) for the international coordination of research on HABs to prevent and mitigate their impacts.

References

Adams CM, Larkin SL, Hoagland P et al (2018) Assessing the economic consequences of harmful algal blooms: a summary of existing literature, research methods, data, and information gaps. In: Shumway S, Burkholder J, Morton S (eds) Harmful algal blooms: a compendium desk reference. Wiley, Hoboken, NJ, pp 337–354

Aguayo R, León-Muñoz J, Vargas-Baecheler J et al (2019) The glass half-empty: climate change drives lower freshwater input in the coastal system of the Chilean Northern Patagonia. Clim Change 155:417–435

Anderson CR, Berdalet E, Kudela RM et al (2019) Scaling up from regional case studies to a global harmful algal bloom observing system. Front Mar Sci 6:250

Anderson CR, Moore SK, Tomlinson MC et al (2015) Living with harmful algal blooms in a changing world: strategies for modeling and mitigating their effects in coastal marine ecosystems. In: Shroder JF, Ellis JT, Sherman DJ (eds) Coastal and marine hazards, risks, and disasters. Elsevier, San Francisco, pp 495–561

Anderson D (2014) HABs in a changing world: a perspective on harmful algal blooms, their impacts, and research and management in a dynamic era of climactic and environmental change. In: Kim H, Reguera B, Hallegraeff G, Lee C (eds) Proceedings of the 15th International Conference on Harmful Algae. CECO, Changwon, Gyeongnam, pp 3–17

Anderson DM, Boerlage SF, Dixon MB (2017) Harmful algal blooms (HABs) and desalination: a guide to impacts, monitoring and management. Intergovernmental Oceanographic Commission, Manuals and Guides No. 78. UNESCO, Paris

Anderson DM, Fensin E, Gobler CJ et al (2021) Marine harmful algal blooms (HABs) in the United States: history, current status and future trends. Harmful Algae 102:101975

Anderson DM, Hoagland P, Kaoru Y et al (2000) Estimated annual economic impacts from harmful algal blooms (HABs) in the United States. WHOI-2000-11Woods Hole Oceanogr Inst, Woods Hole, Massachusetts. http://www.whoi.edu/redtide/pertinentinfo/Economics_report.pdf

Anderson CR, Kudela RM, Kahru M et al (2016) Initial skill assessment of the California harmful algae risk mapping (C-HARM) system. Harmful Algae 59:1–18

Anderson DM, Lobel PS (1987) The continuing enigma of ciguatera. Biol Bull 172:89–107

Anderson W (1776) An account of some poisonous fish in the South Seas. In a letter to Sir John Pringle, Bart. PRS from Mr. William Anderson, late surgeon's mate on board his majesty's ship the resolution, now surgeon of that ship. Philos Trans R Soc Lond B Biol Sci 66:544–552

Penna A, Galluzi L (2013) The quantitative real-time PCR applications in the monitoring of marine harmful algal bloom (HAB) species. Environ Sci Pollut Res 20:6851–6862

Arcamo S, Relox Jr J, Lawrence MR et al (2014) Paralytic shellfish monitoring in the Philippines—a management review. In: MacKenzie L (ed) 16th International Conference on Harmful algae. Cawthron Institute, Nelson, pp 274–277

Azanza R (2017) When the blue sea turns red, the story of harmful algal blooms in the Philippines. University of the Philippines Diliman, Quezon City, The Marine Science Institute

Azanza R, Benico G (2013) Toxic *Alexandrium* blooms in fish farming sites in Bolinao, Pangasinan. J Environ Sci Manag 1:44–49

Azanza RV, Brosnahan ML, Anderson DM et al (2018) The role of life cycle characteristics in harmful algal bloom dynamics. In: Glibert P, Berdalet E, Burford M, Pitcher G, Zhou M (eds) Global ecology and oceanography of harmful algal blooms. Ecological Studies, vol 232. Springer, Cham, pp 133–161

Azanza RV, Fukuyo Y, Yap LG et al (2005) *Prorocentrum minimum* bloom and its possible link to a massive fish kill in Bolinao, Pangasinan, Northern Philippines. Harmful Algae 4:519–524

Azanza RV, Taylor FM (2001) Are *Pyrodinium* blooms in the Southeast Asian region recurring and spreading? A view at the end of the millennium. AMBIO: A J Hum Environ 30:356–364

Berdalet E, Fleming LE, Gowen R et al (2016) Marine harmful algal blooms, human health and well-being: challenges and opportunities in the 21stcentury. J Mar Biol Assoc UK 96:61–91

Berdalet E, Pavaux AS, Abós-Herràndiz R et al (2022) Environmental, human health and socioeconomic impacts of *Ostreopsis* spp. blooms in the NW Mediterranean. Harmful Algae (in press)

Berdalet E, Tester PA, Chinain M et al (2017) Harmful algal blooms in benthic systems: recent progress and future research. Oceanography 30:36–45

BFAR (2019) Philippine Fisheries Profile 2013. Department of Agriculture, Bureau of Fisheries and Aquatic Resources. https://www.bfar.da.gov.ph/publication.jsp?id=2375#post

Binzer SB, Svenssen DK, Daugbjerg N et al.(2019) A-, B- and C-type prymnesins are clade specific compounds and chemotaxonomic markers in *Prymnesium parvum*. Harmful Algae 81:10–17

Bjørndal T (2002) The competitiveness of the Chilean salmon aquaculture industry. Aquac Econ Manag 6:97–116

Borbor-Cordova MJ, Torres G, Mantilla-Saltos G et al (2019) Oceanography of harmful algal blooms on the Ecuadorian coast (1997–2017): integrating remote sensing and biological data. Front Mar Sci 6:13

Brescianini C, Grillo C, Melchiorre N et al (2006) *Ostreopsis ovata* algal blooms affecting human health in Genova, Italy, 2005 and 2006. Euro Surveillance 11:E060907

Bricker SB, Longstaff B, Dennison W et al (2008) Effects of nutrient enrichment in the nation's estuaries: a decade of change. Harmful Algae 8:21–32

Brosnahan ML, Ralston DK, Fischer AD et al (2017) Bloom termination of the toxic dinoflagellate *Alexandrium catenella*: vertical migration behavior, sediment infiltration, and benthic cyst yield. Limnol Oceanogr 62:2829–2849

Brown AR, Lilley M, Shutler J et al (2020) Assessing risks and mitigating impacts of harmful algal blooms on mariculture and marine fisheries. Rev Aquac 12:1663–1688

Caballero I, Fernández R, Escalante OM et al (2020) New capabilities of Sentinel-2A/B satellites combined with in situ data for monitoring small harmful algal blooms in complex coastal waters. Sci Rep 10:1–14

Chai ZY, Wang H, Deng Y et al (2020) Harmful algal blooms significantly reduce the resource use efficiency in a coastal plankton community. Sci Total Environ 704:135381

Chen S, De Bruyne C, Bollempalli M (2020) Blue economy: community case studies addressing the poverty-environment nexus in ocean and coastal management. Sustainability 12:4654

Chen XM, Pang JX, Huang CX et al (2021) Two new and nontoxigenic *Pseudo-nitzschia* species (Bacillariophyceae) from Chinese Southeast coastal waters. J Phycol 57:335–344

Chenouf S, Perez J, Raux P (2020) Methodology for the estimation of scallop production areas closures in the Eastern English Channel. https://archimer.ifremer.fr/doc/00635/74713

Chinain M, Gatti C, Darius H et al (2020) Ciguatera poisonings: a global review of occurrences and trends. Harmful Algae 101873

Cusack C, Dabrowski T, Lyons K et al (2016) Harmful algal bloom forecast system for SW Ireland. Part II: are operational oceanographic models useful in a HAB warning system? Harmful Algae 53:86–101

Daugbjerg N, Hansen G, Larsen J, Moestrup Ø (2000) Phylogeny of some of the major genera of dinoflagellates based on ultrastructure and partial LSU rDNA sequence data, including the erection of three new genera of unarmoured dinoflagellates. Phycologia 39:302–317

David C, Maria YS, Siringan F et al (2009) Coastal pollution due to increasing nutrient flux in aquaculture sites. Environ Geol 58:447–454

Davidson K, Gowen RJ, Harrison PJ et al (2014) Anthropogenic nutrients and harmful algae in coastal waters. J Environ Manage 146:206–216

Davidson K, Whyte C, Aleynik D et al (2021) HABreports: online early warning of harmful algal and biotoxin risk for the Scottish shellfish and finfish aquaculture industries. Front Mar Sci 8:350

Desrochers, A, Cox SA., Oxenford, HA et al (2020) *Sargassum* uses guide: a resource for Caribbean researchers, entrepreneurs and policy makers. CERMES Technical Report No. 97

Díaz PA, Álvarez G, Varela D et al (2019) Impacts of harmful algal blooms on the aquaculture industry: Chile as a case study. Perspect Phycol 6:39–50

Dittami SM, Hostyeva V, Egge ES et al (2013) Seasonal dynamics of harmful algae in outer Oslofjorden monitored by microarray, qPCR, and microscopy. Environ Sci Pollut Res 20:6719–6732

Dorantes-Aranda JJ, Seger A, Mardones JI et al (2015) Progress in understanding algal bloom-mediated fish kills: the role of superoxide radicals, phycotoxins and fatty acids. PLoS ONE 10(7):e0133549

Doucette GJ, Medlin LK, McCarron P et al (2018) Detection and surveillance of harmful algal bloom species and toxins. In: Shumway S, Burkholder JM, Morton SL (eds) Harmful algal blooms: a compendium desk reference. Wiley, Hoboken, NJ, pp 39–113

Drouet K, Jauzein C, Herviot-Heath D et al (2021) Current distribution and potential expansion of the harmful benthic dinoflagellate *Ostreopsis* cf. *siamensis* towards the warming waters of the Bay of Biscay, North-East Atlantic. Environ Microbiol 23:4956–4979

Eckford-Soper L, Daugbjerg N (2016) The ichthyotoxic genus *Pseudochattonella* (Dictyochophyceae): distribution, toxicity, enumeration, ecological impact, succession and life history—A review. Harmful Algae 58:51–58

Esenkulova S, Sutherland BJ, Tabata A et al (2020) Comparing metabarcoding and morphological approaches to identify phytoplankton taxa associated with harmful algal blooms. FACETS 5:784–811

FAO/WHO (2016) Toxicity equivalence factors for marine biotoxins associated with bivalve molluscs. Food and Agriculture Organization (FAO) and World Health Organization (WHO), Rome. https://www.fao.org/3/i5970e/i5970e.pdf

Flores-Leñero A, Vargas-Torres V, Paredes-Mella J, Norambuena L, Fuenzalida G, Lee-Chang K, Mardones JI (2022) Heterosigma akashiwo in Patagonian fjords: Genetics, growth, pigment signature and role of PUFA and ROS in ichthyotoxicity. Toxins 14:577

Flynn KJ, McGillicuddy DJ (2018) Modeling marine harmful algal blooms: current status and future prospects. In: Burkholder JM, Morton SL (eds) Harmful algal blooms: a compendium desk reference. Wiley, pp 115–134

Friedman MA, Fernandez M, Backer LC et al (2017) An updated review of ciguatera fish poisoning: clinical, epidemiological, environmental, and public health management. Mar Drugs 15:72

Friedman MA, Fleming LE, Fernandez M et al (2008) Ciguatera fish poisoning: treatment, prevention and management. Mar Drugs 6:456–479

Fukuyo Y, Imai I, Kodama M et al (2002) Red tides and other harmful algal blooms in Japan. In: Taylor F, Trainer VL (eds) Harmful algal blooms in the PICES region of the North Pacific. PICES Sci. Rep. No. 23:7–20

Funari E, Manganelli M, Testai E (2015) *Ostreospis* cf. *ovata* blooms in coastal water: Italian guidelines to assess and manage the risk associated to bathing waters and recreational activities. Harmful Algae 50:45–56

Gallitelli M, Ungaro N, Addante LM et al (2005) Respiratory illness as a reaction to tropical algal blooms occurring in a temperate climate. JAMA 293:2595–2600

Garreaud R (2018) Record-breaking climate anomalies lead to severe drought and environmental disruption in western Patagonia in 2016. Clim Res 74:217–229

Gatti C, Oelher E, Legrand A (2008) Severe seafood poisoning in French Polynesia: a retrospective analysis of 129 medical files. Toxicon 51:746–753

GEOHAB (2001) Global ecology and oceanography of harmful algal blooms, science plan. SCOR and IOC, Baltimore and Paris

Gillet R (2016) Fisheries in the economies of Pacific island countries and territories. Pacific Community, Noumea, New Caledonia. https://www.spc.int/sites/default/files/wordpresscontent/wp-content/uploads/2016/11/Gillett_16_Benefish-fisheries-in-economies-of-pacificcountries.pdf

Giussani V, Asnaghi V, Pedroncini A et al (2017) Management of harmful benthic dinoflagellates requires targeted sampling methods and alarm thresholds. Harmful Algae 68:97–104

Glibert PM (2017) Eutrophication, harmful algae and biodiversity—challenging paradigms in a world of complex nutrient changes. Mar Pollut Bull 142:591–606

Glibert PM (2020) Harmful algae at the complex nexus of eutrophication and climate change. Harmful Algae 91:101583

Glibert PM, Allen JI, Bouwman A et al (2010) Modeling of HABs and eutrophication: status, advances, challenges. J Mar Syst 83(3–4):262–275

Glibert PM, Berdalet E, Burford MA et al (2018a) Harmful algal blooms and the importance of understanding their ecology and oceanography. In: Glibert P, Berdalet E, Burford M, Pitcher G, Zhou B (eds) Global ecology and oceanography of harmful algal blooms. Ecological Studies, vol 232. Springer, Cham, pp 9–25

Glibert PM, Beusen AH, Harrison JA et al (2018b) Changing land-, sea-, and airscapes: sources of nutrient pollution affecting habitat suitability for harmful algae. In: Glibert P, Berdalet E, Burford M, Pitcher G, Zhou B (eds) Global ecology and oceanography of harmful algal blooms. Springer, Cham, pp 53–76

GLOBEFISH (2018) GLOBEFISH highlights. A quarterly update on world seafood markets. October 2018 ISSUE, with Jan–Jun 2018 Statistics. FAO. https://www.fao.org/3/cb5518en/cb5518en.pdf

Granéli E, Flynn K (2006) Chemical and physical factors influencing toxin content. In: Granéli E, Turner J (eds) Ecology of harmful algae. Springer, Berlin Heidelberg, pp 229–241

Griffith AW, Doherty OM, Gobler CJ (2019) Ocean warming along temperate western boundaries of the Northern Hemisphere promotes an expansion of *Cochlodinium polykrikoides* blooms. Proc Royal Soc B 286(1904):20190340

Griffith AW, Gobler CJ (2020) Harmful algal blooms: a climate change co-stressor in marine and freshwater ecosystems. Harmful Algae 91:101590

Guillotreau P, Le Bihan V, Morineau B et al (2021) The vulnerability of shellfish farmers to HAB events: an optimal matching analysis of closure decrees. Harmful Algae 101:101968

Hallegraeff GM, Anderson DM, Belin C et al (2021) Perceived global increase in algal blooms is attributable to intensified monitoring and emerging bloom impacts. Commun Earth Environ 2:1–10

Hardison DR, Holland WC, Currier RD et al (2019) HABscope: a tool for use by citizen scientists to facilitate early warning of respiratory irritation caused by toxic blooms of *Karenia brevis*. PLoS ONE 14:e0218489

Harley JR, Lanphier K, Kennedy EGC et al (2020) The Southeast Alaska Tribal Ocean Research (SEATOR) partnership: addressing data gaps in harmful algal bloom monitoring and shellfish safety in Southeast Alaska. Toxins 12:407

Häussermann V, Gutstein CS, Bedington M et al (2017) Largest baleen whale mass mortality during strong El Niño event is likely related to harmful toxic algal bloom. PeerJ 5:e3123

He X, Chen C, Zhang Z et al (2021) Temporal and spatial characteristics of harmful algal blooms in the offshore waters, China during 1990 to 2019. J Appl Remote Sens 16:012004

Heisler J, Glibert PM, Burkholder JM et al (2008) Eutrophication and harmful algal blooms: a scientific consensus. Harmful Algae 8:3–13

Hess P (2018) Algal toxin discovery, management and regulation over the last 25 years. Harmful Algae News 59:15–16

IOCCG (2021) Observation of harmful algal blooms with ocean colour radiometry. IOCCG Report Series, No. 20. International Ocean Colour Coordinating Group, Dartmouth. https://doi.org/10.25607/OBP-1042

John U, Litaker RW, Montresor M et al (2014) Formal revision of the *Alexandrium tamarense* species complex (Dinophyceae) taxonomy: the introduction of five species with emphasis on molecular-based (rDNA) classification. Protist 165:779–804

Kermarec F, Dor F, Armengaud A et al (2008) Les risques sanitaires liés à la présence d'*Ostreopsis ovata* dans les eaux de baignade ou d'activités nautiques. Environ Risques Et St 7:357–363

Kim TW, Kim JH, Song M-S et al (2017) Convergence technique study on red tide prediction in the littoral sea. J Coastal Res 79:254–258

Konstantinou ZI, Krestenitis YN, Latinopoulos D et al (2012) Aspects of mussel-farming activity in Chalastra, Thermaikos Gulf, Greece: an effort to untie a management Gordian Knot. Ecol Soc 17(1):1

Kotaki Y, Furio EF, Bajarias FA et al (2006) New stage of the study on domoic acid-producing diatoms—a finding of *Nitzschia navis-varingica* that produces domoic acid derivatives as major toxin components. Coast Mar Sci 30:116–120

Kotaki Y, Furio EF, Satake M et al (2005) Production of isodomoic acids A and B as major toxin components of a pennate diatom *Nitzschia navis-varingica*. Toxicon 46:946–953

Kudela R, Berdalet E, Bernard S et al (2015) Harmful algal blooms: a scientific summary for policy makers (IOC/INF-1320). IOC/UNESCO Paris.

Kudela RM, Berdalet E, Enevoldsen H et al (2017) GEOHAB: the global ecology and oceanography of harmful algal blooms program: motivation, goals and legacy. Oceanography 30:12–21

Lassus P, Chomerat N, Hess P et al (2016) Toxic and harmful microalgae of the world ocean/ Micro-algues toxiques et nuisibles de l'océan mondial. IOC Manuals and Guides, 68 (Bilingual English/French). International Society for the Study of Harmful Algae/Intergovernmental Oceanographic Commission of UNESCO, Denmark.

Lee K-H, Noh J, Khim JS (2020) The Blue Economy and the United Nations' sustainable development goals: challenges and opportunities. Environ Int 137:105528

Lemée R, Mangialajo L, Cohu S et al (2012) Interactions between scientists, managers and policy makers in the framework of the French MediOs project on *Ostreopsis* (2008–2010). Cryptogam, Algol 33:137–142

León-Muñoz J, Urbina MA, Garreaud R et al (2018) Hydroclimatic conditions trigger record harmful algal bloom in western Patagonia (summer 2016). Sci Rep 8:1–10

Liu D, Zhou M (2018) Green tides of the Yellow Sea: massive free-floating blooms of *Ulva prolifera.* In: Global ecology and oceanography of harmful algal blooms. Springer, pp 317–326

Lundholm N, Moestrup Ø, Hasle GR et al (2003) A study of the *Pseudo-nitzschia pseudodelicatissima*/*cuspidata* complex (Bacillariophyceae): what is *P. pseudodelicatissima*? J Phycol 39:797–813

Maguire J, Cusack C, Ruiz-Villarreal M et al (2016) Applied simulations and integrated modelling for the understanding of toxic and harmful algal blooms (ASIMUTH): integrated HAB forecast systems for Europe's Atlantic Arc. Harmful Algae 53:160–166

Marasigan AN, Sato S, Fukuyo Y et al (2001) Accumulation of a high level of diarrhetic shellfish toxins in the green mussel *Perna viridis* during a bloom of *Dinophysis caudata* and *Dinophysis miles* in Sapian Bay, Panay Island, the Philippines. Fish Sci 67:994–996

Mardones JI, Paredes J, Godoy M et al (2020a) Disentangling the environmental processes responsible for the world's largest farmed fish-killing harmful algal bloom: Chile, 2016. Sci Total Environ 144383

Mardones JI, Holland DS, Anderson L et al (2020b) Estimating and mitigating the economic costs of Harmful Algal Blooms on commercial and recreational shellfish harvesters. In: Trainer VL (ed) GlobalHAB. Evaluating, reducing and mitigating the cost of harmful algal blooms: a compendium of case studies. PICES Sci. Rep. No. 59. pp 66–83

Mardones JI, Norambuena L, Paredes J et al (2020c) Unraveling the *Karenia selliformis* complex with the description of a non-gymnodimine producing Patagonian phylotype. Harmful Algae 98:101892

Martino S, Gianella F, Davidson K (2020) An approach for evaluating the economic impacts of harmful algal blooms: the effects of blooms of toxic *Dinophysis* spp. on the productivity of Scottish shellfish farms. Harmful Algae 99:101912

McGillicuddy D Jr, Townsend D, He R et al (2011) Suppression of the 2010 *Alexandrium fundyense* bloom by changes in physical, biological, and chemical properties of the Gulf of Maine. Limnol Oceanogr 56:2411–2426

McKibben SM, Peterson W, Wood AM et al (2017) Climatic regulation of the neurotoxin domoic acid. PNAS 114:239–244

McNamee SE, Medlin LK, Kegel J et al (2016) Distribution, occurrence and biotoxin composition of the main shellfish toxin producing microalgae within European waters: a comparison of methods of analysis. Harmful Algae 55:112–120

Medlin LK, Orozco J (2017) Molecular techniques for the detection of organisms in aquatic environments, with emphasis on harmful algal bloom species. Sens 17:1184

Meroni L, Chiantore M, Petrillo M et al (2018) Habitat effects on *Ostreopsis* cf. *ovata* bloom dynamics. Harmful Algae 80:64–71

Moestrup Ø, Akselmann-Cardella R, Churro C et al (2021) IOC-UNESCO Taxonomic Reference List of Harmful Micro Algae. https://doi.org/10.14284/362. Accessed at http://www.marinespecies.org/hab.

Moore SK, Cline MR, Blair K et al (2019) An index of fisheries closures due to harmful algal blooms and a framework for identifying vulnerable fishing communities on the US West Coast. Mar Policy 110:103543

Moore SK, Dreyer SJ, Ekstrom JA et al (2020) Harmful algal blooms and coastal communities: socioeconomic impacts and actions taken to cope with the 2015 US West Coast domoic acid event. Harmful Algae 96:101799

Moore SK, Mantua NJ, Hickey BM et al (2009) Recent trends in paralytic shellfish toxins in Puget Sound, relationships to climate, and capacity for prediction of toxic events. Harmful Algae 8:463–477

Morán XAG, López-Urrutia Á, Calvo-Díaz A et al (2010) Increasing importance of small phytoplankton in a warmer ocean. Glob Change Biol 16:1137–1144

Morin E, Gatti C, Bambridge T et al (2016) Ciguatera fish poisoning: incidence, health costs and risk perception on Moorea Island (Society archipelago, French Polynesia). Harmful Algae 60:1–10

Nagai S, Chen H, Kawakami Y et al (2019) Monitoring of the toxic dinoflagellate *Alexandrium catenella* in Osaka Bay, Japan using a massively parallel sequencing (MPS)-based technique. Harmful Algae 89:101660

Navedo JG, Vargas-Chacoff L (2021) Salmon aquaculture threatens Patagonia. Sci 372:695–696

Ng S, Gregory J (2000) An outbreak of ciguatera fish poisoning in Victoria. Commun Dis Intell 24:344–346

Nguyen-Ngoc L, Doan-Nhu H, Larsen J et al (2021) Morphological and genetic analyses of *Ostreopsis* (Dinophyceae, Gonyaulacales, Ostreopsidaceae) species from Vietnamese waters with a re-description of the type species *O. Siamensis*. J Phycol 57:1059–1083

O'Mahony M (2018) EU regulatory risk management of marine biotoxins in the marine bivalve mollusc food-chain. Toxins 10:118

Olsen DA (1988) The impact of ciguatera fish poisoning within a changing Caribbean environment. Popul Environ 10:14–31

Pavaux AS, Berdalet E, Lemée R (2020) Chemical ecology of the benthic dinoflagellate genus *Ostreopsis*: review of progress and future directions. Front Mar Sci 7:498

Pfannkuchen M, Godrijan J, Marić Pfannkuchen D et al (2012) Toxin-producing *Ostreopsis* cf. *ovata* are likely to bloom undetected along coastal areas. Environ Sci Technol 46:5574–5582

Pitcher GC (2012) Harmful algae—The requirement for species-specific information. Harmful Algae (14):1–4

Pomati F, Jokela J, Simona M et al (2011) An automated platform for phytoplankton ecology and aquatic ecosystem monitoring. Environ Sci Technol 45:9658–9665

Radke EG, Grattan LM, Cook RL et al (2013) Ciguatera incidence in the US Virgin Islands has not increased over a 30-year time period despite rising seawater temperatures. Am J Trop Med Hyg 88:908

Reverté L, Soliño L, Carnicer O et al (2014) Alternative methods for the detection of emerging marine toxins: biosensors, biochemical assays and cell-based assays. Mar Drugs 12:5719–5763

Ritzman J, Brodbeck A, Brostrom S et al (2018) Economic and sociocultural impacts of fisheries closures in two fishing-dependent communities following the massive 2015 US West Coast harmful algal bloom. Harmful Algae 80:35–45

Rodríguez GR, Villasante S, García-Negro MC (2011) Are red tides affecting economically the commercialization of the Galician (NW Spain) mussel farming? Mar Policy 35:252–257

Rodríguez-Benito CV, Navarro G, Caballero I (2020) Using Copernicus Sentinel-2 and Sentinel-3 data to monitor harmful algal blooms in Southern Chile during the COVID-19 lockdown. Mar Pollut Bull 161:111722

Rongo T, van Woesik R (2011) Ciguatera poisoning in Rarotonga, southern Cook islands. Harmful Algae 10:345–355

Rongo T, van Woesik R (2012) Socioeconomic consequences of ciguatera poisoning in Rarotonga, southern Cook Islands. Harmful Algae 20:92–100

San Diego-McGlone ML, Azanza RV, Villanoy CL et al (2008) Eutrophic waters, algal bloom and fish kill in fish farming areas in Bolinao, Pangasinan, Philippines. Mar Pollut Bull 57:295–301

Sandifer PA, Keener P, Scott GI et al (2021) Oceans and human health and the new blue economy. In: Hotaling L, Spinrad R (eds) Preparing a workforce for the new blue economy. Elsevier, Amsterdam, pp 213–236

Sanseverino I, Conduto D, Pozzoli L et al (2016) Algal bloom and its economic impact. European Commission, Joint Research Centre Institute for Environment and Sustainability. EUR 27905 EN. https://doi.org/10.2788/660478

Sansoni G, Borghini B, Camici G et al (2003) Fioriture algali di *Ostreopsis ovata* (Gonyaulacales: Dinophyceae): un problema emergente. Biol Ambient 17:17–23

Scholin CA, Birch J, Jensen S et al (2017) The quest to develop ecogenomic sensors: a 25-year history of the Environmental Sample Processor (ESP) as a case study. Oceanography 30:100–113
Scholin C, Doucette G, Jensen S et al (2009) Remote detection of marine microbes, small invertebrates, harmful algae, and biotoxins using the Environmental Sample Processor (ESP). Oceanography 22:158–167
Serre-Fredj L, Jacqueline F, Navon MP et al (2021) Coupling high frequency monitoring and bioassay experiments to investigate a harmful algal bloom in the Bay of Seine (French-English Channel). Mar Pollut Bull 168:112387
Shapiro J, Dixon LK, Schofield OM et al (2015) New sensors for ocean observing: the optical phytoplankton discriminator. In: Liu Y, Kerkering H, Weisberg R (eds) Coastal ocean observing systems. Academic Press, Boston, pp 326–350
Shultz D, Campbell L, Kudela RM (2019) Trends in *Dinophysis* abundance and diarrhetic shellfish toxin levels in California mussels (*Mytilus californianus*) from Monterey Bay, California. Harmful Algae 88:101641
Siano R, Chapelle A, Antoine V et al (2020) Citizen participation in monitoring phytoplankton seawater discolorations. Mar Policy 117:103039
Silva A, Pinto L, Rodrigues S et al (2016) A HAB warning system for shellfish harvesting in Portugal. Harmful Algae 53:33–39
Smayda TJ (1997a) What is a bloom? A commentary. Limnol Oceanogr 42:1132–1136
Smayda TJ (1997b) Harmful algal blooms: their ecophysiology and general relevance to phytoplankton blooms in the sea. Limnol Oceanogr 42:1137–1153
Smetacek V, Zingone A (2013) Green and golden seaweed tides on the rise. Nat 504(7478):84–88
Stauffer BA, Bowers HA, Buckley E et al (2019) Considerations in harmful algal bloom research and monitoring: perspectives from a consensus-building workshop and technology testing. Front Mar Sci 6:399
Takata Y, Sato S, Ha DV et al (2009) Occurrence of domoic acid in tropical bivalves. Fish Sci 75:473–480
Tester PA, Feldman RL, Nau AW et al (2010) Ciguatera fish poisoning and sea surface temperatures in the Caribbean Sea and the West Indies. Toxicon 56:698–710
Tester PA, Litaker RW, Berdalet E (2020) Climate change and harmful benthic microalgae. Harmful Algae 91:101655
Theodorou JA, Moutopoulos DK, Tzovenis I (2020) Semi-quantitative risk assessment of Mediterranean mussel (*Mytilus galloprovincialis* L.) harvesting bans due to harmful algal bloom (HAB) incidents in Greece. Aquac Econ Manag 24:273–293
Tillmann U, Elbrächter M, Krock B et al (2009) *Azadinium spinosum* gen. et sp. nov. (Dinophyceae) identified as a primary producer of azaspiracid toxins. Eur J Phycol 44:63–79
Trainer VL (2020) GlobalHAB: Evaluating, reducing and mitigating the cost of harmful algal blooms: a compendium of case studies. PICES Sci. Rep. No. 59
Trainer VL, Kudela RM, Hunter MV et al (2020a) Climate extreme seeds a new domoic acid hotspot on the US west coast. Front Clim 2:23
Trainer VL, Moore SK, Hallegraeff G et al (2020b) Pelagic harmful algal blooms and climate change: Lessons from nature's experiments with extremes. Harmful Algae 91:101591
Trottet A, George C, Drillet G et al (2021) Aquaculture in coastal urbanized areas: a comparative review of the challenges posed by harmful algal blooms. Crit Rev Environ Sci. https://doi.org/10.1080/10643389.2021.1897372
Tubaro A, Durando P, Del Favero G et al (2011) Case definitions for human poisonings postulated to palytoxins exposure. Toxicon 57:478–495
UNDP (2018) Blue economy, community solutions. UNDP, New York. https://www.undp.org/publications/blue-economy-community-solutions
Vancouver G (1798) A voyage of discovery to the North Pacific Ocean and around the world in the years 1790–95, vol 2. London, UK

van Tussenbroek BI, Arana HAH, Rodríguez-Martínez RE et al (2017) Severe impacts of brown tides caused by *Sargassum* spp. on near-shore Caribbean seagrass communities. Mar Pollut Bull 122:272–281

Vila M, Abós-Herràndiz R, Isern-Fontanet J et al (2016) Establishing the link between *Ostreopsis* cf. *ovata* blooms and human health impacts using ecology and epidemiology. Sci Mar 80:107–115

Villanoy CL, Azanza RV, Altemerano A et al (2006) Attempts to model the bloom dynamics of *Pyrodinium*, a tropical toxic dinoflagellate. Harmful Algae 5:156–183

Wang M, Hu C, Barnes BB et al (2019) The great Atlantic *Sargassum* belt. Sci 365:83–87

Wells ML, Karlson B, Wulff A et al (2020) Future HAB science: Directions and challenges in a changing climate. Harmful Algae 91:101632

Wenhai L, Cusack C, Baker M et al (2019) Successful blue economy examples with an emphasis on international perspectives. Front Mar Sci 6:261

Willis C, Papathanasopoulou E, Russel D et al (2018) Harmful algal blooms: the impacts on cultural ecosystem services and human well-being in a case study setting, Cornwall, UK. Mar Policy 97:232–238

World Bank and United Nations Department of Economic Social Affairs (2017) The potential of the blue economy: increasing long-term benefits of the sustainable use of marine resources for small island developing states and coastal least developed countries

Yñiguez AT, Lim PT, Leaw CP et al (2021) Over 30 years of HABs in the Philippines and Malaysia: what have we learned? Harmful Algae 102:101776

Yñiguez AT, Maister J, Villanoy CL et al (2018) Insights into the dynamics of harmful algal blooms in a tropical estuary through an integrated hydrodynamic-*Pyrodinium*-shellfish model. Harmful Algae 80:1–14

Young N, Sharpe RA, Barciela R et al (2020) Marine harmful algal blooms and human health: a systematic scoping review. Harmful Algae 98:101901

Chapter 11
Ocean Acidification and Blue Economies

Edward R. Urban Jr. and Haimanti Biswas

Abstract The pH of the surface ocean is decreasing worldwide as a result of anthropogenic carbon dioxide entering the surface ocean from the atmosphere; nearly 40% of the CO_2 emitted to the atmosphere between 1800 and 2007 has been absorbed by the ocean. This consequent decrease in surface water pH is called "ocean acidification" and is a major threat to the blue economies of developing coastal nations and small islands. At particular risk are coral reefs, which serve as the basis for ecotourism and fisheries, and which provide protection from waves and resulting damage to property and loss of life. In addition, ocean acidification has been shown to negatively affect plankton, shellfish and other organisms that deposit carbonate structures. Ocean acidification is recognized by the UN 2030 Agenda for Sustainable Development, and specifically by Sustainable Development Goal 14 on "Life Under Water", as a major challenge. Ocean science, both observations and research, can play a significant role in understanding the potential impacts of ocean acidification, as well as creating mitigation and adaptation approaches. This chapter will explain the causes and impacts of ocean acidification and will proceed to blue economy implications and the need for new ocean science.

Keywords Ocean acidification · pH · Carbonate

11.1 Introduction

As global human population has increased, particularly in the past two to three hundred years, most of Earth's natural elemental cycles have been perturbed due

E. R. Urban Jr. (✉)
Scientific Committee On Oceanic Research (retired), Newark, Delaware, USA
e-mail: ed.urban@scor-int.org

H. Biswas
Biological Oceanography Division, CSIR National Institute of Oceanography, Dona Paula, India
e-mail: haimanti.biswas@nio.org

Academy of Scientific and Innovative Research (AcSIR), Ghaziabad, India

E. R. Urban Jr. and V. Ittekkot (eds.), *Blue Economy*,
https://doi.org/10.1007/978-981-19-5065-0_11

to human changes to natural systems. The global carbon cycle is perhaps the most affected biogeochemical cycle on Earth, with multidimensional impacts on the Earth system. One of these impacts is ocean acidification, which is the decrease in surface ocean pH that has occurred for the past two centuries, already amounting to 0.1 pH units (Orr et al. 2005). According to the latest assessment of the Intergovernmental Panel on Climate Change (IPCC), "[i]t is *virtually certain* that human-caused CO_2 emissions are the main driver of current global acidification of the surface open ocean" (IPCC 2021). The causes of ocean acidification are easier to understand than predicting its biological and economic effects, which could be significant not only for ecosystems but also for society.

Immediately before the Industrial Revolution[1] and throughout much of human history, the fluxes of carbon dioxide (CO_2) between the atmosphere and ocean were in balance most of the time. There was (and is) an annual cycle of uptake of CO_2 by terrestrial and oceanic systems in the spring and summer and release of CO_2 in the fall and winter as vegetation dies, as illustrated by the Keeling Curve (Keeling et al. 1976).

With the Industrial Revolution hydrocarbons that developed underground over hundreds of millions of years were extracted and combusted over the past two and one-half centuries, releasing CO_2 to the atmosphere at a much faster rate than they developed. Consequently, the atmospheric CO_2 concentration has increased from an estimated 277 parts per million (ppm) in 1750 (Joos and Spahni 2008) to 420 ppm in mid-April 2022.[2] Additional CO_2 was emitted to the atmosphere as a result of cement production, burning trees and peat (Woodwell et al. 1983) and the clearing of land for agricultural purposes (land-use change). About 40% of the CO_2 emitted to the atmosphere from fossil fuel burning and cement production between 1800 and 2007 has been absorbed by the ocean (Gruber et al. 2019).

The rapid build-up of CO_2 in the atmosphere from human activities disturbed the CO_2 "source to sink" balance between the ocean and atmosphere, leading to increased net transfer of CO_2 from the atmosphere to the ocean. The increased dissolution of CO_2 in the surface ocean drives the well-understood chemical reactions shown in Fig. 11.1.

Slow fluxes of CO_2 from the atmosphere to the ocean have been counteracted through geologic time by the weak buffering system of seawater, carbonate dissolution in sediments, and weathering on land (Hoenisch et al. 2012). Rapid increases in atmospheric CO_2 (over less than 10,000 years) unbalance this buffering system, leading to decreased pH (increasing H^+ concentration) and calcium carbonate saturation (mostly due to increasing bicarbonate ion levels with decreasing carbonate ion concentrations) in seawater at the same time. The main importance of ocean acidification is that the pH of seawater affects intracellular solubility of carbonate minerals in calcifying marine organisms that use these minerals in constructing shells, bones,

[1] The Industrial Revolution refers to the period from the mid-1700s to the mid-1800s during which industrial processes transitioned from hand production of goods to machines fueled by burning wood and hydrocarbons.

[2] https://gml.noaa.gov/ccgg/trends/monthly.html, accessed 16 April 2022.

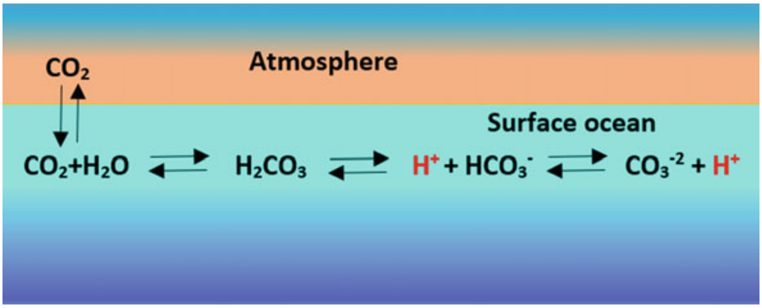


Fig. 11.1 Chemical reactions related to ocean acidification

and cell walls. Impacts of decreasing calcium carbonate saturation state on the base of marine ecosystems are particularly important because they ripple upward through marine food webs.

Surface ocean CO_2 closely follows atmospheric CO_2 concentration, and surface ocean CO_2 concentration is correlated with surface ocean pH (Fig. 11.2). These relationships are expected based on the understanding of CO_2 gas transfer across the air-sea interface and understanding of the carbon system parameters in seawater. This makes it straightforward to predict the extent of ocean acidification globally, based on predicted atmospheric CO_2 concentrations. The chemical changes due to ocean acidification were predicted long before they was observed since the carbonate system in the ocean was described (see review in Brewer 2013) long before the increase in atmospheric CO_2 was systematically observed (Keeling et al. 1976).

The importance of ocean acidification as a priority challenge is recognized by the UN 2030 Agenda for Sustainable Development and specifically by Sustainable Development Goal 14 on "Life Under Water". Target 14.3 is "Minimize and address the impacts of ocean acidification, including through enhanced scientific cooperation at all levels"[3] The indicator identified is "average marine acidity (pH) measured at agreed suite of representative sampling stations".

Information on the impact of ocean acidification is spread across several chapters, which deal with specific resources and threats. This chapter looks at the causes of ocean acidification, traces the history of its impact through time, and describes the likely impacts of ocean acidification on blue economies.

11.2 Causes of Ocean Acidification

Before the Industrial Revolution, CO_2 levels in the ocean and atmosphere changed over time based on natural events and processes, such as releases of CO_2 from Earth's interior due to volcanism (Black et al. 2021) and times of significant production of

---

[3] https://sdgs.un.org/goals/goal14, accessed 2 January 2022.

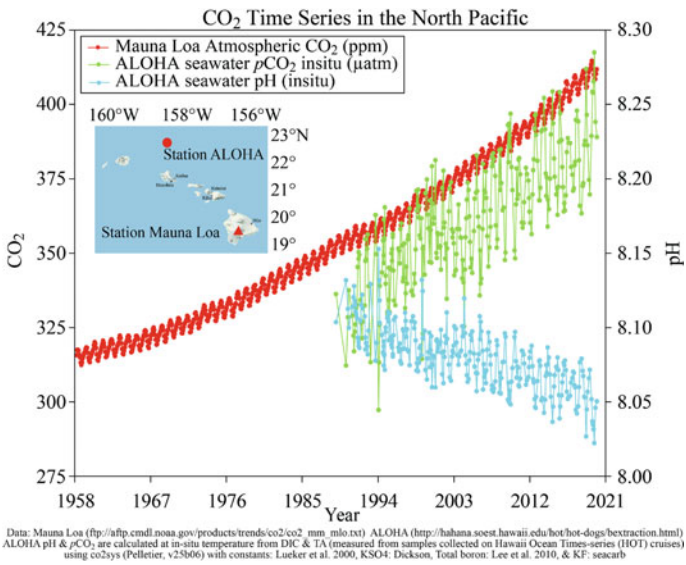


Fig. 11.2 Time series of atmospheric CO_2 at Mauna Loa and at Ocean Station ALOHA in the subtropical North Pacific Ocean (in parts per million volume, ppmv) (top trend line), surface ocean pCO_2 (µatm) (middle trend line), and surface ocean pH (lower trend line) (*Source* https://www.pmel.noaa.gov/co2/file/Hawaii+Carbon+Dioxide+Time-Series, accessed 9 March 2022; Feely et al. 2018)

plant biomass on the land and in the ocean. Over time, the burial of organic carbon in terrestrial and oceanic deposits, plate tectonics, weathering of silicate rocks, and functioning of the oceanic carbonate buffer system, returned the balance of CO_2 fluxes between the atmosphere and ocean (e.g., Berner 1982; Berner et al. 1983).

As described in Sect. 11.1, ocean acidification is caused by the rapid increase of CO_2 in the atmosphere as a result of human activities. The following sections will briefly discuss natural and human sources of ocean acidification to put the current situation into context.

11.2.1 Ocean Acidification in the Geological Record

On the geologic time scale (hundreds of millions of years), changes in the partitioning between CO_2 in the atmosphere and ocean occurred repeatedly and often, sometimes leading to extinctions of organisms sensitive to low seawater pH (Hoenisch et al. 2012). Examination of ocean acidification and its effects in the geologic record can provide hints of possible effects that will occur from the current trend of ocean acidification, although the current rate appears to be much faster than for previous events.

Hoenisch et al. (2012) used proxies to search data for proxies of ocean temperature, oxygen, and pH from the past 300 million years for ocean acidification events that might improve understanding of current increases in ocean acidification. They showed that rapid increases in atmospheric CO_2 result in closer coupling between ocean pH and carbonate saturation. The authors characterized an acidification event as one featuring massive release of CO_2 to the atmosphere (e.g., 30% increase in CO_2 during the Late Pleistocene deglacial transition), and both a reduction in pH and a "substantial lowering" of carbon carbonate saturation for periods of 10,000 years of less. Hoenisch et al. (2012) identified several events that fit these criteria at various times in the past: 11.6–17.8 thousand years ago and 2.6–34, 51–56, 65, 93, 120, 183, and 200 million years ago. The authors noted that the geologically recorded effects on calcifying organisms in the ocean as a result of ocean acidification provide some clues to future impacts, although the faster current rate of ocean acidification compared to the past makes predictions uncertain. The speed of current ocean acidification may have no good analog for the past 300 million years. Hupp et al. (2022) corrected planktonic foraminiferal samples for sediment mixing to re-examine the Paleocene–Eocene Thermal Maximum (PETM) from about 56 million years ago and found a transient decrease in foraminiferal diversity due to heat stress (based on shifts poleward in distributions), with some of these plankton showing signs of reduced calcification, which may have been caused by ocean acidification.

An important lesson from modelling future climate based on past climate excursions is that it is likely to take tens to hundreds of thousands of years for atmospheric CO_2 to return to pre-industrial levels after atmospheric CO_2 levels peak (Tierney et al. 2020). This implies that ocean acidification will be a long-term problem if carbon emissions are not curtailed.

11.2.2 Ocean Acidification Since the Industrial Revolution: Observations and Predictions

The carbonate buffering system of the ocean has been overwhelmed by the amount and speed at which CO_2 has entered the surface ocean from the atmosphere, and consequently, the pH of seawater has been observed to be decreasing steadily (Fig. 11.2).

Ocean acidification as a global problem is well monitored and predictable based on different scenarios for future atmospheric CO_2 levels, but local conditions can lower or raise pH compared to global levels. Some local effects are uncontrollable (e.g., CO_2 venting and upwelling, non-point pollution discharges), whereas other effects can be controlled or mitigated to some degree (e.g., point-source pollution). The extent of ocean acidification and effects on calcium carbonate saturation states vary regionally and can be exacerbated in subsurface coastal waters, including reef areas, by inorganic nutrient pollution (leading to eutrophication and increased dissolved CO_2 from respiration), the input of organic matter (leading to hypoxia) (Cai et al.

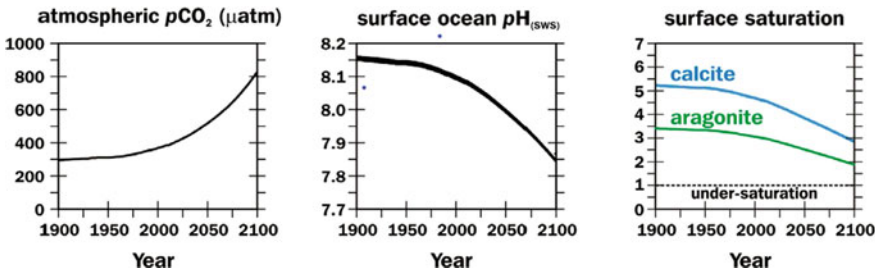


Fig. 11.3 Global ocean surface averages for (left to right): CO_2 partial pressure, pH (seawater scale) and calcite and aragonite saturation. Republished with permission of Elsevier Science &Technology Journals, from Turley C, Eby M, Ridgwell A (2010) The societal challenge of ocean acidification. Mar Pollut Bull 60:787–792; permission conveyed through Copyright Clearance Center, Inc

2011; Cyronak et al. 2014; Wallace et al. 2014), and input of "acid rain" from atmospheric pollution by nitrogen and sulfur compounds (Doney et al. 2007). On the other hand, Su et al. (2020) showed that aquatic vegetation, by uptake of CO_2 in the process of photosynthesis, can reduce ocean acidification locally and downstream from seagrass beds, demonstrating the importance of underwater vegetation in promoting blue economies (see Chap. 3).

It is predicted that ocean pH will decrease by 0.3–0.4 units from pre-industrial levels by 2100 in case of unabated CO_2 release into the atmosphere (Orr et al. 2005, see Fig. 11.3). This may appear to be a small decrease in pH, but is a nearly doubling of hydrogen ions, which will have major effects on seawater carbon chemistry, dissolved inorganic carbon species distribution, and more specifically the solubility of calcium carbonate, which organisms create from calcium and bicarbonate ions in seawater to build their shells and bones. The saturation levels of calcite and aragonite are predicted to decrease with decreasing pH (Fig. 11.3). The minimum pH in 2100 depends on the year in which peak emissions occur (if emissions peak before 2100) and how quickly emissions are reduced; however, in 2500, the pH depends primarily on the cumulative CO_2 emissions to the atmosphere and absorption to the ocean (Bernie et al. 2010).

11.3 Impact of Ocean Acidification on Ocean Ecosystems and Their Products and Services

The history of human civilization has been tightly linked with the ocean as a source of food, means of transport, and provider of other resources. Today, the global economy is heavily dependent on the development of national blue economies, which face challenges due to climate change, particularly ocean acidification. The blue economy concept is largely defined by activities that are linked to the sea, and connected with fisheries and aquaculture, tourism, maritime transport, and energy.

Development of sustainable blue economies will depend on protecting these sectors from the negative effects of ocean acidification and other environmental threats. The most serious problem related to ocean acidification is that it threatens products from the ocean and ecosystem services to society. Pendleton et al. (2016) note that "Increasing levels of atmospheric CO_2 will cause the most immediate and serious problems where (a) human dependence on coral reef ecosystems is high, (b) sea surface temperature reaches critical levels soonest, and (c) OA [ocean acidification] levels are most severe." Brander (2012) provided a summary of the impact pathways for ocean acidification (Fig. 11.4). The primary impacts of ocean acidification on blue economies expected at this point are on marine ecosystems (reef fish and coral populations, marine food webs, biodiversity), resulting in decreases in reef fish catches (Speers et al. 2016) and aquaculture production (Pernet and Browman 2021), reduced ecotourism, and diminished coastal protection. Aquaculture impacts will result from increased difficulties for aquaculture of calcifying organisms, specifically affecting the shellfish industry, because of the adverse effects of lowered pH on their larval development (Kapsenberg et al. 2018). The impacts of ocean acidification on tourism and coastal protection are longer term, because it will take longer for negative effects of ocean acidification on the integrity of coral reefs to be manifested (Brander et al. 2012). Narita et al. (2012) and Speers et al. (2016) estimated the potential economic losses that ocean acidification will cause to global mollusc production ($6–100 billion annually) and reef fish fisheries (5.4–8.4 billion annually), respectively. These figures do not account for subsistence and recreational harvests, in most cases. The high end of the estimates of economic losses are based on the highest anticipated levels of CO_2 increases; it is assumed that lifestyle improvements will lead to greater demand for high-value fish, shellfish and ecotourism in coral reef areas; and likely increases in prices due to increased demand. However, aggregated global numbers do not provide a good representation of the effects of ocean acidification on local communities whose dependence on ocean ecosystems may be mainly in non-market terms.

Economic estimates of the losses from ocean acidification are relatively small in relation to global GDP. This is not surprising, since it is difficult to put all impacts of ocean acidification into economic terms, especially effects that do not enter into market systems, such as subsistence harvests of fish and shellfish, and cultural values of the marine environment.

A variety of organisms are affected by the changes in surface ocean pH (Doney et al. 2009; Kroeker et al. 2010, 2013 and Fig. 11.5) and organisms may be affected differently at different life stages. At the base of marine food webs, calcareous phytoplankton (e.g., coccolithophores), may experience less calcification and more malformation of the plates that surround their cells (Meyer and Riebesell 2015), but increased photosynthesis (Krumhardt et al. 2019), when exposed to higher CO_2. Like other phytoplankton, coccolithophores are consumed by zooplankton, small fish, and larvae of other marine organisms. They also play a key role in transferring calcium carbonate from the surface ocean to depth and thus facilitate the "biological carbon pump." Diatoms, also important phytoplankton at the base of ocean food webs, may change in size and nutritional quality that could affect higher levels of

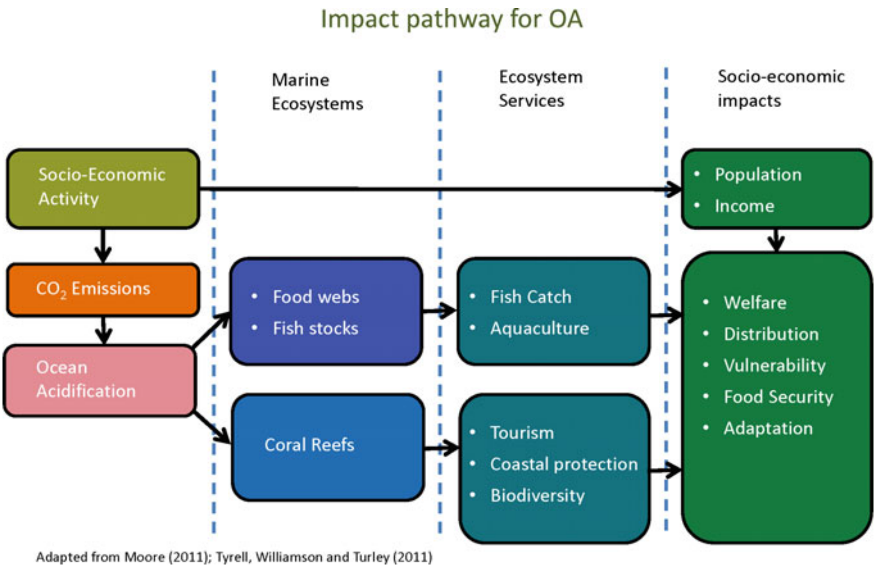


Fig. 11.4 Impact pathways for ocean acidification (Brander 2012). From presentation at Third Symposium on the Ocean in a High-CO_2 World, Monterey, California, USA, 24–27 September 2012

food webs, beginning with zooplankton that graze on the diatoms (Duncan et al. 2022 and references therein). Pteropods, marine snails that float in the water column, are also beginning to show erosion of their shells, presumably from ocean acidification (Bednaršek et al. 2021). Pteropods are major food sources for some fish (e.g., juvenile pink salmon: Armstrong et al. 2005) and marine mammal species. Other molluscs (particularly their larval stages) also appear to be susceptible to ocean acidification (Barton et al. 2012).

Ocean acidification, especially in coastal areas, occurs in an already stressed context. It is predicted that coral reefs, already impacted by marine heatwaves, will experience additional stress from ocean acidification (Cornwall et al. 2021; Klein et al. 2021). It has been recognized in recent years that ocean organisms and ecosystems will be affected by decreasing pH and oxygen, increasing temperature and other factors occurring at the same time as a result of increasing global atmospheric CO_2 concentrations and global temperatures (Sarà et al. 2018; Guan et al. 2020). Some marine plants are expected to benefit from higher seawater CO_2 levels, as exemplified by seagrasses (Palacios and Zimmerman 2007), although species already at their temperature maxima may be negatively impacted by temperature increases (Koch et al. 2013).

The aragonite form of calcium carbonate is particularly susceptible to ocean acidification, but the calcite form of calcium carbonate is also affected. The solubility of CO_2 in seawater is increased by decreases in seawater temperatures, so the impacts of ocean acidification may be seen first in polar regions (Orr et al. 2005; Figuerola

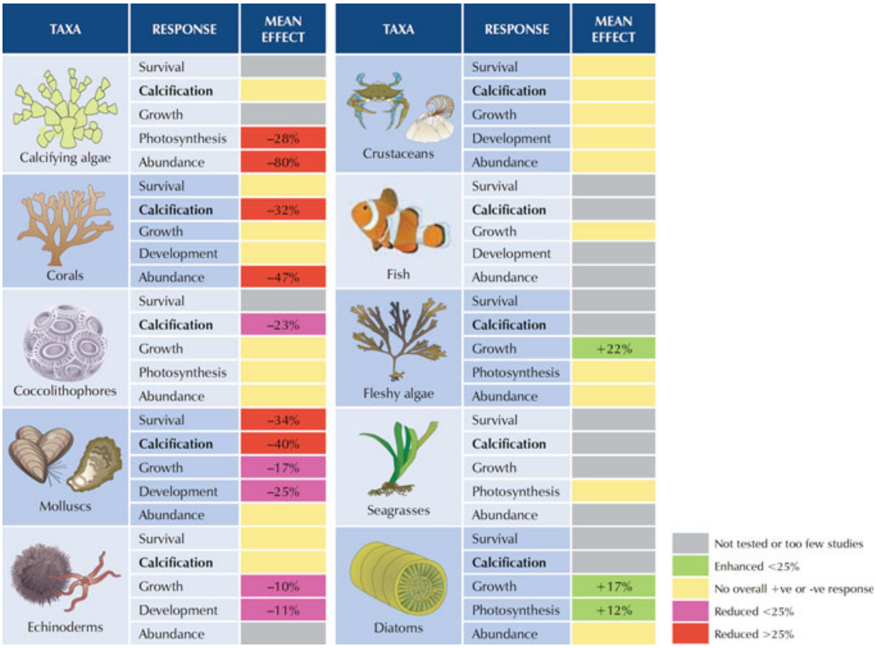


Fig. 11.5 Summary of the responses of selected marine organisms in response to simulated ocean acidification. Republished with permission of Blackwell Publishing LTD., from Kroeker KJ, Kordas RL, Crim R et al. (2013) Impacts of ocean acidification on marine organisms: Quantifying sensitivities and interaction with warming. Glob Change Biol 19:1884–1896; permission conveyed through Copyright Clearance Center, Inc

et al. 2021). The potential negative impacts of ocean acidification on organisms and ecosystems can be seen from areas where CO_2 vents from the seafloor (Aiuppa et al. 2021) and at times when low pH water upwells from the deep ocean to shallow waters (Feely et al. 2008).

In terms of their relevance for blue economies in many tropical developing countries, coral reefs are a major supplier of both products and services (Hoegh-Guldberg et al. 2019). De Groot et al. (2012) estimated that coral reefs have the highest monetary value per hectare of any natural ecosystem. Reefs are threatened by a range of impacts of changing climate, including ocean acidification, but also increasing sea surface temperatures, changes in salinity due to changes in hydrologic cycles, increased damage from cyclones and hurricanes, enhanced suspended particles, increased pollution in areas where more pollutants are washed from land to sea, and increases in coral diseases. Chapter 2 provides more in-depth information about the importance of reefs to blue economies.

11.4 Relevance to Blue Economic Sectors

11.4.1 Impacts of Ocean Acidification on Blue Economies

Other chapters of this book present information on the impacts of ocean acidification on ocean products and services. Chapter 2 presents a short history of the scientific understanding of the impacts of ocean acidification on coral reefs. Chapter 4 points out the dual threats of acidification and temperature increases on coral reefs that support local fisheries and communities. Chapter 9 notes the interactions of various forms of pollution, including ocean acidification. Chapter 10 discusses how ocean acidification, as well as other perturbations to coral reef systems, may lead to increases in the growth of benthic diatoms, including those that cause ciguatera and various other harmful algae-related toxic blooms. Chapter 12 includes a brief section on ocean acidification (Sect. 12.2.5). Chapter 15 on Ocean Observations lists ocean acidification as one of the variables that should be monitored locally for blue economy purposes.

Like many environmental policies, those related to ocean acidification require balancing immediate and tangible economic costs of actions against benefits that will accumulate over decades and centuries. Moore and Fuller (2020) provide a review and synthesis of previous studies on the economic impacts of ocean acidification and the authors provide a comprehensive list of references related to this topic. They defined the following economic sectors: "commercial mollusk harvest, commercial crustacean harvest, commercial finfish harvest, subsistence and recreational fishing, and coral reef recreation." The value of shoreline protection from coral reefs was not included because good estimates were not available. Moore and Fuller (2020) found the largest economic impacts were predicted from the loss of the recreational value of coral reefs. They concluded that more studies of the economic effects of ocean acidification, conducted with comparable methods, are needed. Speers et al. (2016) estimated a major decrease in revenue from reef fishes, with the estimated loss depending on how quickly (if at all) coral species can adapt to increased temperatures to maintain existing reef structures. Costs are mostly borne by local consumers in Asia, particularly in the Coral Triangle,[4] because of their dependence on reef fish for dietary protein. Tal et al. (2021) examined the combined effects of ocean acidification, increased temperature, and deoxygenation on harvests of 210 shellfish species and estimated a 12% decrease in global harvests in 2100 under the highest CO_2 scenario (RCP 8.5), with about one-quarter of the decrease due to ocean acidification. The results of their models also predicted a shift in catches away from the tropics toward the poles, in the RCP 8.5 scenario.

The approach taken by Pendleton et al. (2016) is particularly relevant for this book, in that the authors identified reef areas at high risk from ocean acidification and increasing ocean temperature, where scientific information is also limited.

[4] The Coral Triangle is an area of the Southwest Pacific Ocean dominated by coral reefs, around Indonesia, Malaysia, Papua New Guinea, and the Philippines.

Pendleton et al. (2016) used an indicator approach to identify countries where dependence on local populations for reef-related fishing and protection of shorelines by reefs coincided with the vulnerability of reefs to heat and pH stress. High-risk areas identified by this method include Western Mexico, Micronesia, Indonesia, parts of Australia, and Southeast Asia (Fig. 11.6). Areas that are predicted to show ocean acidification effects and high temperature effects on reefs do not overlap because acidification is worst at lower temperatures and coral bleaching is worst at higher temperatures (Van Hooidonk et al. 2014). Cooley et al. (2012) examined the vulnerability of national mollusc harvests, exports and imports, and reliance on molluscs as protein for human diets, as a function of predicted ocean acidification in terms of carbonate saturation. They predicted transition decades (2020s–2070s) by country and region, when mollusc production would begin to decrease from current production levels. Cooley et al. (2012) calculated "total hardship points" as an index to rank the severity of effects on different countries. Developing countries top the list.

Since 2010, the Centre Scientifique de Monaco (CSM) and IAEA Environmental Laboratories (IAEA-EL) have cooperated to organize a series of biennial workshops on Bridging the Gap Between Ocean Acidification and Economic Valuation, with the first results reported in Hilmi et al. (2013). Sixty-two experts participated in the fourth workshop, in 2017, which focused on the ecological and socioeconomic risks to coral reefs in 6 regions of the world, as well as potential solutions to mitigate the risks (Allemand and Osborn 2019). Figure 11.7 presents the approaches proposed. Hilmi et al. (2019) provide more detailed explanations of economic, legal, and regulatory approaches to protect coral reefs ranging from international to national levels.

11.4.1.1 Mitigation of Global-Level Impacts

As mentioned earlier, ocean acidification arises because of the rapid release of CO_2 to the atmosphere due to human activities such as industrial production, transportation, farming, deforestation, and construction, and subsequent absorption of CO_2 by the ocean. As with many environmental problems, ocean acidification results because the atmosphere is a "common-pool resource" and the people and countries that produce the most CO_2 are different from those that will suffer the effects of this pollution the most, including global warming, sea level rise, and ocean acidification. As noted by Hilmi et al. (2019), it is possible to control CO_2 emissions using economic instruments such as carbon taxes, subsidies for emission-reduction approaches, and/or emissions trading systems. However, so far, these approaches have not been acceptable to the countries accounting for the most emissions. Billé et al. (2013) recommended that management responses to ocean acidification of four types could be pursued simultaneously: "preventing ocean acidification, strengthening ecosystem resilience, adapting human activities, and repairing damages."

A variety of geoengineering approaches have been discussed to deal with global change, but approaches that only reduce incoming solar radiation would not reduce ocean acidification. Fertilization of the ocean with iron or other nutrients to increase the removal of CO_2 from the surface ocean has been tested at various scales (Boyd

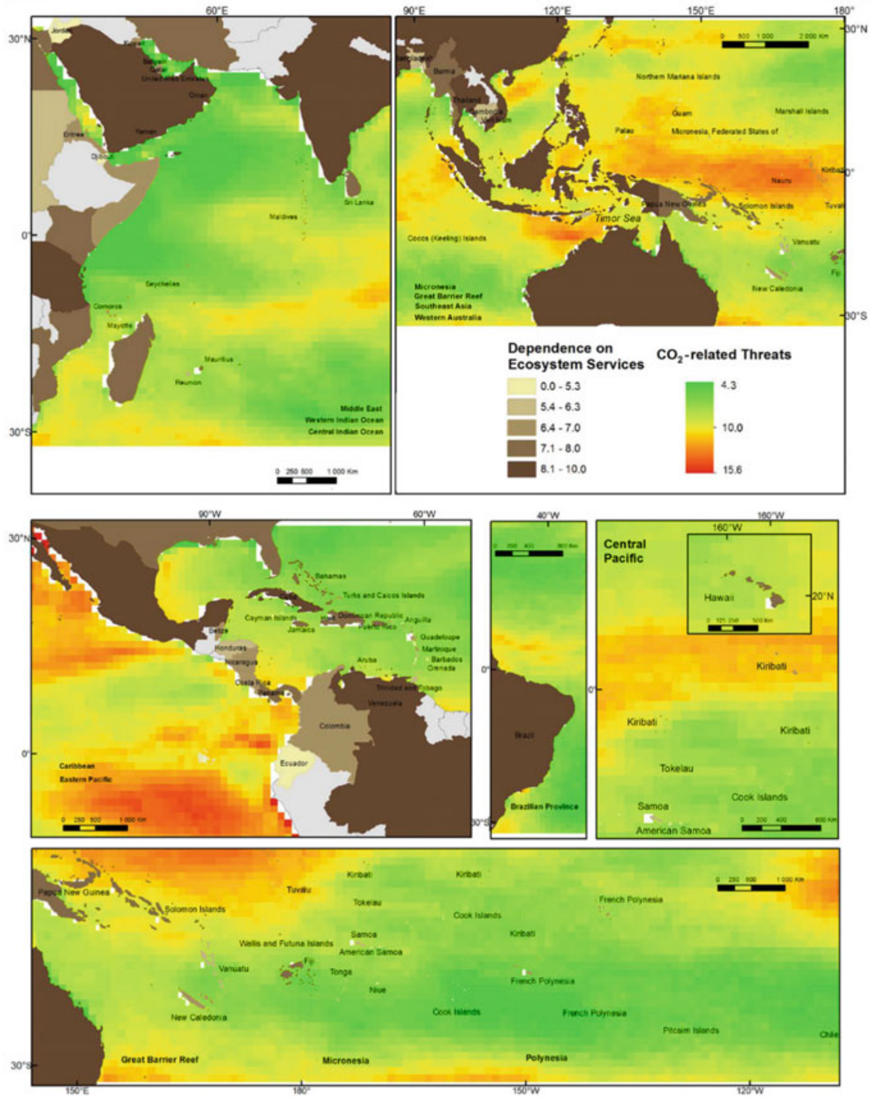


Fig. 11.6 Country-level dependence on coral reef ecosystem services and future combined normalized scores (2 ± 20) for CO_2-related threats (e.g., ocean acidification and thermal stress). Ocean Provinces are indicated in each panel in bold. Higher scores indicate higher dependence and higher ecological risk. From Pendleton et al. (2016) Reuse by CC0 1.0 Universal (CC0 1.0). Public Domain Dedication

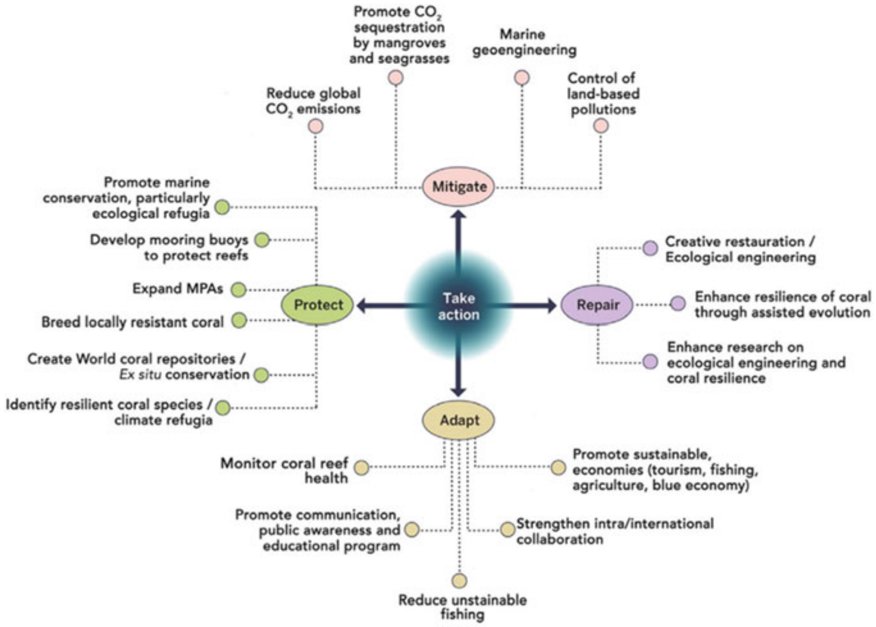


Fig. 11.7 Solutions for coral reefs against climate change impact. Republished with permission of Elsevier Science & Technology Journals, from Allemand D, Osborn D (2019) Ocean acidification impacts on coral reefs: From sciences to solutions. Regional Studies in Marine Science 28:100, 558, permission conveyed through Copyright Clearance Center, Inc

et al. 2012) and, through experiments and modelling, have been shown to be ineffective and would probably have large-scale unintended consequences (Wallace et al. 2010), and perhaps intensify ocean acidification. Bach and Boyd (2021) recommend that geoengineering approaches be assessed based on natural analogs such as "(1) equatorial upwelling as a natural analog for artificial upwelling, (2) downstream of Kerguelen Island for ocean iron fertilization, (3) the Black and Caspian Seas for ocean alkalinity enhancement, and (4) the Great Atlantic Sargassum Belt for ocean afforestation." Ocean alkalinity enhancement has received much attention (e.g., Hartmann et al. 2013), although it is probably most cost-effective at a local, rather than global, scale.

Renewable, non-carbon energy sources are slowly increasing their share of the global energy portfolio, but the transition could take decades (see Chap. 7). Non-carbon energy sources are needed to solve the global ocean acidification problem. Harrould-Kolieb and Hoegh-Guldberg (2019) note that there is no over-arching international framework to address the issue of ocean acidification. They discuss how a network of existing governance structures might be applied, with the objectives (1) to "limit future acidification via mitigation; (2) to alleviate the impacts of OA through adaption; and (3) to redress residual harm." However, Harrould-Kolieb (2020) suggests that the UN Convention on the Law of the Sea (UNCLOS) could be comprehensive enough to establish a “governing framework” to address ocean acidification, particularly if the UN Framework Convention on Climate Change is not successful at reducing carbon dioxide emissions. Part XII of UNCLOS (Protection and Preservation of the Marine Environment) might be particularly useful. Harrould-Kolieb (2020) interprets Part XII (based on the arbitrated cases in the South China Sea and Chagos Islands) to “convey that States are required to take active steps to ‘protect’ from future damage and to ‘preserve’ the current state of the marine environment or improve it if necessary.” Articles 192 and 194 cover the area of marine pollution, of which CO_2 pollution and the resulting ocean acidification can be considered as examples. Use of UNCLOS to manage ocean acidification could be accomplished through the development of new implementing agreements, addition to existing implementing agreements (e.g., the United Nations Fish Stocks Agreement), and/or through international standards and rules developed in relation to UNCLOS (e.g., the London Protocol [LP] to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter and the International Convention for the Prevention of Pollution from Ships).

11.4.1.2 Mitigation of Local Impacts

Local measures could be used to mitigate or adapt to ocean acidification. Albright and Cooley (2019) provide a useful inventory of possible approaches, including “passive approaches” (measures to remove sources of stress that hinder natural recovery) and active approaches (measures that physically manipulate local systems to improve function) Passive approaches include use of marine spatial planning to move damaging activities away from sensitive reef areas and establishment of marine protected areas to protect reef areas; and mitigating other sources of stress to reef areas (e.g., improved wastewater treatment to decrease eutrophication, Guan et al. 2020), Active approaches include physical restoration of reefs, including with farmed corals (National Academies of Sciences, Engineering, and Medicine 2019) that have been selected for temperature tolerance of corals and the zooxanthellae algae they host; increasing the extent of seagrass beds near coral reefs (phytoremediation); and/or chemical remediation to buffer ocean acidification.

Albright and Cooley (2019) note that, although these approaches may be too expensive to apply globally (see Table 11.1), they could be used to mitigate impacts in particularly high-value reef environments. Van Oppen et al. (2017) further explore the options for active approaches and they propose options that could be used to maintain some coral reefs (and the products and services they provide) when environmental conditions make it impossible to save all reefs, and they include a decision tree for determining intervention steps. Local and national mitigation efforts can be costly, but local measures such as park entrance fees and tourist taxes can help support such efforts. For example, Chap. 6 describes the Pristine Paradise Environmental Fee implemented in Palau in 2018. The $100 fee is assessed on each incoming air ticket of visitors and is used, at least partially, to help support the Palau National Marine Sanctuary.

Table 11.1 Comparison of OA mitigation and adaptation strategies on the basis of cost, readiness, and obstacles. Where possible, costs are standardized to $USD ha^{-1}$. "Readiness" reflects a spectrum of development starting with a theoretical understanding based on a combination of lab studies, natural analogs, and computational models, moving on to field tests (small to medium-scale implementation), and finally broad-scale implementation. Primary barriers to implementation include knowledge, economic, technical, and political obstacles. Adapted from Albright and Cooley (2019) and Rau et al. (2013). Republished with permission of Elsevier Science & Technology Journals, from Albright R, Cooley S (2019) A review of interventions proposed to abate impacts of ocean acidification on coral reefs. Regional Studies in Marine Science 29:100,612; permission conveyed through Copyright Clearance Center, Inc

Intervention	Cost	Readiness	Primary barrier(s) to implementation
Phytoremediation	\$400,000–\$700,000 USD ha^{-1} (Goreau 2014)	Field tests and model calculations based on natural analogs	Knowledge, technical
Liming	\$150–\$1000 metric ton^{-1} CO_2 (Duarte et al. 2010)	Theoretical understanding based on model calculations	Technical, economic, political
Electrolytic buffering	< \$100 per metric ton of CO_2 mitigated Rau et al. (2013)	Theoretical understanding based on lab studies	Economic, logistical
Coral gardening & Sexual propagation	\$10,000–\$160,000 USD ha^{-1} (Young et al. 2012; Goreau 2014)	Field tests and broad-scale implementation	Technical, economic
Assisted evolution		Theoretical understanding based on lab studies	Knowledge
Physical restoration (Artificial reefs)	\$1–10 million USD ha^{-1} (McLeod et al. 2008)	Field tests and broad-scale implementation	Political, technical, economic

11.5 Outreach and Networks

Ocean acidification has gained prominence as a major global change issue in the scientific community and policy discussions, beginning with the first symposium on The Ocean in a High-CO_2 World, convened by the Scientific Committee on Oceanic Research and the Intergovernmental Oceanographic Commission in 2004 (Cicerone et al. 2004). These symposia (four completed and one planned for 2022) stimulated the advance of the field of ocean acidification research by bringing marine biologists and chemists together once every four years to present recent research and to plan new studies (Cicerone et al. 2004; Orr et al. 2009).

In this context, the role that the Marine Environment Laboratories (MEL) in Monaco, the IAEA Ocean Acidification International Coordination Centre (OA-ICC) is playing in the provision of ocean science for humanity should be mentioned. The OA-ICC is working to increase awareness, organize workshops, build capacity, develop new collaborations, and promote research in the field of ocean acidification. The Centre also provides a data portal, helps in calibrating methods, and is developing best practice guides for ocean acidification research. The OA-ICC involves many international partners and supports global and regional ocean acidification networks, including the Global Ocean Acidification Observing Network (GOA-ON), and also popularizes the concept of sustainable development to ensure uninterrupted ecosystem services and flourishing blue economies for future generations.

11.6 Science to Address Ocean Acidification Impacts on Blue Economy Resources

Ocean acidification alone may drive significant ecological changes that are directly related to society and livelihood, but now the concept of multiple stressors is coming into prominence (Kroeker et al. 2017). Other climate change variables and increasing levels of pollutants may synergistically be intensified by ocean acidification and the adverse impacts are highly unpredictable. For example, increasing eutrophication may impact coastal primary producers differently from open ocean phytoplankton in low-nutrient environments, in the context of ocean acidification. However, some stressors may help to alleviate the adverse impact of ocean acidification on certain marine organisms (Wu et al. 2014). Therefore, a "multiple stressor approach" needs to be adopted for future experimental studies (Boyd et al. 2018) for marine organisms from various trophic levels.

Some organisms at higher trophic levels can be impacted indirectly by ocean acidification due to the change in availability of their preferred prey, while the direct impacts of ocean acidification on the predator is negligible. Such information about trophic effects of ocean acidification is necessary to predict the changes in food webs that could be caused by ocean acidification.

Research and observations will be necessary to provide more complete information to implement any of the proposed approaches to develop and maintain blue economies. Albright and Cooley (2019) note that "Many obstacles can stand between an intervention and its implementation. Most commonly, knowledge barriers slow the use of interventions. Because scientists have incomplete knowledge of mechanisms, ecological relationships, and socioeconomic responses to OA impacts on coral reef ecosystems, it is difficult for managers to justify and approve interventions." New ocean science activities are necessary on both global and national levels to explore ways to reduce the threats of ocean acidification to blue economies. Increased ocean science (observations and research) is needed to predict, mitigate, and adapt to changes that ocean acidification will bring to coastal areas (Cattano et al. 2018). It is helpful to consider observations and research separately, although there is a continuum between the two; many observations are collected for research purposes and observations collected systematically by governments or other institutions can provide a significant data resource for scientists.

Furthermore, most of the experimental and modeling studies on ocean acidification provide information about sensitive species; however, research on resilient species is also very important. Besides mitigation of ocean acidification, identifying low-pH tolerant species, particularly for aquaculture and shellfish industries, can be based on local information and research. For example, several studies have shown the resilience of larger organisms of commercial importance (e.g., fish) to low pH conditions (Hurst et al. 2013; Gobler and Talmage 2014; Kwan et al. 2021). Moreover, while climate change intensifies, there are also continuous biological adaptations that are happening simultaneously in nature. Future research should also identify those changes and the organisms that may be better suited for conditions in the future ocean.

11.6.1 Observations

Pendleton et al. (2016) concluded that many of the areas in which local communities are most vulnerable to the effects of ocean acidification and increased ocean temperatures are also areas lacking necessary observing, reporting, and analysis systems for environmental parameters related to ocean acidification. The amplification of ocean acidification effects in coastal areas—where international observing systems often are barred because of limited access to exclusive economic zones—implies the need for robust observing systems for pH and other ocean carbon variables deployed as components of national ocean observations (see Chap. 14). Data are sparse in relation to environmental factors affecting reef health and on socioeconomic measures of the importance of reefs to local communities and the impact of local development levels on reef health (Cinner et al. 2009). Pendleton et al. (2016) recommend a global strategy to target new research and observations in areas most at risk and currently lacking information, such as through GOA-ON (Tilbrook et al. 2019).[5] GOA-ON is stimulating training for observations and data management related to ocean acidification, and its program on "Ocean Acidification Research for Sustainability" was approved as an activity of the UN Decade on Ocean Science for Sustainable Development.

As stated previously, understanding of the ocean carbonate system and the skill of global models makes it possible to predict pH levels throughout the global ocean based on different IPCC scenarios. However, because surface ocean pH can be affected by local factors explained earlier, local measurements are necessary for pH and general ocean conditions that interact with pH (e.g., temperature, pH, nutrients, oxygen). Also needed are local observations of the health of organisms and ecosystems affected by low pH, particularly those that are main components of blue economy activities (e.g., coral reefs, shellfish).

Monitoring of coral reefs is an important approach to understand the effects of ocean acidification and other threats to coral reefs. The Global Coral Reef Monitoring

[5] Global Ocean Acidification Observing Network (GOA-ON) Website: http://www.goa-on.org/.

Network leads global efforts to assess the status of coral reefs globally (see Chap. 2). The Global Ocean Observing System includes an Essential Ocean Variable on Hard Coral Cover and Composition.[6]

11.6.2 Research

Research is still needed on a variety of topics at both national and global levels:

- effectiveness of large-scale marine carbon dioxide removal approaches (Bach and Boyd 2021);
- potential impacts of ocean acidification on "species that humans culture, harvest and/or consume (e.g., molluscs, crustaceans, fish)", but also including species important in marine ecosystems, and the timing of impacts (Hilmi et al. 2013);
- effects of projected levels of ocean acidification on important life stages of representative organisms important to help sustain blue economies;
- effects of multiple stressors, including ocean acidification (Boyd et al. 2018);
- abilities of organisms to adapt to and evolve to tolerate rapid pH decreases;
- technical effectiveness and the cost-benefit tradeoffs of local interventions (passive and active) to reverse ocean acidification in small areas (Albright and Cooley 2019); and
- resilience of communities to changes in the products and services provided by coral reefs (Hoegh-Guldberg et al. 2019).

Increased observations and research must be implemented to develop and sustain blue economies.

In summary, ocean acidification is a major likely threat to blue economies, particularly in developing coastal nations and small island developing states. Ocean science—both observations and research—can play a significant role in understanding the potential impacts of ocean acidification, as well as creating mitigation and adaptation approaches.

References

Aiuppa A, Hall-Spencer JM, Milazzo M et al (2021) Volcanic CO_2 seep geochemistry and use in understanding ocean acidification. Biogeochemistry 152:93–115. https://doi.org/10.1007/s10533-020-00737-9

Allemand D, Osborn D (2019) Ocean acidification impacts on coral reefs: from sciences to solutions. Reg Stud Mar Sci 28:100558

[6] https://www.goosocean.org/index.php?option=com_oe&task=viewDocumentRecord&docID=17512, accessed 2 March 2022.

Albright R, Cooley S (2019) A review of interventions proposed to abate impacts of ocean acidification on coral reefs. Reg Stud Mar Sci 29:100612. https://doi.org/10.1016/j.rsma.2019.100612

Armstrong JL, Boldt JL, Cross AD et al (2005) Distribution, size, and interannual, seasonal and diel food habits of northern Gulf of Alaska juvenile pink salmon, *Oncorhynchus gorbuscha*. Deep-Sea Res II 52:247–265

Bach LT, Boyd PW (2021) Seeking natural analogs to fast-forward the assessment of marine CO_2 removal. Proc Natl Acad Sci USA 118(40):e2106147118. https://doi.org/10.1073/pnas.2106147118

Barton A, Hales B, Waldbusser GG et al (2012) The Pacific oyster, *Crassostrea gigas*, shows negative correlation to naturally elevated carbon dioxide levels: implications for near-term ocean acidification effects. Limnol Oceanogr 57:698–710

Bednaršek N, Naish K-A, Feely RA et al (2021) Integrated assessment of ocean acidification risks to pteropods in the northern high latitudes: regional comparison of exposure, sensitivity and adaptive capacity. Front Mar Sci 8:671497. https://doi.org/10.3389/fmars.2021.671497

Berner RA (1982) Burial of organic carbon and pyrite sulfur in the modern ocean: its geochemical and environmental significance. Am J Sci 282:451–473

Berner RA, Lasaga AC, Garrels RM (1983) The carbonate-silicate geochemical cycle and its effect on atmospheric carbon dioxide over the past 100 million years. Am J Sci 283:641–683

Bernie D, Lowe J, Tyrrell T et al (2010) Influence of mitigation policy on ocean acidification. Geophys Res Lett 37:L15704. https://doi.org/10.1029/2010GL043181

Billé R, Kelly R, Biastoch A et al (2013) Taking action against ocean acidification: a review of management and policy options. Environ Manage 52(4):761–779. https://doi.org/10.1007/s00267-013-0132-7

Black BA, Karlstroim L, Mather TA (2021) The life cycle of large igneous provinces. Nat Rev Earth Environ 2(12):840–857. https://doi.org/10.1038/s43017-021-00221-4

Boyd PW, Bakker DCE, Chandler C (2012) A new database to explore the findings from large-scale ocean iron enrichment experiments. Oceanography 25(4):64–71. https://doi.org/10.5670/oceanog.2012.104.

Boyd PW, Collins S, Dupont S et al (2018) Experimental strategies to assess the biological ramifications of multiple drivers of global ocean change—a review. Glob Change Biol 24(6):2239–2261

Brander LM (2012) Presentation given at Third International Symposium on the Ocean in a High-CO_2 World on 26 September 2012 in Monterey, California, USA.

Brander LM, Rehdanz K, Tol RSJ et al (2012) The economic impact of ocean acidification on coral reefs. Clim Chang Econ 3(1):1250002. https://doi.org/10.1142/S2010007812500029

Brewer, PG (2013) A short history of ocean acidification science in the 20th century: a chemist's view. Biogeosciences 10:7411–7422. https://doi.org/10.5194/bg-10-7411-2013

Cai WJ, Hu X, Huang WJ (2011) Acidification of subsurface coastal waters enhanced by eutrophication. Nat Geosci 4:766–770

Cattano C, Claudet J, Domenici P et al (2018) Living in a high CO_2 world: a global meta-analysis shows multiple trait-mediated fish responses to ocean acidification. Ecol Monogr 88(3):320–335

Cicerone R, Orr J, Brewer P et al (2004) The Ocean in a high-CO_2 world. Oceanography 17(3):72–78

Cinner JE, McClanahan TR, Daw TM et al (2009) Linking social and ecological systems to sustain coral reef fisheries. Curr Biol 19:206–212. https://doi.org/10.1016/j.cub.2008.11.055

Cooley SR, Lucey N, Kite-Powell H et al (2012) Nutrition and income from molluscs today imply vulnerability to ocean acidification tomorrow. Fish Fish 13:182–215

Cornwall CE, Comeau S, Kornder NA et al (2021) Global declines in coral reef calcium carbonate production under ocean acidification and warming. Proc Natl Acad Sci USA 118(21):e2015265118. https://doi.org/10.1073/pnas.2015265118

Cyronak T, Schulz KG, Santos IR et al (2014) Enhanced acidification of global coral reefs driven by regional biogeochemical feedbacks. Geophys Res Lett 41:5538–5546. https://doi.org/10.1002/2014GL060849

De Groot R, Brander L, van der Ploeg S et al (2012) Global estimates of the value of ecosystems and their services in monetary units. Ecosyst Serv 1(1):50–61. https://doi.org/10.1016/j.ecoser.2012.07.005

Doney SC, Mahowald N, Lima I et al (2007) Impact of anthropogenic atmospheric nitrogen and sulfur deposition on ocean acidification and the inorganic carbon system. Proc Natl Acad Sci USA 104:14,580–14,585

Doney SC, Fabry VJ, Feely RA et al (2009) Ocean acidification: the other CO_2 problem. Annu Rev Mar Sci 1:169–192. https://doi.org/10.1146/annurev.marine.010908.163834

Duarte CM, Marbà N, Gacia E et al (2010) Seagrass community metabolism: assessing the carbon sink capacity of seagrass meadows. Glob Biogeochem Cycles 24(4), https://doi.org/10.1029/2010GB003793

Duncan RJ, Nielsen DA, Sheehan CE et al (2022) Ocean acidification alters the nutritional value of Antarctic diatoms. New Phytol 233(4):1813–1827. https://doi.org/10.1111/nph.17868

Feely RA, Sabine CL, Hernandez-Ayon M et al (2008) Evidence for upwelling of corrosive "acidified" water onto the continental shelf. Science 320(5882):1490–1492. https://doi.org/10.1126/science.1155676

Feely RA, Wanninkhof R, Carter BR et al (2018) Global ocean carbon cycle. In the State of the Climate in 2017, Global Oceans. Bull Am Meteorol Soc 99(8):S96–S100. https://doi.org/10.1175/2018BAMSStateoftheClimate.1

Figuerola B, Hancock AM, Bax N (2021) A review and meta-analysis of potential impacts of ocean acidification on marine calcifiers from the Southern Ocean. Front Mar Sci 8:584445. https://doi.org/10.3389/fmars.2021.584445

Gobler CJ, Talmage SC (2014) Physiological response and resilience of early life-stage Eastern oysters (*Crassostrea virginica*) to past, present and future ocean acidification. Conserv Physiol 2(1):cou004

Goreau, TJ (2014) Biorock benefits. Biorock Technology, p. 23.

Gruber N, Clement D, Carter BR et al (2019) The oceanic sink for anthropogenic CO_2 from 1994 to 2007. Science 363(6432):1193–1199. https://doi.org/10.1126/science.aau5153

Guan Y, Hohn S, Wild C et al (2020) Vulnerability of global coral reef habitat suitability to ocean warming, acidification and eutrophication. Glob Change Biol 26:5646–5660. https://doi.org/10.1111/gcb.15293

Harrould-Kolieb ER, Hoegh-Guldberg O (2019) A governing framework for international ocean acidification policy. Mar Policy 102:10–20. https://doi.org/10.1016/j.marpol.2019.02.004

Harrould-Kolieb ER (2020) The UN Convention on the Law of the Sea: a governing framework for ocean acidification? RECIEL 29:257–270. https://doi.org/10.1111/reel.12321

Hartmann J, West AJ, Renforth P et al (2013) Enhanced chemical weathering as a geoengineering strategy to reduce atmospheric carbon dioxide, supply nutrients, and mitigate ocean acidification. Rev Geophys 51:113–149

Hilmi N, Allemand D, Dupont S et al (2013) Towards improved socio-economic assessments of ocean acidification's impacts. Mar Biol 160:1773–1787. https://doi.org/10.1007/s00227-012-2031-5

Hilmi N, Osborn D, Acar S et al (2019) Socio-economic tools to mitigate the impacts of ocean acidification on economies and communities reliant on coral reefs—a framework for prioritization. Reg Stud Mar Sci 28:100559

Hoenisch B, Ridgwell A, Schmidt DN et al (2012) The geological record of ocean acidification. Science 335:1058–1063. https://doi.org/10.1126/science.1208277

Hoegh-Guldberg O, Pendleton L, Kaup A (2019) People and the changing nature of coral reefs. Reg Stud Mar Sci 30:100699. https://doi.org/10.1016/j.rsma.2019.100699

Hupp BN, Kelly DC, Williams JW. 2022. Isotopic filtering reveals high sensitivity of planktic calcifiers to Paleocene–Eocene thermal maximum warming and acidification. Proc Natl Acad Sci USA 119(9):e2115561119

Hurst TP, Fernandez ER, Mathis JT (2013) Effects of ocean acidification on hatch size and larval growth of walleye pollock (*Theragra chalcogramma*). ICES J Mar Sci 70(4):812–822

IPCC (2021) Summary for policymakers. In: Masson-Delmotte V, Zhai P, Pirani A et al (eds) Climate change 2021: the physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. In Press

Joos F, Spahni R (2008) Rates of change in natural and anthropogenic radiative forcing over the past 20,000 years. Proc Natl Acad Sci USA 105:1425–1430. https://doi.org/10.1073/pnas.0707386105,2008

Kapsenberg L, Miglioli A, Bitter MC et al (2018) Ocean pH fluctuations affect mussel larvae at key developmental transitions. Proc Roy Soc B 285(1893):20182381

Keeling CD, Bacastow RB, Bainbridge AE et al (1976) Atmospheric carbon dioxide variations at Mauna Loa Observatory Hawaii. Tellus 28(6):538–551. https://doi.org/10.3402/tellusa.v28i6.11322

Klein SG, Geraldi NR, Anton A et al (2021) Projecting responses to intensifying marine heatwaves under ocean acidification. Glob Change Biol. 28(5):1753–1765. https://doi.org/10.1111/gcb.15818

Koch M, Bowes G, Ross C et al (2013) Climate change and ocean acidification effects on seagrasses and marine macroalgae. Glob Change Biol 19(1):103–132

Kroeker KJ, Kordas RL, Crim RN et al (2010) Meta-analysis reveals negative yet variable effects of ocean acidification on marine organisms. Ecol Lett 13:1419–1434. https://doi.org/10.1111/j.1461-0248.2010.01518

Kroeker KJ, Kordas RL, Crim R et al (2013) Impacts of ocean acidification on marine organisms: quantifying sensitivities and interaction with warming. Glob Change Biol 19:1884–1896. https://doi.org/10.1111/gcb.12179

Kroeker KJ, Kordas RL, Harley CD (2017) Embracing interactions in ocean acidification research: confronting multiple stressor scenarios and context dependence. Biol Lett 13(3):20160802

Krumhardt KM, Lovenduski NS, Long MC et al (2019) Coccolithophore growth and calcification in an acidified ocean: insights from community earth system model simulations. J Adv Model Earth Syst 11:1418–1437. https://doi.org/10.1029/2018MS001483

Kwan GT, Shen SG, Drawbridge M et al (2021) Ion-transporting capacity and aerobic respiration of larval white seabass (*Atractoscion nobilis*) may be resilient to ocean acidification conditions. Sci Total Environ 791:148285

McLeod E, Salm RV, Anthony K et al (2008) The Honolulu Declaration on Ocean Acidification and reef management. The Nature Conservancy, USA

Meyer J, Riebesell U (2015) Reviews and syntheses: responses of coccolithophores to ocean acidification: a meta-analysis. Biogeosciences 12(6):1671–1682. https://doi.org/10.5194/bg-12-1671-2015

Moore C, Fuller J (2020) Economic impacts of ocean acidification: a meta-analysis. National Center for Environmental Economics (NCEE) Working Paper 20–02. https://www.epa.gov/sites/default/files/2020-10/documents/2020-02.pdf

Narita D, Rehdanz K, Tol RSJ (2012) Economic costs of ocean acidification: a look into the impacts on global shellfish production. Clim Chang 113:1049–1063

National Academies of Sciences, Engineering, and Medicine (2019) A research review of interventions to increase the persistence and resilience of coral reefs. The National Academies Press, Washington, DC. https://doi.org/10.17226/25279

Orr JC, Fabry VJ, Aumont O et al (2005) Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. Nature 437:681–686

Orr JC, Caldeira K, Fabry V et al (2009) Research priorities for understanding ocean acidification: summary from the Second Symposium on The Ocean in a High-CO_2 World. Oceanography 22(4):182–189

Palacios SL, Zimmerman RC (2007) Response of eelgrass *Zostera marina* to CO_2 enrichment: possible impacts of climate change and potential for remediation of coastal habitats. Mar Ecol Prog Ser 344:1–13. https://doi.org/10.3354/meps07084

Pendleton L, Comte A, Langdon C et al (2016) Coral reefs and people in a high-CO_2 world: where can science make a difference to people? PLoS ONE 11(11):e0164699. https://doi.org/10.1371/journal.pone.0164699

Pernet F, Browman HI (2021) The future is now: marine aquaculture in the Anthropocene. ICES J Mar Sci 78(1):315–322. https://doi.org/10.1093/icesjms/fsaa248

Rau GH, Carroll SA, Bourcier WL et al (2013) Direct electrolytic dissolution of silicate minerals for air CO_2 mitigation and carbon-negative H_2 production. Proc Natl Acad Sci USA 110(25):10095–10100. https://doi.org/10.1073/pnas.1222358110

Sarà G, Mangano MC, Johnson M et al (2018) Integrating multiple stressors in aquaculture to build the blue growth in a changing sea. Hydrobiologia 809:5–17

Speers AE, Besedin EY, Palardy JE et al (2016) Impacts of climate change and ocean acidification on coral reef fisheries: an integrated ecological–economic model. Ecol Econ 128:33–43. https://doi.org/10.1016/j.ecolecon.2016.04.012

Su J, Cai WJ, Brodeur J et al (2020) Chesapeake Bay acidification buffered by spatially decoupled carbonate mineral cycling. Nat Geosci 13(6):441–447. https://doi.org/10.1038/s41561-020-0584-3

Tai TC, Sumaila UR, Cheung WWL (2021) Ocean acidification amplifies multi-stressor impacts on global marine invertebrate fisheries. Front Mar Sci 8:596644. https://doi.org/10.3389/fmars.2021.596644

Tierney JE, Poulsen CJ, Montañez IP et al (2020) Past climates inform our future. Science 370(6517). https://doi.org/10.1126/science.aay3701

Tilbrook B, Jewett EB, DeGrandpre MD et al (2019) An enhanced ocean acidification observing network: from people to technology to data synthesis and information exchange. Front Mar Sci 6:337. https://doi.org/10.3389/fmars.2019.00337

Turley C, Eby M, Ridgwell A (2010) The societal challenge of ocean acidification. Mar Pollut Bull 60:787–792

Van Hooidonk R, Maynard JA, Manzello D et al (2014) Opposite latitudinal gradients in projected ocean acidification and bleaching impacts on coral reefs. Glob Change Biol 20:103–112. https://doi.org/10.1111/gcb.1239

Van Oppen MJH, Gates RD, Blackall LL et al (2017) Shifting paradigms in restoration of the world's coral reefs. Glob Change Biol 23:3437–3448. https://doi.org/10.1111/gcb.13647

Wallace DWR, Law CS, Boyd PW et al (2010) Ocean fertilization. A scientific summary for policy makers. IOC/UNESCO, Paris (IOC/BRO/2010/2).

Wallace RB, Baumann H, Grear JS et al (2014) Coastal ocean acidification: the other eutrophication problem. Estuar Coast Shelf Sci 148:1–13

Woodwell GM, Hobbie JE, Houghton RA et al (1983) Global deforestation: contribution to atmospheric carbon dioxide. Science 222(4628):1081–1086. https://doi.org/10.1126/science.222.4628.1081

Wu Y, Campbell DA, Gao K (2014) Faster recovery of a diatom from UV damage under ocean acidification. J Photochem Photobiol, B 140:249–254

Young CN, Schopmeyer SA, Lirman D (2012) A review of reef restoration and coral propagation using the threatened genus *Acropora* in the Caribbean and Western Atlantic. Bull Mar Sci 88:1075–1098. https://doi.org/10.5343/bms.2011.1143

Chapter 12
Climate Change and Coastal Systems

P. N. Vinayachandran, Denis Chang Seng, and Fiona Amrai Schmid

Abstract Coastal zones are inhabited by about 37% of the global population, most of which depend on the ocean for their livelihood. Coastal zones have also been the centers of rapid economic development and are likely to remain so in the development of blue economies. Climate change threatens blue economies because of rising sea temperatures and sea levels, and increasing frequency of extreme events, salinization, ocean acidification and deoxygenation, affecting coastal habitats, ecosystems and resources that are the foundations of blue economies. Land- and sea-based human activities related to coastal development add to these climate-induced pressures. This chapter addresses these pressures, their trends and impact on coastal systems, resources and the associated blue economy sectors, as well as strategies for management and adaptation. Case studies from the Seychelles and Bangladesh describe the efforts and pending needs for combating or adapting to the impacts of climate change. They identify improved scientific assessments based on observations and models as a critical need for effective coastal management that can support the development of sustainable blue economies.

Keywords Climate change · Sea level rise · Extreme events · Coastal zone · Coastal erosion · Habitat destruction · Small islands

12.1 Introduction

Coasts are transition regions between the ocean and land. The landward and shoreward extents of coastal zones are not clearly defined, but the region that extends seaward up to the limit of terrestrial influence and landward up to the limit of oceanic

P. N. Vinayachandran (✉)
Centre for Atmospheric and Oceanic Sciences, Indian Institute of Science, Bengaluru, India
e-mail: vinay@iisc.ac.in

D. C. Seng · F. A. Schmid
Intergovernmental Oceanographic Commission of UNESCO, Paris, France
e-mail: d-chang-seng@unesco.org

E. R. Urban Jr. and V. Ittekkot (eds.), *Blue Economy*,
https://doi.org/10.1007/978-981-19-5065-0_12

influence is termed as the coastal zone (Carter 1988). According to Crossland et al. (2006), the coastal zone "is a zone of transition between the purely terrestrial and purely marine components on Earth's surface". A coastal zone can vary in width, depth and length, as coastal settings and features differ depending on legal definitions as well as the geographic location and the sediment flow, primary production, and the chemical elements it contains. The contiguous area along the coastline that has an elevation 10 m below mean sea level, known as LECZ (low elevation coastal zone) has been found to be useful for practical applications (UNESCO). In 2017, approximately 600 million people (accounting for 10% of the world's population) were living in the range of 10 m above sea level. In total, around 37% of the global population live in coastal communities and depend on the ocean, as well as coastal or marine resources for their livelihoods (UN Ocean Conference 2017).

Owing primarily to its economic significance, the coastal environment continues to be subjected to varying degrees of societal (e.g., rapid urbanization), social, cultural, and political stresses that alter the dynamics of components that constitute coastal systems, thus amplifying the risk of livelihood losses and property damages. Documenting such changes, associating them with the causative phenomena, and identifying the underlying processes and mechanisms constitute the challenges posed by the science of coastal system changes. Planning and adapting to the changes through appropriate management strategies and socio-economic developments is required for mitigating the harmful impacts caused by climate change and natural changes in order to protect natural ecosystems and decrease the vulnerability of dependent societies.

Coastal zones are affected by both slow and rapid changes from the ocean, terrestrial landforms, and the overlying atmosphere, as well as interactions between all the three components. Major climate-related drivers for changing coastal systems are sea level (SL), storms (tropical and extratropical) and associated storm surges, winds, waves, freshwater intrusion, salinization, sea temperature (ST), ocean acidification (OA) and deoxygenation (see Table 12.1 in Wong et al. 2014). Additionally, human activities such as infrastructure development, tourism and recreational activities, aquaculture, freshwater and raw material exploration and exploitation also affect coastal systems and often exert elevated pressures and impacts. The major impacts that threaten the health of coastal ecosystems and associated local and regional economies are coastal erosion, shrinking of coral reefs, destruction of vegetation such as mangroves, salinization of coastal areas, and excess accumulation or erosion of sediments and nutrients. The purpose of this chapter is to examine the current status of science on climate change and human development pressures, trends and impacts on coastal systems—resources and economies—as well as strategies for managing and adapting to stresses. It is not intended to offer a comprehensive review, but rather to highlight important aspects of climate change, development pressures, coastal systems and selected key coastal economies.

In this chapter, we first provide a synthesis of the main drivers of climate change on the coastal systems. An assessment of the impacts is given in Sect. 12.3. The risks and impacts on coastal resources and selected coastal key economies are examined in Sect. 12.4. Management strategies and mitigation are explored in Sect. 12.5. A summary and concluding points are provided in the final two sections of the chapter.

Table 12.1 Summary of coastal resources impacted by different climate change drivers, repercussions on coastal resources, ecosystems, and dependent economies, and management options

Coastal resources	Main climate change-related drivers affecting coastal resources	Impact on resource and ecosystem	Impact on economies	Management opportunities for blue economy
Barrier islands, beaches, dunes	• GMSLR • Storm surges and extreme sea level events • Wave energy	• Disruption of (re-) generation (FitzGerald et al. 2018) • Reduction of extension or disappearance (Vousdoukas et al. 2020) • Loss of ecosystems and habitats (fauna and flora) (Defeo et al. 2008) • Loss of important nesting areas for marine turtles (Defeo et al. 2008) • Loss or decline of natural protection (Zinnert et al. 2019) • Landward migration (Cooper et al. 2020)	• Loss of primary resource for concrete, artificial islands, and ports • Decline in tourist numbers (Manning 2009) due to reduced recreational and touristic value	• Global Ocean and Coastal observations • Disaster Risk Reduction tools and strategies (e.g., Effective EWS) • Operational Ocean Monitoring and Forecasting Systems • Flood management • Ecosystem-based solutions • Maritime Spatial Planning • Technological engineering solutions
Coral reefs and fish	• Ocean warming • Ocean acidification • Extreme weather events (heavy precipitation)	• Loss or decline of natural protection against erosion, storms and tsunamis (Ferrario et al. 2014; Deutz et al. 2018; Narayan et al. 2016; Hoegh-Guldberg 2011) • Reduced calcification rates of corals (Sabine et al. 2004)	• Decline in tourist numbers (Manning 2009) due to reduced recreational and touristic value • Decline in fish yield (both subsistence and commercial fisheries), threatening food security	
Deltas	• GMSLR • Marine flooding • Saltwater/brackish water intrusion • Cyclones/storm surges	• Reduction of provisioning, supporting, and regulating ecosystem services	• Loss of important inhabited land (Edmonds et al. 2020), leading to economic damages (besides possible loss of lives [Ericson et al. 2006]) • Reduction of agricultural productivity and hence decreased food security (Smajgl et al. 2015)	

(continued)

Table 12.1 (continued)

Coastal resources	Main climate change-related drivers affecting coastal resources	Impact on resource and ecosystem	Impact on economies	Management opportunities for blue economy
Estuaries	• GMSLR • Marine flooding • Saltwater intrusion • Ocean warming • Extreme weather events (heavy precipitation)	• Loss of ecosystems and habitats • Freshwater and agricultural land contamination and degradation (Kennish 2002) • Eutrophication, hypoxia, anoxia	• Damage to or loss of critical infrastructure • Reduction of agricultural productivity, threatening food security	
Wetlands (mangroves, salt marshes, seagrass meadows, kelp forests)	• SST rise • GMSLR • Extreme weather events (storm surges) • Ocean warming • Salinization	• Loss of important carbon sinks (UNESCO 2021) • Loss of ecosystems and habitats (Wong et al. 2014) • Species migration • Loss of natural protection against wave energy (McLeod et al. 2011; Zhang et al. 2012; Narayan et al. 2016) • Loss of regulating ecosystem services (water purification, carbon sequestration	• Risks to surrounding properties without appropriate natural protection loss of economic value and considerable damages in the case of an event (McLeod et al. 2011) • Decline in tourist numbers (Watson et al. 1996; Manning 2009) due to reduced recreational and touristic value • Loss of provisioning ecosystem services (food, raw materials)	

12.2 Climate Change Related Stresses in the Coastal Zone

Oceans take up 30% of greenhouse gases emitted by humans (IPCC 2014, high confidence). The fifth and the sixth Assessment Reports (AR5 and AR6) (IPCC 2014, 2021) assessed with high confidence changes to the climate system and an increase of global surface temperatures over land and oceans (1.09 °C higher in 2011–2020 than in 1850–1900), as well as an increasing frequency of marine heatwaves, especially in the tropical ocean and the Southern Ocean (medium confidence). Scientific evidence suggests that a warming of air temperature by 1.5 °C could be a tipping point and lead to a surpassing of critical thresholds. Even under the most optimistic scenario, warming of the global atmospheric temperature by 1.5 °C would have critical impacts on coastal zones in the future and put at risk fauna, flora, and livelihoods along the global coastlines. These physical changes of ocean elements impact and threaten the ocean's natural balance and affect, mostly adversely, the ocean-coast socio-ecosystems. Ocean and inland hazards impacting coastal zones include increased storm surges, more extreme marine weather events, sea level rise (SLR), OA, deoxygenation, as well as heavy precipitation. Seawater chemistry (i.e., oxygen and pH) is changing (IPCC 2019) in response to the warming of the ocean.

12.2.1 Ocean Warming

The ocean is inevitably warming because of the warming of the atmosphere. According to the IPCC's Special Report SR15[1] (2018) and AR6 (IPCC 2021), it is virtually certain that the ocean from the sea surface to 700 m depth has warmed since the 1970s. Human influence is seen as the main driver for this change (extremely likely) and the observations over the past decade indicate the most rapid warming since the last deglacial transition occurred around 11,000 years ago (IPCC 2021). The ocean absorbs excess heat from the atmosphere and has stored more than 90% of the energy released between 1971 and 2010 (IPCC 2014). This results in ocean warming globally, especially of the upper 75 m of the ocean. From 1950 to 2016, surfaces of the Indian, the Atlantic and the Pacific oceans have warmed by 0.11 °C, 0.07 °C and 0.05 °C respectively per decade, with the most pronounced warming at higher latitudes (Hoegh-Guldberg et al. 2018). The IPCC (2014, 2021) assessed with high confidence that global warming has led to a doubling of and an increasing duration of marine heatwaves. In addition, the evaporation of ocean water has increased since the 1950s due to warmer air temperatures and thus, oceans are getting more saline (IPCC 2014).

[1] "An IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty." https://www.ipcc.ch/sr15/.

12.2.2 Global Mean Sea Level Rise

During the 1901–2018 period, the global mean sea level (GMSL) increased by about 1.56 mm/year (Frederikse et al. 2020) and by a total of 0.2 m (IPCC 2021). GMSL rise has accelerated as follows (high confidence): 1.3 mm annually from 1901 to 1971, 1.9 mm annually from 1971 to 2006 and 3.7 mm annually between 2006 and 2018. It is very likely that human influence is the main driver of GMSL rise since at least 1971. The rate of increase at the turn of this century has been high owing to the large contributions from glacier mass loss and thermostatic processes. The rise of GMSL is unprecedented in at least the past 3000 years (high confidence, IPCC 2021). With high confidence, the IPCC (2014, 2021) assessed that 92% of this rise between 1971 and 2018 is due to ice sheet loss (20%), massive glacier loss (22%), as well as thermal expansion (50%). In the case of future warming of 1.5 °C, GMSL is projected to rise between 0.26 and 0.77 m relative to 1986–2005 (medium confidence; IPCC 2014). All existing Representative Concentration Pathways (RCP) scenarios and the newly established Shared Socio-economic Pathways (SSP) scenarios (based on a more holistic approach from physical sciences impact, and adaptation and mitigation research) project a rise of GMSL, and it is very likely that the rise will be higher than the current rate. Considering projections with at least medium confidence, the SSP5-8.5 scenario will lead to a global mean sea level rise (GMSLR) of 0.23 m by 2050 and 0.77 m by 2100, relative to the period from 1995 to 2014 (Fig. 12.1; IPCC 2021). Due to thermal expansion, ocean dynamics, and land ice loss contributions, SLR will affect regions non-uniformly, as described in IPCC's AR5, AR6 and in the Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) (IPCC 2014, 2019, 2021). Under the previously used RCP8.5 scenario (2081–2100), SLR will be most pronounced in the northwestern Atlantic Ocean along the east coasts of the United States of America and Canada, and in the South Atlantic Ocean and Indian Ocean between approximately 35 and 45 °S. The smallest positive SLR will be observed around Eastern Greenland and the Antarctic region (IPCC 2021). Even a drop of sea level is projected, especially in the Hudson Bay and western coasts of Greenland.

12.2.3 Storms, Storm Surges and Waves

Tropical and extratropical storms and resulting surges and storm waves account for most ocean-related extreme weather events occurring in coastal areas and are of destructive nature. The frequency and intensity of storms have increased, and it is very likely that their frequency will continue to increase in the future, as rising sea surface temperatures favor the formation of more cyclones. Owing to the influence of storms, low atmospheric pressure and high winds can lead to rises in coastal water level, known as storm surges. Flooding induced by storm surges is a major component of casualties and property damage associated with both tropical and

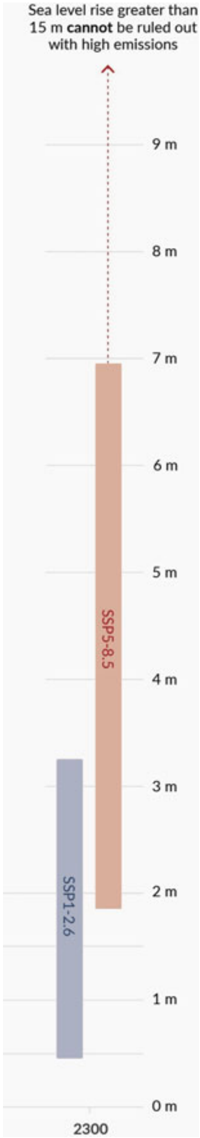


Fig. 12.1 IPCC 2021: "Global mean sea level change (in meters) at 2300 relative to 1900. Only SSP1-2.6 and SSP5-8.5 are projected at 2300, as simulations that extend beyond 2100 for other scenarios are too few for robust results. The 17th–83rd percentile ranges are shaded. The dashed arrow illustrates the 83rd percentile of SSP5-8.5 projections that include low-likelihood, high-impact ice sheet processes that cannot be ruled out"

extratropical cyclones (Karim and Mimura 2008). Model projections suggest that 63% of inundation that would occur by 2100 would be due to the combined effect of tides and storm surges (Kirezci et al. 2020). When combined with high rainfall events, high storm surges lead to increased flooding of coastal regions which are likely to increase with the projected global warming scenarios (Hsiao et al. 2021). Coastal inundation is also influenced by wave-induced flooding which occurs along with storms or extreme wind events (Storlazzi et al. 2018).

12.2.4 Heavy Precipitation Events and Flooding

Globally, climate change has induced more intense and frequent heavy precipitation events since the 1950s (over most land areas) (high confidence; IPCC 2021) leading to riverine flooding and altered sediment and nutrient flows towards coastal areas, including coastal seas. The intensity of high precipitation events has been increasing with global warming and their frequency is expected to double with every degree of warming (Myhre et al. 2019). In northern and northeastern Europe, for example, heavy precipitation events have increased and, on average, the frequency of days with very heavy rainfall has also increased by about 45% for the period from 1981 to 2013, compared to 1951–1980 (European Environmental Agency 2019). Thus, more frequent higher intensity rainfall events, flooding in certain coastal regions will occur more often. Coastal Asia, north and west Eastern Europe, northern Australia, western South Africa, southeastern South America, eastern North America, and Greenland have experienced increases in heavy precipitation events.

12.2.5 Acidification

The ocean is also one of the main sinks of anthropogenic CO_2, causing continuous OA. Uptake of CO_2 from the atmosphere leads to a lowering of pH of seawater. The average pH of the global ocean has decreased by 0.1 since 1950, which accounts for a 26% increase in acidity (Fig. 12.2). OA is getting stronger owing to increasing impact of natural processes as well as the human-induced CO_2 emissions (Lauvset et al. 2020; IPCC 2021). Increasing acidity also results in decreasing carbonate ion concentration, seriously affecting marine and coastal (land and sea) biodiversity in many different ways (survival, sexual reproduction, growth rate, migration, calcification rates, species composition) (Olischläger and Wild 2020; Auzoux-Bordenave et al. 2020; Schlenger et al. 2021) and threatening dependent economies, such as small-scale fisheries. Arctic and Antarctic waters are more at risk as CO_2 is particularly dissolvable in colder waters, which could lead to an undersaturation of calcite (Feely et al. 2009).

12.2.6 Deoxygenation

Warming of the ocean, along with decreased ventilation of the deeper part of the ocean, has been causing a decrease in dissolved oxygen levels. Global oxygen concentrations in coastal waters have decreased since the 1960s by more than 2%, with the largest drop observed in the northern and equatorial Pacific oceans (Schmidtko et al. 2017), a process called deoxygenation (IPCC 2014). The deoxygenation in coastal waters is amplified by increased nutrient loading, burning of fossil fuels, and

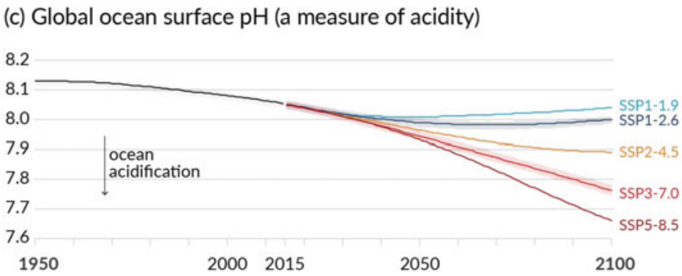


Fig. 12.2 IPCC 2021: "Global ocean surface pH (a measure of acidity) based on CMIP6 model simulations. Very likely ranges are shown for SSP1-2.6 and SSP3-7.0"

upwelling of oxygen-depleted waters. Several locations along the world's coastal regions have slipped to oxygen concentrations below the hypoxic levels since the 1950s (Breitburg et al. 2018) which cause a large impact on coastal biogeochemistry and ecosystems.

12.3 Impact of Climate Change

Coastal zones are vulnerable and exposed to oceanic drivers and hazards as they are situated between the ocean and land. The impacts of climate change are thus felt by natural coastal ecosystems and human settlements. Such impacts include coastal flooding, coastal erosion, saline intrusion and most importantly impacts on coastal ecosystems. Extreme consequences are mostly endured by totally disappearing coastal ecosystems and reliant economies. Wong et al. (2014) argued that if climate change trends continue, around 1300 km^2 of coastal land could be lost by 2050, especially after periodic events such as extreme SLR events and associated storm surges, but also because of slower gradual changes in SL that are affecting coastal areas, such as deltas. McFadden et al. (2007) project through modeling losses of global wetlands between the years 2000 and 2080. In the case of a 0.5 m SLR, 32% of global wetlands could be lost and if SLR reaches 1 m, 44% would be affected.

12.3.1 Geophysical Impacts

12.3.1.1 Coastal Flooding

Increases in water levels near the coast will lead to an increase in flooding events. A 10–20 cm rise in SL is likely to double the frequency of flooding events and the vulnerability of tropical coasts to such episodes is the largest (Vitousek et al. 2017). Extreme SLRs are projected to affect most coastlines of the world by the end of this century (Vousdoukas et al. 2018). While extreme flooding events in coastal regions are increasing, they are likely to become commonplace in the Twenty-First Century as the sea level is rising. Along the U.S. coast, extreme coastal flooding is estimated to double every 5 years by 2050 or 2100 (Taherkhani et al. 2020). The effects of GMSL are threatening to destabilize coastal systems by erosion and inundation, such as coasts where mangrove and coral reef protection is already weakened, as these systems are unable to absorb persistent shocks as much as in a healthy state. The intensity of flooding in coastal zones is magnified during compound events such as those accompanied by riverine floods (Paprotny et al. 2021; Bevacqua et al. 2019). Such events affect sediment input in coastal areas, including coastal seas, and could disturb sensitive ecosystems such as coral reefs and kelp forests.

12.3.1.2 Coastal Erosion

Mentaschi et al. (2018, Fig. 12.3) estimated land losses and gains using satellite data for the period 1984–2015 and found that about 28,000 km^2 of surface area was eroded compared to a land gain of about 14,000 km^2. These changes are caused by both natural and human-induced processes.

12.3.1.3 Saltwater Intrusion (See also Chap. 5)

Excessive withdrawal of groundwater from coastal areas can alter the equilibrium that exists between the levels of freshwater and seawater and may result in the landward movement of seawater into the coastal aquifer, a process known as seawater intrusion, which usually takes place when the groundwater table falls below the sea level (Prusty and Farooq 2020). Seawater intrusion has been reported from several parts of the global coastline. For example, from the analysis of about 250,000 observations, Jasechko et al. (2020) found landward hydraulic gradient to be the major causative factor of seawater intrusion, which would be exacerbated by future increase in sea level along the coasts of North America. The IPCC (2021) confirmed with high confidence that GMSL rise will lead to higher rates of saltwater intrusion into coastal wetlands.

12.3.2 Ecosystem Impacts

12.3.2.1 Coastal Ecosystem Impacts of Climate Change

Warming of the ocean, increase in sea level, intense storms, and acidification - all these processes pose serious threats to coastal ecosystems and low-lying coastal regions. For example, warming sea surface temperatures lead directly to changes in species communities and reproduction rates as well as to species migration towards

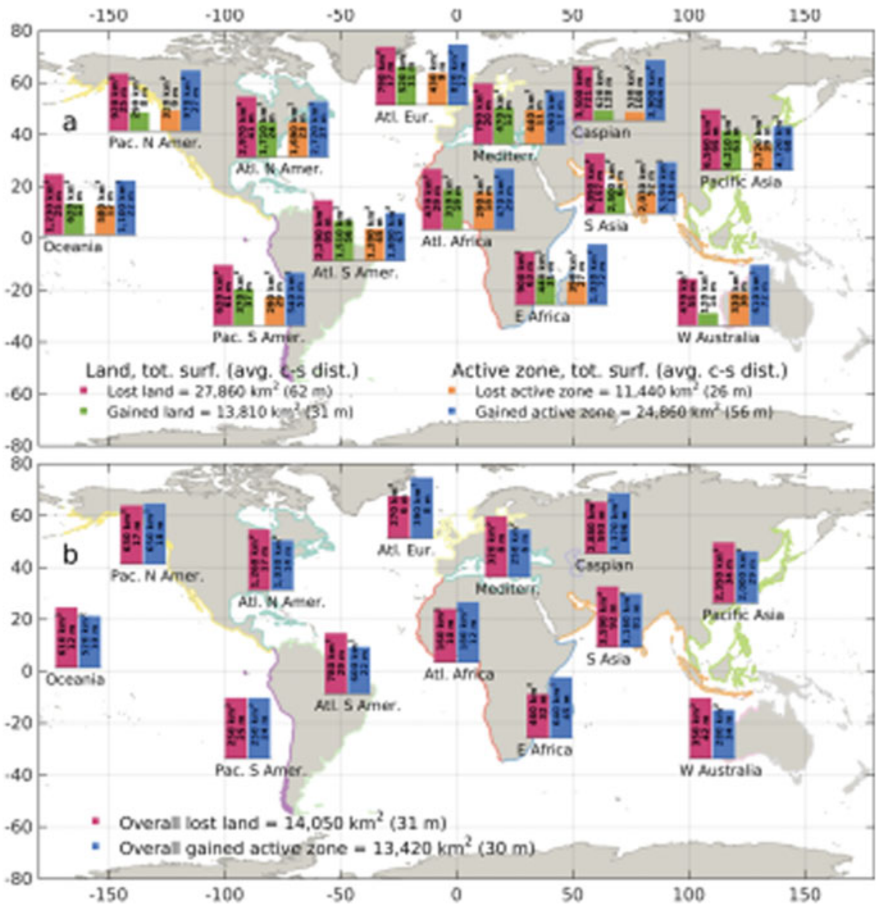


Fig. 12.3 "Overall gained and lost (a), and gained-lost neat balance (b) of land and active zone, aggregated by continent/ocean and expressed in km^2 and in cross-shore distance. The global aggregate quantities are also shown in both panels. Coastline colors identify the considered areas." From Mentaschi et al. (2018)

cooler waters (mostly towards higher latitudes) (Schiel et al. 2004; Hofstede et al. 2010; Wernberg et al. 2011), threatening the natural balance of coastal and marine ecosystems. Higher surface water temperatures also mean more pronounced and longer stratification periods of upper ocean water layers, affecting marine productivity in general (IPCC 2014). The IPCC report states with high confidence that harmful algal blooms (HABs) will expand and occur with higher frequency as a consequence of both climatic and other human-related drivers (see also Chap. 10). Examples are rising ocean temperatures and associated marine heatwaves (IPCC 2014; Tamvakis et al. 2021) as well as over-enrichment of nutrients due to runoff from agricultural use (IPCC 2014).

Extreme marine weather events such as storm surges are often rapid and recurrent (Defeo et al. 2008). While destruction of coastal socio-ecological systems can happen rapidly, recoverying may take long periods of time. Barrier islands off the coast of Louisiana, acting as important buffer zones for storms and habitat for wildlife, have been altered by hurricane Katrina (Sheikh 2005), leading to island and seagrass bed loss. Breton Sound lost around 78 km^2 of marshes that were converted into open water.

Direct human activities can also exacerbate the consequences of climate change on coastal ecosystems. He and Silliman (2019) argued that "local human impacts can mediate the susceptibility of organisms to a climate change stressor, and vice versa, a climate change stressor can mediate the susceptibility of organisms to a local human stressor (e.g., heavy metal pollution)", thus making ecosystems more vulnerable to climate change. By weakening intact ecosystems, human activities can lead to a decreased resilience of ecosystems (see Box 12.1).

Box 12.1 Case Study: Seychelles

Background: Climate Change, Key Impacts, Development Trends and Pressures

The Seychelles archipelago is made up of 115 islands (granitic and coralline) scattered over an exclusive economic zone (EEZ) of 1,374,000 km^2. Coastal tourism alone contributes 40% of GDP in Seychelles (The World Bank 2010) and with fisheries, they are the island's two key economic sectors. Concentrating development activities and population on narrow coastal zones increases vulnerability and risks to climate change. Ocean warming has caused significant impacts, including coral mortality and decrease in the level of the fringing reef in the Seychelles (Sheppard et al. 2005), increased coastal erosion and inundation due to amplified wave energy, as well as damage to coastal resources and economies.

Sea-level rise and higher waves are causing severe erosion and inundation, impacting coastal roads, beaches and tourism-related establishments.

The severe tropical cyclones Bondo in 2006 (Chang Seng 2007a, b; Chang Seng and Guillande 2008) and Fantala in 2016 (Government of Seychelles 2016) impacted the outer coralline islands of Seychelles for the first time in recorded history, causing widespread damage to nearly all private and public buildings, including the destruction of essential desalination facilities (Government of Seychelles 2016). The socio-ecological system experienced serious losses and damages, including vegetation (coconut palm tree groves, mixed vegetation areas, coastal and native shrubs, mangroves) and biologically and structurally complex coral reef ecosystems (corals, algae, seagrass beds, and sandbanks). Fantala's damages were estimated to account for US$2.7 million in physical damages and US$4.8 million in changes in economic flows or losses.

The impact on the environment was estimated at US$3.0 million (39.1% of the total damages).

Large-scale development projects are also causing considerable stress and permanent impact on coastal ecosystems and resources in addition to climate change impacts. In one recent case, residents questioned such large coastal tourism-related projects and current monitoring and enforcement capacities of planning authorities vis-à-vis international investment tourism development groups. The ongoing construction was reported to have caused a large "red earth sludge" dispersal along the entire northeastern coastline following a heavy rainfall event in 2021 affecting beaches, coral reefs, and seagrass. The impact on coastal marine life and ecosystems remains unassessed.

Management and Mitigation

In the Seychelles, there is an increasing concern that coastal and marine resources are being overexploited and damaged, thus quickly losing their value. In order to reverse this trend, Cesar et al. (2004) have recommended proper management of the coastal zones, with measures spanning from credible enforcement, enhancing the attractiveness of tourism by maintaining and restoring the environment and ecosystems, monitoring, developing new marine parks in areas with high-quality biodiversity, which are not yet protected, to help conserve and protect the coastal resources.

Marine Protected Area

An important achievement in this respect is the legal designation of one-third of Seychelles' ocean territory, outside the main islands, as a Marine Protected Area. Seychelles had already tripled the UN Convention of Biological Diversity Target 11 for 10% marine protection by 2020, and the UN Sustainable Development Goal SDG14 for 10% coastal and marine protection. Despite being seen as a major milestone, more attention and science-based actions should focus on higher coastal risks spots, and where they are increasing at an unprecedented pace. Considering recent developments, the following is suggested for continued improvement in the management of coastal resources and mitigation of impacts for coastal tourism.

Hazards and Coastal Erosion Assessments

The Seychelles Coastal Management Plan (CMP), 2019–2024 (World Bank and Ministry of Environment, Energy and Climate Change of Seychelles), is the most recent assessment of several coastal hazard analyses, erosion, and inundation. It helps to maintain and protect coastal zones, to reduce coastal risk, support healthy ecosystems, and enable sustainable coastal economic development. There is a need to leverage and integrate higher resolution physical and non-physical data (e.g. bathymetry, Digital Elevation Models, coastal population, socio-economic, environmental and ecosystem data), as well as holistic ocean-to-coast and land-to-coast approaches. Associating various assessment methods focusing on evaluating long-term impacts of measures on the vital coastal resources and economy, including the tourism sector is essential.

Policies, Strategies, Institutional Settings and Governance

Scientific advice based on sound process understanding is an important tool to better-informed decision making in comprehensive risk management and the development of policies, through science-policy collaboration and co-creation (OECD 2017; UNDRR 2021). There are many policy and institutional instruments, acts and assessments to help govern climate change impacts and coastal development in the Seychelles, and these include the Environment Protection Act 1992 to the recent Blue Economy Roadmap 2017. Environmental Impact Assessment (EIA) is an important operational standard tool used in evaluating the likely environmental impacts of a proposed project or development, which is in sharp increase, taking into account inter-related socio-economic, cultural and human-health impacts, both beneficial and adverse. However, the EIA application process at times lacks transparency in implementation, and procedural uniformity among concerned parties and stakeholders. The Seychelles Government elected in October 2020 has started to strengthen and enforce these institutional instruments. People need to empower themselves to act early, rather than at the later stages of the project proposal. With increasing development pressures, EIAs need to be holistic and take an integrated impact-based approach, from land to coast and ocean to coast. The policy instrument that regulates coastal settlement and infrastructure development in Seychelles at 25 meters away from the coastline also needs refinement to take into consideration the geomorphological coastline (steep coast) and better enforcement. On the other hand, addressing coral bleaching, which may further deteriorate reefs in the Seychelles, requires the leverage of alternative activities such as turtle and whale shark tours that still need to be developed.

Ocean Observation, Monitoring, Modeling, Early Warning

In recent years, observational gaps in marine-weather observations in the Indian Ocean have been largely filled due to the Indian Ocean Observing System (IndOOS) with the joint effort of the Indian Ocean Observing System (IOGOOS) - one of the thirteen GOOS Regional Alliances. India operates a Wave Glider network in the southwest Indian Ocean, and one is located in the Seychelles EEZ. Consequently, marine-weather observations have improved in and around the Seychelles EEZ. However, systematic and sustained higher resolution and near real-time coastal ocean observation (physical, biogeochemical, biological) are still lacking and not readily available and accessible. A wide range of users - namely fishermen, ports and harbors, coast guards, defense, shipping for safe navigation and operation at sea as well as tourism departments and activities - require timely and accurate forecasting information on ocean state and marine meteorological parameters in light of growing coastal tourism and the Blue Economy concept in Seychelles. In order to tailor these increasing needs, the Ministry of Earth Sciences, Government of India developed an integrated high-resolution ocean forecasting system for Seychelles through the Indian National Centre for Ocean Information Services (INCOIS), Hyderabad and Regional Integrated Multi-Hazard Early-warning Systems (RIMES). The daily ocean forecast is available for wind, waves, swells, currents and temperature in both map and numerical data form for the region. In addition, location-specific forecast products are available for several locations; however, these products need to be better applied to support Blue Economy activities. A sustained and expanded coral and beach monitoring program may also help to detect the extent of climate change-induced coastal erosion and coral bleaching in Seychelles, as it threatens very important economic sectors such as tourism.

A multi-disciplinary approach towards observing, monitoring, data harmonization, modeling, analyses and forecasting, and use of other tools (MSP) would trigger synergies and foster more effective and sustainable long-term coastal zone management and development, thus supporting Blue Economy activities in the Seychelles.

12.4 Risks and Impacts on Coastal Resources and Blue Economy

This section discusses the risks and impacts of climate change, as well as implications for key coastal resources and economies. We raise two guiding questions as follows:

1. How and to what extent will climate change impact coastal resources?
2. What are the vulnerabilities, risks and impacts on blue economy resources?

12.4.1 Risks and Impacts of Climate Change on Coastal Resources

Coastal Areas and Resources: Coastal zones, including coastal waters and adjacent shorelines, are special habitats that display a variety of land- and seascapes, providing many different ecological services and the basis for various economic sectors. Coastal resources include barrier islands, beaches, coral reefs, deltas, dunes, estuaries, floodplains, marine wildlife (in particular fish), as well as wetlands (salt marshes, seagrass meadows and kelp forests). For many centuries, humans have exploited coastal areas as trading routes, source of raw materials, protein source and attractive businesses and living space. As a buffer between sea and land, coastal areas are an important and appealing habitat for many societies. 75% of all megacities with more than 10 million inhabitants are situated in coastal zones. 90% of global fisheries take place in coastal waters (World Ocean Review 2017), which are therefore important protein food sources for humans. Chen (2003) and Bauer et al. (2013) pointed out that the coastal seas alone are believed to provide up to 30% of global marine primary production and produce around 50% of the organic carbon deposited in the deep ocean, while occupying only 7.6% of the global ocean. Sand and other sediments are steadily extracted, despite being valuable resources for maintaining healthy beach and dune systems.

Barrier islands, beaches, and dunes: Barrier islands, beaches, especially sandy beaches and dunes provide habitats for dune vegetation, benthic fauna, sea birds, and are also nesting areas for marine turtles (Defeo et al. 2008). As a raw material, sand is used for concrete, glass, to build artificial islands (e.g., The Palm, Dubai) or to expand ports. However, sand mining can deplete beaches and drive further coastal erosion and amplify climate change impacts. In many countries, including the Seychelles, sand mining is prohibited by law. These coastal resources are mostly impacted by GMSLR, storm surges associated with extreme sea level events as well as un-buffered wave energy, due to climate change-related loss of protecting natural features such as coral reefs. Coastal shoreline erosion, and therefore erosion of beaches is not limited to a specific geographic location but occurs worldwide. The erosion negatively affects soil accretion rates and dependent land-based ecosystems. Extreme events, such as storms, can lead to an irreversible destruction of flora in the impacted region and lead to a vegetation transformation.

Barrier islands can be found along 20,000 km of coasts (Stutz and Pilkey 2011) and their stability is being disrupted by rising sea levels and associated storm surges (FitzGerald et al. 2018). They act as an offshore barrier, protect the coastal zone and the mainland from ocean-related hazards, and are a sediment reserve (Zinnert et al. 2019). SLR pushes barrier islands to displace landward if enough space is available. This happens through a process where sediment is transported onto the fringe marsh platform via overwash (Deaton et al. 2017).

SLR and associated coastal hazards could lead to the almost disappearance of around 50% of the world's sandy beaches by 2100 (Vousdoukas et al. 2020). Projected shoreline erosion will become more important as greenhouse gas (GHG) emissions increase. However, moderate RCP scenarios could prevent 40% of shoreline retreat (IPCC 2014). Cooper et al. (2020) suggest that beaches in certain places are likely to migrate landwards with rising sea level. They found that in most coastal settings worldwide an 'accommodation space' exists, enabling beaches to migrate and avoid 'extinction'.

Coral reefs and fish (see also Chap. 2): Coral reefs are highly productive ecosystems in shallow tropical waters (−100 m), that are not disturbed by sediment inputs (e.g., from river inputs). They are home to many marine species and provide a resource of food (small-scale fisheries as well as commercial fishing) for over 500 million people (Hoegh-Guldberg 2011). Moreover, coral reefs are valued among tourists as hotspots of biodiversity and are used for snorkeling or diving. These ecosystems not only provide a social and economic value, but they also protect coastal shores from erosion from oceanic waves (Narayan et al. 2016). Healthy coral reefs can reduce up to 97% of incoming wave energy and thus protect around 63 million people (Ferrario et al. 2014; Deutz et al. 2018).

Despite the manifold ecosystem services coral reefs provide, these ecosystems are threatened by climate change-related oceanic drivers. Among the most important drivers are ocean warming and acidification. According to the SROCC report (IPCC 2019), ocean warming has already increased the number of "large-scale coral bleaching events, causing worldwide reef degradation since 1997", and with very high confidence, almost all coral reefs will be degraded even if global warming remains below 2 °C. The bleaching is a response to stress (Hoegh-Guldberg 2011). Corals are likely to be replaced by more heat-tolerant species, as corals usually need thermally stable waters and can only cope with a two-degree Celsius tolerance above the threshold of the normal range (can vary regionally). Thus, species composition, as well as diversity, might alter in the future (IPCC 2019; FAO 2014, 2020). According to Hoegh-Guldberg (2011), the most fatal, irreversible and global coral bleaching event that led to a mass mortality, linked to abnormal ocean temperatures, started in the eastern Pacific in 1997 and expanded worldwide in the following year. Severely affected regions for example were the Seychelles, the Maldives, Okinawa and Palau.

Corals being calcifying organisms depend on high carbonate ion availability in oceans. OA is lowering the availability of free carbonate ions, reducing availability of aragonite (Burke et al. 2011; Gattuso et al. 1999; Kleypas et al. 1999), altering their concentration in the open water and therefore decreasing the calcification rates of corals worldwide. Sabine et al. (2004) assessed the potential of atmospheric CO_2 in decreasing available carbonate ion concentration. It is believed that "a doubling of atmospheric CO_2 from pre-industrial levels will result in a 30% decrease in carbonate ion concentration". Lower calcification rates also mean less corals and thus less protection against wave energy, that is, more coastal erosion.

These ocean-to-coast driven climate hazards are very important, but land-to-coast related climate hazards should not be neglected regarding coral reefs. Coastal vegetation loss due to droughts can destabilize soils within river catchments (Hoegh-Guldberg 2011). In combination with extreme weather events (heavy rainfall), the sediment and nutrient flow into coastal waters can be exacerbated, negatively affecting coral reefs. The turbidity reduces the sunlight is available for the algae living coral tissues, decreasing coral growth rate.

Deltas: River deltas have always been an important living space for people, as they provide plentiful protein, soils and are generally suitable for agriculture. The connectedness with rivers makes trade and transportation easier. Deltas are therefore provisioning and supporting ecosystems and provide regulating ecosystem services. An analysis for the year 2017 showed that approximately 339 million people lived in river deltas (Edmonds et al. 2020). From 2000 to 2017, the delta population globally rose by around 87 million people. 97% of the total delta population are living in developing and least-developed countries. 78% of the total delta population is concentrated in only 10 deltas, accounting for 48% of the total geomorphic delta area (Edmonds et al. 2020).

Low-lying deltas are mainly affected by SLR, intrusion of saline or brackish water as well as cyclones and associated storm surges, flooding, as well as tsunamis. They are naturally prone to both slow- and rapid-onset hazards as deltas are close to the sea, but their vulnerability is exacerbated by rising numbers of people living in these areas. The fact that most people living in deltaic regions live in developing or least developed countries increases their vulnerability as their socio-economic and infrastructure conditions are in general less resilient. Densely urbanized megacities in deltas are the most vulnerable to ocean-related hazards. The Ganges–Brahmaputra delta (GBD) in the Bay of Bengal hosts 108 million people, with a population density of 1280 people per km^2, and is the most populated delta worldwide (Ericson et al. 2006). Here, the biggest impact on population loss is expected to take place in the case of any sudden rapid-onset event which is a key challenge for early warning systems to effect and organize timely coastal evacuation, in particular to local tsunamis.[2] The Mekong Delta in Vietnam extends more than 40,000 km^2, is home to 17 million people and produces around 25 million tons of rice every year, also contributing to the country's food security. With export of agricultural products, this area also accounts for about 19% of the national GDP (Governmental Statistics Office 2016; Dung et al. 2019; Eslami et al. 2019; Piesse 2019). However, the productivity and dependent food security are threatened from salinity intrusion due to SLR, sea level extreme events and storm surges (Smajgl et al. 2015). Specifically, rice crops that have a low tolerance to salt will be impacted.

Estuaries[3]: Tidal estuaries not only provide an important habitat for people as well as for fauna and flora, but they are also home to critical infrastructure, such as ports and coastal harbors, that concentrate different economic sectors such as trade, tourism or communication. In some situations, estuaries act as a kind of shelter from direct impacts of high-energy waves (Phillips 2008; Uncles 2010), as they are semi-enclosed coastal bodies (Pritchard 1967). Rising sea levels increase seawater intrusion and raise salinity in estuaries, impacting dependent agriculture. Moreover, warming and droughts are believed to exacerbate the effects of salinization in estuaries. Estuarine coastal systems become especially vulnerable to these hazards when human settlements are built without adequate planning, leading to overpopulation. Estuaries are resilient to certain rates of SLR, as they have a high sediment relocation capacity. However, adaptation would not be able to keep pace if IPCC scenario RCP8.5 occurs. A comprehensive study of the Apodi Mossoró estuary in Northeast Brazil, using modeling, showed the extreme vulnerability of estuaries to sea level-induced flooding (Boori et al. 2012). Results indicated expected minimum inundation rates of almost 16% (216 km^2). Under expected maximum inundation levels, more than 26% (363 km^2) of the estuary area could disappear.

As estuaries are densely populated and agricultural used coastal areas with one or more rivers or streams flowing into this region, heavy precipitation events that are likely to increase with climate change, lead to excessive nutrient and sewage inputs (Kennish 2002), thus threatening their healthy ecosystems and putting at risk communities dependent on the habitat and freshwater resources. These inputs can lead to more pronounced eutrophication events, as well as hypoxia and anoxia. Moreover, chemicals from inundated agricultural land can contaminate the estuaries

[2] Non-climate hazard.

[3] 'An estuarine system is a coastal indentation that has a restricted connection to the ocean and remains open at least intermittently'; Kjerfve (1989, p. 3).

and reach coastal waters, adversely impacting human health and fish stocks. Urban stormwater run-off increases the presence of polycyclic aromatic hydrocarbons (PAHs) in estuarine ecosystems (Kennish 2002).

Wetlands: mangroves, salt marshes, seagrass meadows and kelp forests (see Chap. 3): Wetlands are mainly composed of salt marshes, subtidal seagrass meadows and mangrove forests. These so-called "blue carbon ecosystems" are important carbon sinks storing the "equivalent to about 10% of global greenhouse gas emissions in 2018" (UNESCO Marine World Heritage 2021). They are highly productive and provide many ecosystem services, as well as a basis for economies. Wetlands are threatened in particular by SST warming, GMSLR and extreme weather events that usually have destructive forces and irreversible effects. Wetlands have declined globally by nearly 50% relative to pre-industrial levels, oftentimes due to sea-level extremes, with irreversible losses (Wong et al. 2014). This trend will continue under increasing SLR and associated storm surges (high confidence). Ocean warming in general is associated with species migration towards colder waters and a shift in species composition (fauna and flora) can already be observed. Species that are more tolerant to higher temperatures will stay in the warming waters. Among these more resilient species can be more aggressive grazers, thus amplifying the problem of wetland damage. Wetland erosion is accompanied by vast habitat loss for many coastal species (Wong et al. 2014) and release of significant amounts of stocked carbon dioxide, as carbon sequestration in wetlands is very important globally (UNESCO Marine World Heritage 2021).

Mangrove forests host very high biodiversity (Duarte et al. 2013) and provide physical protection against extreme events such as storms and floods (McLeod et al. 2011). A swath of only 1 km of mangrove forest can reduce hurricane surge level by up to half a meter (Zhang et al. 2012) or reduce wave height up to 31% (Narayan et al. 2016). A net loss of 4% of mangrove forests was observed globally between 1996 and 2016, mostly due to deforestation (Worthington and Spalding 2018; Global Mangrove Watch 2020). Warming ocean waters push mangrove forests to encroach into subtropical salt marshes. Moreover, a poleward migration of mangroves due to climate change is observed (Saintilan et al. 2014).

Adams (2020) analyzed salt marsh change in South Africa. With an extent of only 15,000 ha, South Africa's salt marshes are nevertheless an important habitat for migratory fish and birds. Around 43% of the salt marshes were lost in the period between the 1930s and 2018, due to human development activities. Through analysis of features such as changing inundation patterns and salinity gradients, as well as increased storm frequency due to climate change, Adams (2020) showed that in the context of South Africa, salt marshes are threatened by several different ocean and coastal hazards. SLR and coastal erosion will lead to salt marsh subsidence and eventually salt marsh dieback and loss, if they cannot build elevation at sufficient rates or have no space to expand landwards, changing species composition and nutrient cycles in ecosystems. Intact salt marsh ecosystems can reduce wave height by up to 71% (Narayan et al. 2016) and should be conserved to maintain the natural protection they provide. Storm surges and increasing wave height lead directly to salt marsh losses and put at risk surrounding properties, leading to loss of economic value.

Seagrass meadows, found mostly in shallow ocean and sea waters globally, provide manifold ecosystem services such as providing raw materials and food, coastal protection from wave erosion, carbon sequestration, water purification and habitat for coastal species that are important for both commercial and recreational purposes (Watson et al. 1996; De la Torre-Castro and Rönnbäck 2004). Economic value estimations are still missing but should not be neglected (Barbier et al. 2011). As natural protection, these systems show a capacity to reduce wave height by up to 36% (Narayan et al. 2016). They also provide a nursery ground and food for fish and invertebrates. The most limiting factor to seagrass meadows and marine plants is ocean temperature (Duarte et al. 2018). With rising ocean temperatures, marine plants are threatened by extinction and thus, the nursery ground for fish and invertebrates could be severely affected. As described earlier, ocean warming induces species migration, could favor grazing and therefore alter ecosystem composition or even unbalance seagrass systems. To a certain extent, seagrass meadows are able to cope with rising salinity levels as well as to contract towards lower latitudes, if available space allows the encroachment.

Large brown macroalgae, mostly found in temperate and subpolar latitudes, are known as kelps. Owing to their diversity and high productivity, they are important for the marine ecosystems and support important fish habitats (Smale 2020). Climate change has affected the structure, shape, and primary productivity of kelp forests in many locations. They show higher mass mortality during extreme events as extreme temperature rises and are less able to migrate (very high confidence; IPCC 2018). Future warming and marine heat waves are likely to affect kelp forests even though the extent of impacts remains presently unknown.

The peer-reviewed literature cited and analyzed above shows that all coastal resources are already impacted by climate change-induced hazards. With increasing climate change, they might even be threatened by displacement, disappearance, and extinction, causing problems as many blue economies rely on healthy coastal ecosystems. Disturbed and shrinking coastal resources will adversely impact the associated economies either directly or indirectly. The next section explores the extent of these impacts on economies.

12.4.2 Risks and Impacts of Climate Change on Coastal Economies

Coastal Economy: The National Ocean Economics Program (2007) recognizes and defines 'Ocean Economy' consisting of "the economic activity, which indirectly or directly uses the ocean (or Great Lakes) as an input", whereas the 'Coastal Economy' is defined as "all activity, which takes place in the coastal areas". The coastal economy includes several key sectors: tourism and recreation, commercial fisheries, mariculture, transport and shipping, and port activities. According to the World Bank (2017), the 'Blue economy' refers to the "sustainable use of ocean resources for economic growth, improved livelihoods and jobs, and ocean ecosystem health". The OECD (2020) acknowledged that the ocean-related economy will accelerate, and its economic value has the potential to double from 2010 to 2030. Ocean economy is expected to account for USD 3 trillion in 2030, with marine aquaculture, capture fisheries, fish processing, offshore wind and port activities projected to be the main drivers. However, exploitation that targets these resources puts pressure on the ocean worldwide and impacts for marine and coastal environments are expected to worsen.

As pointed out earlier, most coastal systems can cope with gradually changing conditions, such as rising water temperatures or higher acidification rates, up to a certain point. A resilient ecosystem may shift to a new balance, which might allow it to survive. However, this new balance might affect economies and favor the exposure to more severe impacts associated with climate change, ending up in a vicious cycle. Blue economy activities are mostly negatively affected by the risks described in Sect. 12.3 and their repercussions on coastal resources as described in Sect. 12.4.1. This section focuses on climate change implications for coastal economic sectors that are particularly critical to many developing countries: tourism and recreational activities as well as fisheries and mariculture. This is by no means an exhaustive list. Many other economic sectors can be affected, at every spatial scale.

*Tourism and recreational activities (see Chap. 6):*Tourism is one of the biggest economic sectors worldwide. In the year 2019, there were 1460 million international tourist arrivals, of which 55% could be attributed to 'leisure, recreation, and holidays' (World Tourism Organization 2021). International tourism receipts accounted for USD 1481 billion in the same year, and the tourism sector is an important part of GDP worldwide. The largest share of tourism in GDP (direct tourism GDP as a % of total GDP) was observed in Macao (China) where it accounts for 48%. Europe accounted for 50% of the world's international arrivals, whereas Asia and the Pacific accounted for a quarter of total arrivals, and Africa accounted for only 5%. An estimated 121 million people benefit from marine-based activities every year for recreational purposes, accounting for 47 billion USD profit in 2003 and generating one million jobs (Cisneros-Montemayor and Sumaila 2010). These coastal activities can be consumptive (e.g., fishing) or non-consumptive (e.g., swimming, diving, etc.) (UNEP 2009), but both exert additional pressures on the coastal ecosystems and will mostly be negatively affected by climate change.

Coastal tourism was related to the therapeutic properties of sea and sun in its beginnings in the mid-eighteenth century (UNEP 2009). However, in the late twentieth century, mass tourism started to develop, and coastal areas did not stay unscathed from this development trend. Eventually, many individuals in small island developing states (SIDS) became dependent on tourism. It often constitutes their major source of income.

Storm surges, SLR, wave impacts and temperature extremes can damage key ecosystems and all coastal resources for example wetlands, lagoons, beaches, or reefs as described in Sect. 12.4.1; often representing the principal tourism assets for many SIDS. In SIDS, the areas where impacts are greatest coincide with maximum vulnerability and concentration of tourism-related infrastructure. Tourism is dependent on the maintenance of key assets (natural and cultural), predominant reasons for tourists to travel to a certain location (Manning 2009). Manning (2009) pointed out that if these resources are depleted or degraded, tourism diminishes and eventually disappears.

Tourism is a critical building block for sustainability in particular in small islands. Tourism activities impact key ecosystems, as most activities are often concentrated at the most sensitive sites. Tourists visit SIDS because of the reefs, the beaches, the unique cultures, ecosystems, and landscapes. Without suitable planning and management strategies, tourism can be the agent for destruction of the resources on which it depends. Despite the substantial actions and costs necessary to achieve benefits and reverse the current trend, it is widely believed that the long-term costs of not managing the coastal areas will be much higher (Cesar et al. 2004).

In this regard, climate change not only threatens natural coastal ecosystems and resources but also affects coastal tourism worldwide, whereas developing countries are even more at risk, as they often lack appropriate means to adapt to the changing climatic conditions and associated hazards. The Seychelles is one of the countries worldwide that rely heavily on tourism. According to the National Bureau of Statistics, the Seychelles registered in 2018 a total of more than 361,000 visitor arrivals,[4] compared to only 3,000 annual visitor arrivals in the early 1970s (Payet in Leary et al. 2008). More than 65% of tourists chose to visit the Seychelles for the predominantly pristine nature of their coastal resources and the natural beauty in general (Cesar et al. 2004). For example, divers are the most critical observers of a reefs' health and are generally more willing to pay for their experience and contribute to conservation activities and are rather pessimistic about what the Seychelles has to offer in terms of diving. We showcase the impacts of climate change on coastal resources and economy in the Seychelles in a case study (see Box 12.1).

For tourism and recreational activities to be attractive, healthy, and functional coastal ecosystems are indispensable. Beaches are very important for the tourism sector, as many people seek especially sandy beaches for recreational activities. Disappearance of coral reef ecosystems or even the bleaching due to climate change-induced hazards or flooding will lead to decreasing tourist numbers in tropical and subtropical coastal areas. Coastal riverine flooding, which is likely to worsen under climate change, leads to more sediment and nutrient inputs into salt marshes, thus favoring algal blooms. This adversely affects human health and wellbeing and can reduce recreational and touristic value.

For the aforementioned reasons, it is important to understand which resources are available, recognize the sensitivity of such resources to stresses (climate change and development), and comprehend measures to sustain coastal resource assets. Thus, managing risks and impacts on coastal resources and economies begins with better understanding of risk drivers - both climate change-induced and coastal development, and addressing risk and pressures using an adaptive and integrated approach (Box 12.2).

[4] https://www.nbs.gov.sc/statistics/tourism.

Box 12.2 Case Study: Bangladesh

Bangladesh is a typical example of the devastating physical, environmental and socio-economic impacts of extreme events increased by climate change. About 30% of the country (~47,150 km^2) is classified as a coastal zone, which holds a population of about 38.5 million. The length of the coastline is about 710 km, connecting several rivers originating from the Himalayas and draining into the Bay of Bengal. Agriculture, which provides a significant portion of employment and contributes a substantial portion to the GDP, is highly susceptible to damage resulting from both climate and environmental damage. The coastal areas are highly productive in agriculture but also highly vulnerable to disasters. Coastal Bangladesh is subjected to increasing sea level, intense floods, severe droughts, coastal inundation, salinity intrusion, and a larger number of high-intensity cyclones. The estimate of relative SLR at the Daulat khan tide gauge station for the 1960–2011 period is about 14 mm/year (Islam et al. 2015). The sea level is projected to rise from 30 to 50 cm under different scenarios (Harrison 2020).

The world's largest mangrove ecosystem (6,017 km^2) is in the Sundarbans, which is home to diverse species of fish (120) and birds (270) (Ahmad 2019) and home to the Bengal Tiger, which is an endangered species. The mangrove forests have the capability to reduce the current speed of storm surges by 29–92% and the surge height by 4–16.5 cm (Dasgupta et al. 2019). The forest cover by mangroves is projected to decrease by 14 km^2/year for a regional SLR of 1.48 m by 2100 Ghosh et al. (2019). Bangladesh is one of the world's largest aquaculture producing countries, with a major focus on shrimp farming. With the increase in shrimp production, the mangrove forest area has been subjected to widespread destruction (Ahmed et al. 2017). Wetland ecosystems are likely to lose their resilience on being exposed to the changes in the environmental conditions and human influence. The value of coastal ecosystems is projected to decrease by millions of dollars due to regional SLR, coastal erosion, rise in SST and more storms (Mehvar et al. 2019).

One of the socio-economic impacts of environmental disasters in Bangladesh is the displacement of local population and migration. Floods, soil salinity and crop failure are the main reasons for migration. The contamination of freshwater sources during disaster events put the people inhabiting the coastal regions under extreme distress (Abedin et al. 2019). Owing to SLR and reduction in rainfall during the dry season the river flow is likely to reduce, which may result in an increase in salinity intrusion in the future (Szabo et al. 2016).

Lack of assessments based on observations and regional models is a major shortcoming in the present status of documentation of climate change impact and projections for Bangladesh (Sarwar and Woodroffe 2013; Islam et al. 2015). Various ministries under the government of Bangladesh have adopted policies for mitigating regional GHG emission but these efforts offer limited targets in the agricultural sector (Chowdhury et al. 2021). Efforts are also in place for adaptation to climate change, but the inclusive nature of actors in different sectors of governance needs careful consideration for adapting to climate change. Ishtiaque et al. (2021) suggested that even though both top-down and bottom-up actions co-exist in the ongoing governance procedure, increasing the equitable distribution of power is suggested in order to increase the efficiency of the adaptation process.

Fisheries (see Chap. 4): Worldwide, more than 4.5 billion people get around 15% of their proteins from seafood (Béné et al. 2015). Fish provided an additional 3.3 billion people with almost 20% of their average per capita intake of animal protein FAO (2020). In 2017, fish consumption accounted for about 29% of animal protein intake in least developed countries (LDCs), 19% in other developing countries, and about 18% in low-income food-deficit countries (LIFDCs). It is estimated that one quarter of the total fish catch in developing countries is derived from coral reef-associated fish (Burke et al. 2011). Healthy reefs can provide up to 15 tons of fish and seafood per km^2/year. In Bangladesh, Cambodia, the Gambia, Ghana, Indonesia, Sierra Leone, Sri Lanka and some SIDS, fish contribute to around 50% or more of total animal protein intake (FAO 2020). One of the most important coral reef regions in the world is the "Coral Triangle", including the coasts of Indonesia, Malaysia, Papua New Guinea, the Philippines, the Solomon Islands, and Timor-Leste. Accounting for only 1.1% of Earth's surface, these coastal waters host a third of all coral reefs (Cabral and Geronimo 2018). Indonesia and the Philippines have the greatest absolute numbers of reef fishers (Burke et al. 2011). Not only would an unhealthy ocean negatively impact fish production worldwide, increase fish prices and lower availability, but it would also mean an increased food insecurity as many communities rely on fish as their primary resource for (animal) protein. Fish yield associated with coral reefs could therefore play a critical role in ensuring food security in many tropical regions and the severity of climate change could influence the magnitude and scale of ecological and economic changes. Hoegh-Guldberg et al. (2018) concluded that global warming poses a serious threat to food security on a global as well as a regional scale, mostly impacted are low-latitude areas (medium confidence). The Special Report on the Ocean and Cryosphere in a Changing Climate (SCROCC) (IPCC 2019) argues that total global future fishery yields under different climate change scenarios would be impacted by a 4% decrease per degree Celsius warming, which equals a loss of around 3.4 million tons of fish. Regionally, impacts could have more serious threats on food security: tropical regions could lose up to half of their current fish yields by the end of the Twenty-First Century.

Mariculture coastal aquaculture: Mariculture[5] is increasingly important to ensure food security and to meet the increasing seafood demand (Campbell and Pauly 2013; FAO 2018). It relies on suitable ocean settings, among others related to its chemistry and temperature. From 2000 to 2016, the share of mariculture in total aquaculture production has increased from 14 to 37% (FAO 2018). In 2018, mariculture and coastal aquaculture accounted for 30.8 million tons of aquatic animals, worth around USD 106.5 billion (FAO 2020). The impacts of climate change-induced coastal hazards on mariculture, such as SST increase, GMSLR, OA, changes in salinity and more pronounced wave action and storms vary regionally. Whereas SST increase is putting at risk mariculture in tropical and subtropical coastal waters through altered growth rates (calcification rates in the case of bivalves), disease susceptibility and survival rates in general (Cochrane et al. 2009; Handisyde et al. 2006), it could increase yields in higher latitudes (Froehlich et al. 2018; Klinger et al. 2017), making other parts of the world suitable for this kind of aquaculture.

12.5 Management and Mitigation

The previous sections have shown the impacts of climate change on coastal resources, the importance of coastal resources for healthy and productive ecosystems, as well as for a sustained economy. The concept of Blue Economy suggests that human development pathways are grounded on a healthy and resilient ecosystem. Thus, it becomes clear that effective, efficient, and well-planned management and mitigation measures must be implemented. Section 12.5 explores some of the currently used management strategies and highlights innovation in spatial observation.

For example, Cesar et al. (2004) evaluated the socio-economic impacts of marine ecosystem degradation in the Seychelles by examining the (i) assessment of the economic value of marine ecosystems and resources, their components, and the corresponding economic sectors; (ii) impacts on socio-economic sectors; and (iii) development of an adaptation strategy. Such studies illustrate the economic and societal benefits of coastal management, equipping policymakers with useful information for investing in coastal zone management and marine protected area management, as well as designs of feasible management plans.

[5] Mariculture is a form of aquaculture where 'cultivation of the end product takes place in seawater, such as fjords, inshore and open waters, and inland seas or inland facilities (Recirculating Aquaculture Systems) in which the salinity exceeds 20 PSU' (FAO 2014).

12.5.1 Coastal Observation: Enabling Resilient and Sustainable Blue Economies

Chapter 14 of the present book discusses ocean observations in-depth. This chapter emphasizes that the IOC/UNESCO Global Ocean Observing System (GOOS) and its community have developed the 'GOOS 2030 Strategy' (IOC 2019) to support the development of innovative activities, in response to increasing ocean pressures induced by climate change and human development. Without correcting actions, these pressures will intensify in the coming decades leading to more economic losses with extreme weather events and natural disasters. The new strategy will enable resilient and sustainable blue economies. Greater knowledge based on continuous observations will support better understanding of climate change and variability, as well as ocean weather and environmental hazards. Ocean information will be essential to supporting evidence-based decisions on the pathway to sustainable development (IOC 2019).

In addition, GOOS has proposed three programs around integration in the framework of the UN Decade of Ocean Science for Sustainable Development, placing ocean observation at its heart. Attaining a fit-for-purpose ocean observing and forecasting system will be a fundamental step towards success in the Ocean Decade, as sound decisions cannot be made without information. GOOS took up the transformational challenge and identified three key areas for action, where bridging gaps will have a significant impact on Ocean Decade outcomes: connecting the open ocean to the coast; integrated system design; and connection from observing through to communities. With strong partnerships, five linked GOOS Ocean Decade programs, all with a focus on transforming the observing system through integration, have been developed:

1. Ocean Observing Co-Design (ObsCoDe)—creating the process, infrastructure and tools for the co-design of a fit-for-purpose GOOS;
2. CoastPredict—transforming the science of observing and predicting the Global Coastal Ocean, from river catchments, including urban scales, to the oceanic slope waters;
3. Observing Together—supporting communities to bring needed observations and forecasts to users and into global data streams, making every observation count;
4. ForeSea—for strong international coordination and community building of an ocean prediction capacity for the future.
5. Operational Ocean Monitoring and Forecasting System—supporting Blue Growth and Scientific Innovation.

Every country in the world with a coastline engages in marine activities for national security, environmental protection, and maritime economic development.

Such activities require daily monitoring and forecasting of the physical, biogeochemical and sea ice state of the ocean. Operational oceanography relies on expertise and provides the relevant ocean data for monitoring. It involves operational ocean monitoring and forecasting systems which encompass the collection of ocean observations, modeling of the current ocean state, short-range predictions and ocean reanalysis, and scientific verification.[6] It also supplies routine products and information at agreed service levels to enable marine policy implementation, support Blue Growth and scientific innovation. The GOOS Operational Ocean Forecasting System (OOFS) and experts are working on standards and best practice documents to strengthen capacities in developing countries, SIDS and Africa.

The scientific and technical knowledge assembled, for example, in the form of guides, training and capacity development serve to facilitate the implementation of an efficient OOFS. New partnerships and links need to be established with other international organizations and programs (e.g., Mercator Ocean International, OceanPredict, WMO).

12.5.2 Effective Early Warning Systems

Globally, 318 natural hazard events that affected 122 countries were registered in 2017 (9,503 deaths; 96 million people displaced; socioeconomic damages of around USD 314 billion (EM-DAT 2018[7]). 90% of casualties could be connected to hydrometeorological disasters.

In order to anticipate the increasing hazards affecting coastal zones due to climate change, early warning systems (EWS) need to play an even more critical role in the future. SIDS and LDCs with coastlines lack effective EWS because of inadequate financial resources and a lack of trained employees. The International Network for Multi-Hazard Early Warning Systems (IN-MHEWS) was established mainly by the United Nations Office for Disaster Risk Reduction (UNISDR) and the World Meteorological Organization (WMO) Secretariat along with other international agencies to facilitate the sharing of expertise and good practices on strengthening multi-hazard early warning systems as an integral component of national strategies for disaster risk reduction, climate change adaptation, and building resilience. The network is contributing to the achievement of Target G of the Sendai Framework.[8] The Third Multi-Hazard Early Warning Conference (MHEWCIII) held in Bali, Indonesia in May 2022 was an opportunity to stock take to Scaling Actions on Target G: Accelerating the Knowledge and Practice of Early Warning Systems for Risk-Informed Resilience. It is not always possible to quantify the number of lives saved by EWS in the case of an event but, in general, effective EWS and adequate responses from authorities and populations are believed to considerably reduce the loss of lives and socioeconomic losses, reduce damages and reduce desruptions to livelihoods. The IOC UNESCO global tsunami early warning systems in the four-ocean basins, 1) Pacific Ocean, 2) Indian Ocean, 3) Caribbean Sea and North-Eastern Atlantic Ocean

[6] http://oceanpredict.org.

[7] https://mhews.wmo.int/en/side-event-7.

[8] https://mhews.wmo.int/en/partners.

and 4) Mediterranean Sea, for instance, have played a paramount role in providing safety, security and coastal resilience for many coastal populations.

In this regard, more efforts have to be made in order to decrease vulnerability to ocean-to-coast and inland-to-coast hazards and to protect both inhabitants and tourists. Birkmann et al. (2013) highlighted the need for developing people-centered EWS for exposed and vulnerable societies. The MHEWCIII Conference noted that the effectiveness of MHEWS is challenged by the rapidly changing risk landscape driven by climate change and business as usual development pathways. In response, EWS should consider multiple hazards, cascading and concurrent events, vulnerabilities, and capacities of the communities at risk, and should be gender-sensitive and inclusive. It should also integrate research and policy, enables good governance, public engagement and decision making, and is flexible to adapt to the changing risk landscape. Climate Risk and Early Warning Systems (CREWS) were launched by France in 2015, financing important initiatives in SIDS and LDCs with respect to people-centered and solution-based actions. This initiative is based on four pillars: (i) disaster risk knowledge; (ii) detection, monitoring, analysis, and forecasting; (iii) warning dissemination and communication and (iv) preparedness and response capabilities.[9] The Caribbean's unprecedented hurricane season in 2017, linked to increasing sea surface and air temperatures, in particular the hurricanes Harvey, Irma and Maria, which considerably impacted more than 12 island states, led to a systematic review of EWS by CREWS (Rahat 2018). Gaps were identified to be properly addressed. For example, the National Oceanic and Atmospheric Administration (NOAA) issued a warning that the 2017 hurricane season was likely to be stronger than initially predicted, as El Niño failed to develop and a shift to La Niña phenomenon left scientists to reevaluate the storm intensity. Despite possessing this important information, it was not used to raise awareness among the public, leading to a decrease in efficiency of the existing EWS. Identified gaps highlight the importance of people-centered EWS.

12.5.3 Flood Management

As of today, in many coastal cities the risks of flooding are ubiquitous. Thus, urban planners try to integrate water resource planning with innovative approaches, instead of considering it as a source of danger. One of these innovative ideas is to actively integrate heavy precipitation or water from flooding into the water cycle. In the case of an extreme weather event or extreme SLR event, the surplus water is not as destructive to the city. Instead of being directly discharged, the water can be used or stored for later usage. Artificial wetlands, lakes or underground water tanks can be used on a regional scale. On local scales, more permeable grounds, the greening of cities and the construction of raingardens can be observed. These concepts are known worldwide and called Sponge City (SC) in China, Low Impact Development

[9] https://www.crews-initiative.org/en/about-us/who-we-arehttp/oceanpredict.org.

(LID) in the United States, Sustainable Urban Drainage System in Great Britain, and Water Sensitive City in Australia (Chan et al. 2018).

12.5.4 Ecosystem-Based Solution

Vegetation on beaches, dunes and barrier islands favor the resilience of coastal ecosystems in regard to the impacts from climate change-related hazards. A study from Jackson et al. (2019) shows that, contrary to common assumptions, vegetation on dunes has increased in recent years. This 'greening' can probably be attributed to the same effects that climate change is causing but having a positive outcome. Global mean temperature increase, more precipitation and higher nutrient availability, as well as reduced global windiness favor denser vegetation cover on dunes and thus enhancing resilience against storm surges. Well-functioning ecosystems can reduce societies' vulnerability to ocean-related hazards, for example as described in Sect. 12.4.1, highlighting the need for ecosystem-based approaches for comprehensive risk management. Restoration of destroyed coastal systems and strengthening of weakened coastal areas would not only bring back important habitats for many species, but it would also provide natural protection from extreme sea-level events and associated storm surges, protecting economies, lives and livelihoods of many people. In this respect, the current UN Decade on Ecosystem Restoration (2021–2030) could favor and strengthen such ecosystem-based solutions through protecting, managing and reviving existing weakened ecosystems.

12.5.5 Marine Spatial Planning

Marine Spatial Planning (MSP) is an effective public tool for analyzing and allocating the distribution (spatially and temporally) of human activities in coastal and marine areas. Leveraging marine data and multi-stakeholder participation helps to achieve sustainable development at environmental, economic and social scales. Thus, MSP is a strong emerging tool that encourages Blue Economy, anticipates and manages negative impacts of climate change. It is a tool that is very important to SIDS. The Seychelles established the "Seychelles Marine Spatial Plan (SMSP) Initiative" in 2014, to address many different issues, in particular climate change adaptation, marine biodiversity protection and support for the Blue Economy. Through the provision of global best practices, scientific data, local expert knowledge as well as stakeholder input, the SMSP Initiative seeks to produce outreach material, such as maps, in order to disseminate information and knowledge of human activities and ecology (SMSP 2021).

12.5.6 Hard Engineering Solutions

Governments have the option to choose between hard or soft engineering solutions to adapt to climate change and to protect coastal populations and ecosystems from direct ocean hazards. Among the hard engineering techniques are sea walls, groynes, tidal barriers, breakwaters, gabions, rock armours (ripraps) or revetments. These engineering solutions can save lives in the case of a hazardous event, but can be expensive infrastructure, which are often associated with other environmental impacts, and may be aesthetically unpleasant, in particular an important issue to the tourism sector of most SIDS. Soft engineering solutions are similar to the ecosystem-based solutions presented earlier and won't be further discussed.

The Government of the Seychelles through the Coastal Unit, Climate Adaptation, Climate Change Division (CCD) of the Department of Energy and Climate Change (DECC), has carried out several coastal rehabilitation and restoration works of the existing damaged sea wall, the construction of seawalls and repair of damaged outlets. It aims at protecting dunes from erosion and preventing the trees in coastal areas from being uprooted. Coastal rock armoring has emerged as a standard practice and used around the main islands with the idea to mitigate coastal erosion and wave overtopping. However, the likely impact on the tourism sector by degraded and lost value in coastal resources (e.g., sandy beaches) needs to be better understood to inform on an optimal balance between hard and soft measures, that provide sufficient protection from ocean hazards.

12.6 Summary and Outlook

Coastal zones are of great importance to many societies in different ways (habitat, dependent economies, ecosystem services). Effects of SLR, associated storm surges and extreme sea level events, ocean warming and acidification, as well as riverine flooding should be anticipated and mitigated. Impacts of human-made climate change that has induced ocean-to-coast and inland-to-coast hazards on coastal ecosystems, lead to deterioration of coastal ecosystems. It is certain that coastal dynamics will change with ongoing climate change and coastal alterations. Ecosystems may be able to enter a new state of balance and adapt to the new situation that climate change has already imposed or will create in the near future, but many livelihoods and economies globally are at risk. People will be disproportionately affected by these hazards (depending on their socio-economic situation), with many people inevitably losing their lives and economies will shatter if no concrete actions are taken now and EWS are not used accordingly. The UN's new action and ambitious challenge is to ensure every person on Earth is protected by Early Warning Systems within five years and WMO to lead this effort and present an action plan to achieve this goal. Human actions are exacerbating vulnerability and exposure to such hazards. Climate change effects in coastal areas, exceeding critical tipping points, could lead to even more severe impacts in cascading effects.

Hard engineering is usually considered to protect coastal areas from these hazards. However, the literature review has shown that in many cases natural and healthy coastal ecosystems, in particular coral reefs and mangroves, have the capacity to efficiently protect coastal societies and resources from flooding, wave energy and erosion. Nature-based defenses, that is, restoring and conserving these coastal ecosystems could therefore be an approach to effectively counteract some of the climate change-induced hazards.

Blue economy is an important contributor to the well-being of individuals as well as to society. Policymakers, especially in the light of the UN Decade of Ocean Science, should prioritize resiliency and sustainability of economic development. A crucial component here is the correct estimation of impacts and information required for mitigation and adaptation. Assessment of impacts based on systematic observations and data is lacking in many aspects of the science of coastal systems and, in this regard, important work from GOOS could support better understanding of the complex interconnected topics of climate change and variability, and ocean weather and environmental hazards. It is also critical to further encourage integrated and adopt long-term approach, and to optimally apply existing tools and capabilities to supporting blue economies.

Acknowledgements PNV acknowledges partial financial support from J. C. Bose fellowship awarded by the Ministry of Earth Sciences, Govt. of India.

References

Abedin MdA, Collins AE, Habiba U et al (2019) Climate change, water scarcity, and health adaptation in southwestern coastal Bangladesh. Int J Disaster Risk Sci 10:28–42. https://doi.org/10.1007/s13753-018-0211-8

Adams JB (2020) Salt marsh at the tip of Africa: patterns, processes and changes in response to climate change. Estuar Coas Shelf Sci 237:106650. https://doi.org/10.1016/j.ecss.2020.106650

Ahmad H (2019) Bangladesh Coastal Zone Management Status and Future Trends. Coast Zone Manag 22(1):466.

Ahmed N, Cheung WWL, Thompson S et al (2017) Solutions to blue carbon emissions: shrimp cultivation, mangrove deforestation and climate change in coastal Bangladesh. Mar Policy 82:68–75. https://doi.org/10.1016/j.marpol.2017.05.007

Auzoux-Bordenave S, Wessel N, Badou A et al (2020) Ocean acidification impacts growth and shell mineralization in juvenile abalone (*Haliotis tuberculata*). Mar Biol 167: Article No. 11. https://doi.org/10.1007/s00227-019-3623-0

Barbier EB, Hacker SD, Kennedy C et al (2011) The value of estuarine and coastal ecosystem services. Ecol Monogr 81:169–193. https://doi.org/10.1890/10-1510.1

Bauer JE, Cai WJ, Raymond PA et al (2013) The changing carbon cycle of the coastal ocean. Nature 504(7478):61–70. https://doi.org/10.1038/nature12857

Béné C, Barange M, Subasinghe R et al (2015) Feeding 9 billion by 2050 – putting fish back on the menu. Food Security 7:261–274. https://doi.org/10.1007/s12571-015-0427-z

Bevacqua E, Maraun D, Vousdoukas MI et al (2019) Higher probability of compound flooding from precipitation and storm surge in Europe under anthropogenic climate change. Sci Adv 5:eaaw5531. https://doi.org/10.1126/sciadv.aaw5531

Birkmann J, Chang Seng D, Setiadi N (2013) Enhancing early warning in the light of migration and environmental shocks. Environ Sci Policy 27:S76–S88. https://doi.org/10.1016/j.envsci.2012.04.002

Boori MS, Ferreira A, Amaro V (2012) Coastal risk assessment and adaptation of the impact of sea-level rise, climate change and hazards: A RS and GIS based approach in Apodi-Mossoro estuary, Northeast Brazil. Int J Geomat Geosci 2(3):815–832. https://www.researchgate.net/publication/260494736_Coastal_risk_assessment_and_adaptation_of_the_impact_of_sea-level_rise_climate_change_and_hazards_A_RS_and_GIS_based_approach_in_Apodi-Mossoro_estuary_Northeast_Brazil

Burke L, Reytar K, Spalding M et al (2011) Reefs at risk revisited. World Resource Institute. Available via https://digitalarchive.worldfishcenter.org/bitstream/handle/20.500.12348/1107/Reefs-At-Risk-Revisited.pdf?sequence=1&isAllowed=y

Breitburg D, Levin LA, Oschlies A et al (2018) Declining oxygen in the global ocean and coastal waters. Science 359(6371): eaam7240. https://doi.org/10.1126/science.aam7240

Cabral RB, Geronimo RC (2018) How important are coral reefs to food security in the Philippines? Diving deeper than national aggregates and averages. Mar Policy 91:136–141. https://doi.org/10.1016/j.marpol.2018.02.007

Campbell B, Pauly D (2013) Mariculture: a global analysis of production trends since 1950. Mar Policy 39:94–100. https://doi.org/10.1016/j.marpol.2012.10.009

Carter RWG (1988) Coastal environments: an introduction to the physical ecological and cultural systems of coastlines. Academic Press, London

Cesar H, Van Beukering PJH, Payet R et al (2004) Evaluation of the socio-economic impacts of marine ecosystem degradation in the Seychelles. Cesar Environmental Economics Consulting, https://www.researchgate.net/publication/228694102_Evaluation_of_the_Socio-Economic_Impacts_of_Marine_Ecosystem_Degradation_in_the_Seychelles

Chang Seng SD, Guillande R (2008) Disaster Risk Profile of Seychelles. UNDP, Seychelles.

Chang Seng SD (2007a) Seychelles Climate Change Scenarios for Vulnerability and Adaptation Assessment, Second National Communication (SNC), Under the United Nations Framework Convention on Climate Change (UNFCCC), UNDP, Seychelles.

Chang Seng SD (2007b) Climate Variability and Climate Change Assessment for the Seychelles, Second National Communication (SNC), Under the United Nations Framework Convention on Climate.

Chowdhury MMI, Rahman SM, Abubakar IR et al (2021) A review of policies and initiatives for climate change mitigation and environmental sustainability in Bangladesh. Environ Dev Sustain 23:1133–1161. https://doi.org/10.1007/s10668-020-00627-y.

Cisneros-Montemayor AM, Sumaila UR (2010) A global estimate of benefits from ecosystem-based marine recreation: potential impacts and implications for management. J Bioecon 12:245–268. https://doi.org/10.1007/s10818-010-9092-7

Chan FKH, Griffiths JA, Higgitt D et al (2018) "Sponge City" in China - a breakthrough of planning and flood risk management in the urban context. Land Use Policy 76:772–778. https://doi.org/10.1016/j.landusepol.2018.03.005

Chen CTA (2003) New vs. export production on the continental shelf. Deep-Sea Res II 50(6):1327–1333. https://doi.org/10.1016/S0967-0645(03)00026-2

Cochrane K, De Young C, Soto D et al (2009) Climate change implications for fisheries and aquaculture. FAO. Fisheries and Aquaculture Technical Paper 530(212).

Cooper JAG, Masselink G, Coco G et al (2020) Sandy beaches can survive sea-level rise. Nat Clim Chang 10:993–995. https://doi.org/10.1038/s41558-020-00934-2

Crossland CJ et al (2006) The coastal zone—a domain of global Interactions. In: Crossland CJ, Kremer HH, Lindeboom HJ et al (eds) Coastal fluxes in the Anthropocene. Global change—the IGBP series. Springer, Berlin, Heidelberg. https://doi.org/10.1007/3-540-27851-6_1

Deaton CD, Hein CJ, Kirwan ML (2017) Barrier island migration dominates ecogeomorphic feedbacks and drives salt marsh loss along the Virginia Atlantic Coast, USA. Geology 45(2):123–126

Defeo O, McLachlan A, Schoeman D et al (2008). Threats to sandy beach ecosystems: a review. Estuar Coast Shelf Sci 81(1):1–12. https://doi.org/10.1016/j.ecss.2008.09.022

Dasgupta S, Islam MS, Huq M et al (2019) Quantifying the protective capacity of mangroves from storm surges in coastal Bangladesh. PLoS ONE 14(3):e0214079. https://doi.org/10.1371/journal.pone.0214079

De la Torre-Castro M, Rönnbäck P (2004) Links between humans and seagrasses—an example from tropical East Africa. Ocean Coast Manag 47:361–387

Deutz A, Kellet J, Zoltani T (2018) Innovative finance for resilient coasts and communities. A briefing paper prepared by The Nature Conservancy and the United Nations Development Programme for Environment and Climate Change Canada. https://www.nature.org/content/dam/tnc/nature/en/documents/Innovative_Finance_Resilient_Coasts_and_Communities.pdf

Duarte B, Martins I, Rosa R et al (2018) Climate change impacts on seagrass meadows and macroalgal forests: an integrative perspective on acclimation and adaptation potential. Front Mar Sci 5:190. https://doi.org/10.3389/fmars.2018.00190

Duarte CM, Losada IJ, Hendriks IE et al (2013) The role of coastal plant communities for climate change adaptation and mitigation. Nat Clim Change 3:961–968. https://doi.org/10.1038/nclimate1970

Dung TD, van Halsema G, Hellegers PJ et al (2019) Long-term sustainability of the Vietnamese Mekong Delta in question: an economic assessment of water management alternatives. Agric Water Manag 223:105703

Edmonds DA, Caldwell RL, Brondizio ES, Siani SMO (2020) Coastal flooding will disproportionately impact people on river deltas. Nat Commun 11: Article No. 4741. https://doi.org/10.1038/s41467-020-18531-4

Ericson JP, Vörösmarty CJ, Dingman SL et al (2006) Effective sea-level rise and deltas: causes of change and human dimension implications. Globe Planet Change 50(1–2):63–82. https://doi.org/10.1016/j.gloplacha.2005.07.004

Eslami S, Hoekstra P, Trung NN et al (2019) Tidal amplification and salt intrusion in the Mekong Delta driven by anthropogenic sediment starvation. Sci Rep 9:18746

European Environment Agency (2019) Heavy precipitation in Europe. https://www.eea.europa.eu/data-and-maps/indicators/precipitation-extremes-in-europe-3/assessment-1. Accessed 15 Mar 2021

FAO (2014) The state of world fisheries and aquaculture. Opportunities and challenges. Rome, Italy.

FAO (2018) The state of world fisheries and aquaculture 2018—Meeting the sustainable development goals. Rome, Italy

FAO (2020) The state of world fisheries and aquaculture 2020. Sustainability in action. FAO, Rome.https://doi.org/10.4060/ca9229en

Feely RA, Doney SC, Cooley SL (2009) Ocean acidification: present conditions and future changes in a high-CO_2 world. Oceanography 22(4):36–47. https://doi.org/10.5670/oceanog.2009.95

Ferrario F, Beck MW, Storlazzi CD et al (2014) The effectiveness of coral reefs for coastal hazard risk reduction and adaptation. Nat Commun 5: Article No. 3794. https://doi.org/10.1038/ncomms4794

FitzGerald DM, Hein CJ, Hughes Z et al (2018) Runaway barrier island transgression concept: global case studies. In: Moore L, Murray AB (eds) Barrier dynamics and response to changing climate. Springer, Cham, pp 3–56

Frederikse T, Landerer F, Caron L et al (2020) The causes of sea-level rise since 1900. Nature 584:393–397. https://doi.org/10.1038/s41586-020-2591-3

Froehlich HE, Gentry RR, Halpern BS (2018) Global change in marine aquaculture production potential under climate change. Nature Ecology & Evolution 2(11):1745–1750. https://doi.org/10.1038/s41559-018-0669-1

Gattuso JP, Allemand D, Frankignoulle M (1999) Photosynthesis and calcification at cellular, organismal and community levels in coral reefs: a review on interactions and control by carbonate chemistry. Am Zool 39(1):160–183

Ghosh MK, Kumar L, Langat PK (2019) Geospatial modelling of the inundation levels in the Sundarbans mangrove forests due to the impact of sea level rise and identification of affected species and regions. Geomat Nat Haz Risk 10(1):1028–1046. https://doi.org/10.1080/19475705.2018.1564373

Global Mangrove Watch (2020) Global Mangrove Watch 1996–2016. UNEP-WCMC Data Viewer. https://data.unep-wcmc.org/. Accessed 28 Mar 2021

Governmental Statistics Office (GSO) (2016) National Socioeconomic Development Report, 2016. https://www.gso.gov.vn/default.aspx?tabid=621ItemID=16067. Accessed 28 Mar 2021

Government of Seychelles (2016) Seychelles Post Disaster Needs Assessment Tropical Cyclone Fantala April 2016

Handisyde NT, Ross LG, Badjeck MC et al (2006) The effects of climate change on world aquaculture: a global perspective. Aquaculture and Fish Genetics Research Programme, Stirling Institute of Aquaculture. Final Technical Report, DFID, Stirling, 151 p

Harrison B (2020) Review of sea-level rise science, information and services in Bangladesh, UK Met. Office, 34 p

He Q, Silliman BR (2019) Climate change, human impacts, and coastal ecosystems in the Anthropocene. Curr Biol 29(19):R1021–R1035. https://doi.org/10.1016/j.cub.2019.08.042

Hoegh-Guldberg O (2011) Coral reef ecosystems and anthropogenic climate change. Reg Environ Change 11:215–227. https://doi.org/10.1007/s10113-010-0189-2

Hoegh-Guldberg O, Jacob D, Taylor M et al (2018) Impacts of 1.5 °C global warming on natural and human systems. In: Masson-Delmotte V, Zhai P, Pörtner HO et al (eds.). Global Warming of 1.5 °C. An IPCC Special Report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.

Hofstede R, Hiddink JG, Rijnsdorp AD (2010) Regional warming changes fish species richness in the eastern North Atlantic Ocean. Mar Ecol Prog Ser 414:1–9. https://doi.org/10.3354/meps08753

Hsiao SC, Chiang WS, Jang JH et al (2021) Flood risk influenced by the compound effect of storm surge and rainfall under climate change for low-lying coastal areas. Sci Total Environ 764:144439. https://doi.org/10.1016/j.scitotenv.2020.144439

Intergovernmental Oceanographic Commission (IOC) (2019). The Global Ocean Observing System 2030 Strategy. Paris, IOC Brochure 2019-5 (IOC/BRO/2019/5 rev.2), GOOS Report No.239 https://www.goosocean.org/index.php?option=com_oe&task=viewDocumentRecord&docID=24590

IPCC (2014) Climate Change 2014: synthesis report. Core Writing Team, Pachauri RK, Meyer LA (eds) Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

IPCC (2018) Global Warming of 1.5 °C. In: Masson Delmotte V, Zhai P, Pörtner HO et al (eds) An IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.

IPCC (2019) In: Pörtner HO, Roberts DC, Masson-Delmotte V et al (eds) IPCC Special Report on the Ocean and Cryosphere in a Changing Climate, 151 p

IPCC (2021) Summary for policymakers. Climate Change 2021: The physical science basis. In: Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan C, Berger S, Caud N, Chen Y, Goldfarb L, Gomis MI, Huang M, Leitzell K, Lonnoy E, Matthews JBR, Maycock TK, Waterfield T, Yelekçi O, Yu R, Zhou B (eds) Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, pp 3–32. Cambridge University Press, Cambridge, UK, New York, NY, and USA. https://doi.org/10.1017/9781009157896.001

Ishtiaque A, Eakin H, Vij S et al (2021) Multilevel governance in climate change adaptation in Bangladesh: structure, processes, and power dynamics. Reg Environ Change 21:75. https://doi.org/10.1007/s10113-021-01802-1
Islam MA, Hossain MS, Murshed S (2015) Assessment of coastal vulnerability due to sea level change at Bhola Island, Bangladesh: using geospatial techniques. J Indian Soc Remote Sens 43(3):625–637. https://doi.org/10.1007/s12524-014-0426-0
Jackson DWT, Costas S, González-Villanueva R et al (2019) A global 'greening' of coastal dunes: an integrated consequence of climate change? Global Planet Change 182:103026. https://doi.org/10.1016/j.gloplacha.2019.103026
Jasechko S, Perrone D, Seybold H et al (2020) Groundwater level observations in 250,000 coastal US wells reveal scope of potential seawater intrusion. Nat Commun 11:3229. https://doi.org/10.1038/s41467-020-17038-2
Karim MF, and Mimura N (2008) Impacts of climate change and sea-level rise on cyclonic storm surge floods in Bangladesh. Glob Environ Change 18:490–500. https://doi.org/10.1016/j.gloenvcha.2008.05.002
Kennish MJ (2002) Environmental threats and environmental future of estuaries. Environ Conserv 29(1):78–107. https://doi.org/10.1017/S0376892902000061
Kirezci E, Young IR, Ranasinghe R et al (2020) Projections of global-scale extreme sea levels and resulting episodic coastal flooding over the 21st Century. Sci Rep 10:11629. https://doi.org/10.1038/s41598-020-67736-6
Kjerfve B (1989) Estuarine geomorphology and physical oceanography. In: Day JW, Hasll CAS, Kemp MW, Yáñez-Arancibia A (eds) Estuarine ecology, pp 47–78. John Wiley & Sons, New York
Kleypas JA, McManus JW, Menez LAB (1999) Environmental limits to coral reef development: where do we draw the line? Am Zool 39(1):146–159
Klinger DH, Levin SA, Watson JR (2017) The growth of finfish in global open-ocean aquaculture under climate change. Proc R Soc London, Ser B 284:28420170834. https://doi.org/10.1098/rspb.2017.0834
Lauvset SK, Carter BR, Perez FF et al (2020) Processes driving global interior ocean pH distribution. Global Biogeochem Cycles 34:e2019GB006229. https://doi.org/10.1029/2019GB006229
Leary N, Conde C, Kulkarni J et al (2008) Climate change and vulnerability. Routledge. 992 p
Manning E (2009) The challenge of sustainable tourism in Small Island Developing States (SIDS). https://canadiancor.com/challenge-sustainable-tourism-small-island-developing-states-sids/
McFadden L, Spencer T, Nicholls R (2007) Broad-scale modelling of coastal wetlands: what is required? Hydrobiologia 577:5–15. https://doi.org/10.1007/s10750-006-0413-8
McLeod E, Chmura GL, Bouillon S et al (2011) A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO_2. Front Ecol Environ 9(10):552–560
Mehvar S, Filatova T, Sarker MH et al (2019) Climate change-driven losses in ecosystem services of coastal wetlands: a case study in the west coast of Bangladesh. Ocean Coast Manag 169:273–283. https://doi.org/10.1016/j.ocecoaman.2018.12.009
Mentaschi L, Vousdoukas MI, Pekel JF et al (2018) Global long term observations of coastal erosion and accretion. Sci Rep 8:12876. https://doi.org/10.1038/s41598-018-30904-w
Myhre G, Alterskjær K, Stjern CW et al (2019) Frequency of extreme precipitation increases extensively with event rareness under global warming. Sci Rep 9:16063. https://doi.org/10.1038/s41598-019-52277-4
Narayan S, Beck MW, Reguero BG et al (2016) The effectiveness, costs and coastal protection benefits of natural and nature-based defences. PLoS ONE 11(5):e0154735. https://doi.org/10.1371/journal.pone.0154735
National Ocean Economics Program (2007) A guide to the measurement of the market data for the ocean and coastal economy in the National Ocean Economics Program

OECD (2017) Governing better through evidence-informed policy making. Conference Summary. https://www.oecd.org/gov/governing-better-through-evidence-informed-policy-making-proceedings.pdf
OECD (2020) Work in support of a sustainable ocean. https://www.oecd.org/ocean/OECD-work-in-support-of-a-sustainable-ocean.pdf
Olischläger M, Wild C (2020) How does the sexual reproduction of marine life respond to ocean acidification? Diversity 12:241. https://doi.org/10.3390/d12060241
Paprotny D, Vousdoukas MI, Morales-Nápoles O et al (2021) Compound flood potential in Europe. Hydrol Earth Syst Sci 25:4403–4416
Phillips MR (2008) Consequences of short-term changes in coastal processes: a case study. Earth Surf Process Landforms 2107:2094–2107
Piesse M (2019) The Mekong Delta: land subsidence threatens Vietnam's "food basket". Strategic Analysis Paper, Future Directions International, Australia
Pritchard DW (1967) What is an estuary: physical standpoint. In: Estuaries Lauff GH (ed) American Association for the Advancement of Science, Publication 83, Washington, DC, USA, pp 3–5
Prusty P, Farooq SH (2020) Seawater intrusion in the coastal aquifers of India—a review. HydroResearch 3:61–74. https://doi.org/10.1016/j.hydres.2020.06.001
Rahat S (2018) Desk review of Early Warning Systems (EWS) in the Caribbean. An examination of the level of investment established to strengthen the 4 pillars of EWS at the Regional, National and Community Levels. https://dipecholac.net/docs/xfiles/1054-DESK%20REVIEW-OF-EARLY-WARNING-SYSTEMS-EWS-IN-THE-CARIBBEAN.pdf
Sabine CL, Feely LA, Gruber N et al (2004) The oceanic sink for anthropogenic CO_2. Science 305(5682):367–371. https://doi.org/10.1126/science.1097403
Saintilan N, Wilson NC, Rogers K et al (2014) Mangrove expansion and salt marsh decline at mangrove poleward limits. Glob Change Biol 20:147–157. https://doi.org/10.1111/gcb.12341
Sarwar MGM, Woodroffe CD (2013) Rates of shoreline change along the coast of Bangladesh. J Coast Conserv 17(3):515–526. https://doi.org/10.1007/s11852-013-0251-6
Schiel DR, Steinbeck JR, Foster MS (2004) Ten years of induced ocean warming causes comprehensive changes in marine benthic communities. Ecology 85:1833–1839. https://doi.org/10.1890/03-3107
Schlenger AJ, Beas-Luna R, Ambrose RF (2021) Forecasting ocean acidification impacts on kelp forest ecosystems. PLoS ONE 16(4):e0236218. https://doi.org/10.1371/journal.pone.0236218
Schmidtko S, Stramma L, Visbeck M (2017) Decline in global oceanic oxygen content during the past five decades. Nature 542:335–339. https://doi.org/10.1038/nature21399
Sheikh PA (2005) The impact of Hurricane Katrina on biological resources. Congressional Research Service, the Library of Congress.
Sheppard C, Dixon DJ, Gourlay M et al (2005) Coral mortality increases wave energy reaching shores protected by reef flats: examples from the Seychelles. Estuar Coast Shelf Sci 64(2–3):223–234
Smajgl A, Toan T, Nhan D et al (2015) Responding to rising sea levels in the Mekong Delta. Nature Clim Change 5:167–174. https://doi.org/10.1038/nclimate2469
Smale DA (2020) Impacts of ocean warming on kelp forest ecosystems. New Phyto 225:1447–1454. https://doi.org/10.1111/nph.16107
Seychelles Marine Spatial Plan Initiative (2021) The initiative. https://seymsp.com/the-initiative/. Accessed 2 Sept 2021
Storlazzi CD, Gingerich SB, van Dongeren A et al (2018) Most atolls will be uninhabitable by the mid-21st century because of sea-level rise exacerbating wave-driven flooding. Sci Adv 4:4
Stutz ML, Pilkey OH (2011) Open-ocean barrier islands: global influence of climatic, oceanographic, and depositional settings. J Coastal Res 27(2):207–222
Szabo S, Hossain MS, Adger WN et al (2016) Soil salinity, household wealth and food insecurity in tropical deltas: evidence from south-west coast of Bangladesh. Sustain Sci 11(3):411–421
Taherkhani M, Vitousek S, Barnard PL et al (2020) Sea-level rise exponentially increases coastal flood frequency. Sci Rep 10:6466. https://doi.org/10.1038/s41598-020-62188-4

Tamvakis A, Tsirtsis G, Karydis M et al (2021) Drivers of harmful algal blooms in coastal areas of Eastern Mediterranean: a machine learning methodological approach. Math Biosci Eng 18(5):6484–6505. https://doi.org/10.3934/mbe.2021322
The World Bank (2010) World development indicators. http://data.worldbank.org/data-catalog/world-development-indicators%20. Accessed 19 Mar 2021
The World Bank (2017) What is the blue economy? https://www.worldbank.org/en/news/infographic/2017/06/06/blue-economy. Accessed 15 Mar 2021
UNDRR (2021) UNDRR strategic framework 2022–2025
UNESCO Marine World Heritage (2021) Custodians of the globe's blue carbon assets. https://unesdoc.unesco.org/ark:/48223/pf0000375565/PDF/375565eng.pdf.multi
UNEP (2009) Sustainable coastal tourism. https://wedocs.unep.org/handle/20.500.11822/7819
Uncles RJ (2010) Physical properties and processes in the Bristol Channel and Severn estuary. Mar Pollut Bull 61:5–20
UN Ocean Conference (2017) Factsheet: people and oceans. https://www.un.org/sustainabledevelopment/wp-content/uploads/2017/05/Ocean-fact-sheet-package.pdf. Accessed 18 Mar 2021
World Tourism Organization (2021) International tourism highlights, 2020 Edition, UNWTO, Madrid. https://doi.org/10.18111/9789284422456
Worthington T and Spalding M (2018) Mangrove restoration potential: a global map highlighting a critical opportunity. https://doi.org/10.17863/CAM.39153
Vitousek S, Barnard P, Fletcher C et al (2017) Doubling of coastal flooding frequency within decades due to sea-level rise. Sci Rep 7:1399. https://doi.org/10.1038/s41598-017-01362-7
Vousdoukas MI, Mentaschi L, Voukouvalas E et al (2018) Global probabilistic projections of extreme sea levels show intensification of coastal flood hazard. Nat Commun 9:2360. https://doi.org/10.1038/s41467-018-04692-w
Vousdoukas MI, Ranasinghe R, Mentaschi L et al (2020) Sandy coastlines under threat of erosion. Nat Clim Chang 10:260–263. https://doi.org/10.1038/s41558-020-0697-0
Watson R, Coles R, Lee Long W (1996) Simulation estimates of annual yield and landed value for commercial penaeid prawns from a tropical seagrass habitat, Northern Queensland, Australia. Mar Freshw Res 44:211–219
Wernberg T, Russell BD, Moore PJ et al (2011) Impacts of climate change in a global hotspot for temperate marine biodiversity and ocean warming. J Exp Mar Biol Ecol 400(1–2):7–16. https://doi.org/10.1016/j.jembe.2011.02.021
Wong PP et al (2014) Coastal systems and low-lying areas. In: Field CB et al (ed) 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. Cambridge University Press, Cambridge, United Kingdom and New York, USA, pp. 361–409. ISBN: 978-1-107-05807-1
World Ocean Review (2017) Coasts – a vital habitat under pressure. https://worldoceanreview.com/wp-content/downloads/wor5/WOR5_en.pdf
Zhang K, Liu H, Li Y et al (2012) The role of mangroves in attenuating storm surges. Estuar Coast Shelf Sci 102–103:11–23. https://doi.org/10.1016/j.ecss.2012.02.021
Zinnert JC, Via SM, Nettleton BP et al (2019) Connectivity in coastal systems: Barrier island vegetation influences upland migration in a changing climate. Glob Change Biol 25(7):2419–2430. https://doi.org/10.1111/gcb.14635

Chapter 13
Constructing a Blue Economy Architecture for Small Islands

Ranadhir Mukhopadhyay and Abhishri Gupta

Abstract A host of emerging environmental, economic, and social challenges are threatening the harmonious and responsible growth of small island nations. These islands have bountiful resources in their vast exclusive economic zones but lack adequate infrastructure, skills, and funds to benefit from those assets. Further, although contributing least to the global pool of carbon emissions—actually emitting less than 1% of global greenhouse gas emissions—these islands suffer disproportionately from the effects of climate change. Additionally, threats from sea level rise, extreme events, overfishing, loss of biodiversity due to invasion of alien species, and pollution create harm to these tiny landmasses. In this chapter, we focus on small islands from the Atlantic, Indian and Pacific oceans to identify their challenges and limitations in terms of capability and offer an overview of issues and an approach for the development of the blue economy in these islands. We suggest that appropriate use of science, technology and innovation (STI) can help these islands make optimum use of their natural resources (minerals, pharmaceutical products, hydrocarbons, renewable energy, and fish stocks), energy potential, and commercial activities (sea trade, port facilities, ecotourism, hospitality).

Keywords Blue economy · Small islands · STI interventions · Resources · Energy · Ecosystem economics

13.1 Introduction

Small islands, in one way, are the custodians of much of the world's ocean. For instance, the exclusive economic zones (EEZs) of small islands encompass about 30% of the world's oceanic area and host considerable reserves of minerals, oil and natural

R. Mukhopadhyay (✉)
CSIR - National Institute of Oceanography, Dona Paula 403004, Goa, India
e-mail: mranadhir@yahoo.com

A. Gupta
School of Biology and Environmental Science (SBES), University College Dublin, Dublin, Ireland

E. R. Urban Jr. and V. Ittekkot (eds.), *Blue Economy*,
https://doi.org/10.1007/978-981-19-5065-0_13

gas, fish, and shellfish. EEZs extend for about 370 km from shore, within which coastal states have the right to explore, exploit, conserve and manage both living and non-living resources (UNCLOS 1982). Small islands are particularly known for their huge EEZs compared to their landmasses. The total landmass of all the islands together is 24,111 km^2, compared to their total EEZ area of 666,110 km^2. In other words, 3.5% of small islands is land, while 96.5% is ocean. The EEZ of Tuvalu in the Pacific Ocean, for example, is 27,000 times the size of its land area (Halais 2019).

The percentage of land five meters above the mean sea level (MSL) in these small islands is very limited. About 26.2% of the landmass of small islands are below 5 m above MSL. For instance, the entire Maldives Islands are below 5 m above MSL (Fig. 13.1), while 99% of the Marshall Islands, 96.7% of Kiribati and 87.9% of the Cook Islands have levels less than 5 m above MSL. Although emitting the least carbon of any country, these islands will be highly impacted by climate change (rise in sea level, increased frequency of cyclones, storms, pollution, and degradation of the coastal zone) of the world's nations. The environmental vulnerability index (EVI) for small islands is very high, about 46.7% (UN-OHRLLS 2015; Ferdi-EVI).

There are a total of 58 small island nations in the world, which are a distinct group of mostly developing countries that face some specific and comparable social, economic, and environmental vulnerabilities (Table 13.1). These islands are scattered over the global ocean: 32 in the Atlantic-Caribbean Ocean (A-C), 20 in the Pacific Ocean, and the remaining 6 in the Indian Ocean-China Sea (I-C). The immediate challenges of these islands include growing populations, limited land resources,

Fig. 13.1 The low-lying Maldives are one of the countries most endangered from sea-level rise (*Source* https://pixabay.com/photos/maldives-palm-trees-beach-summer-2122547/ by Uwe Kern)

remoteness, vulnerability to natural disasters, excessive dependence on imports, and fragile environments. Additionally, the lack (and also the high cost) of communication, energy, transportation and public infrastructure have stunted the development of these islands (FAO 2020a; World Bank 2020). Owing to their limited infrastructural capacity and geographic isolation, these islands often find it difficult to monitor and regulate economic activities within their large EEZs, solve territorial disputes and stop the disposal of pollutants by larger nations (O'Rourke 2018; UN 2012, 2018).

Many of these islands are small enough for their land areas to fall entirely within their coastal zones and naturally within the blue economy paradigm. In such cases, the all-around growth of human resources is a prerequisite to taking full advantage of a blue economy ecosystem. In this regard, education, health, capacity building, and ecosystem awareness are important factors for human sustainability.

The importance of blue economy activities for small islands can be illustrated by their degrees of development compared to other developing countries. For example, the human development index (HDI, a composite measure of health, knowledge and standard of living) offers a mixed message (Table 13.1). The average HDI of small islands is only slightly lower (0.684) than the global average of 0.728, as also the Life expectancy (71.2 years compared to 72.2 years of the globe). However, "average" does not show the situation for individual islands. Over 40% of small islands display a low to medium level of HDI (e.g., Palau ranks 60 in HDI; UN-DESA 2018).

Implementation of blue economies in small islands could ensure a combination of relatively high HDI and low GINI coefficient, suggesting a good distribution of wealth (Tables 13.1 and 13.2). The GINI coefficient is a measure of the distribution of income across a population and developed to gauge economic inequality, measuring income or wealth distribution among a population. A distributed economy is most desired as it promotes social inclusion, improves the livelihoods of islanders, and ensures sustainable management of coastal and ocean resources. Such an economy could also seek to turn the geographic location of smaller islands from a liability to an asset for ocean-based economic development (Pauli 2010; Mukhopadhyay et al. 2021). If done scientifically and innovatively, substantial employment opportunities could also be created by diversifying industries (UNDP 2011; World Bank 2016).

The geographic exclusivity, lack of infrastructure, enormous EEZs, and the possible threat of drowning of many of these small islands in the future (Fig. 13.1) merit their separate consideration concerning the development and sustenance of the blue economy paradigm. This type of economy appears to be the best approach for small islands as it supports the sustainable use of vast ocean resources of these islands for economic growth, improved livelihoods, and generating jobs while preserving the health of their ocean ecosystems. Accordingly, in this chapter, we have taken up the three most significant activity areas of the majority of the small island states to explore how an STI-backed blue economy architecture could help strengthen their HDI and economy. The areas are (1) resource potential, (2) energy potential, and (3) ecosystem services. This chapter starts by briefly listing the prospect of these islands in these three areas. Later, we discuss the threats both from natural and human activities. To conclude, we present a possible roadmap for the application of science and technology to accomplish the blue economy development in these small islands.

Table 13.1 Some essential indices of a few global small islands

1	2	3	4	5	6	7	8	9
Islands with million dollar (M$) GDP economies								
American Samoa	200	46,366	259	658	11,200	–	–	–
Anguilla	91	14,731	132	311	29,493	–	9.04	443
British Virgin Islands	153	30,030	260	500	34,200	–	6.86	–
Cook Islands	236.7	17,459	42	363	20,721	–	–	360
Dominica	750	71,625	105	688	9726	742	3.8	–
Federated State of Micronesia	702	104,468	158	367	3584	620	12.5	401
Kiribati	811	119,940	151.9	255	2135	630	8.4	370
Marshall Islands	181	58,413	293	215	3789	567	31.3	408
Montserrat	102	4649	44	63	12,384	–	–	–
Nauru	21	10,670	480	160	12,052	–	13.8	348
Niue	261	1620	6.71	10	5800	–	–	–
Palau	459	17,907	46.7	300	16,296	826	6.5	–
Sao Tome Principe	1001	211,028	199.7	685	3220	625	7.3	563
Tonga	748	10,065	139	655	6496	725	4.5	376
Tuvalu	26	11,646	475.8	39	3566	–	22.7	391
Vanuatu	12,189	307,815	19.7	820	2850	609	9.5	376
Islands with single-digit billion-dollar (B$) GDP economies								
Antigua-Barbuda	440	99,337	186	2.731	29,298	778	7.05	823
Aruba	180	116,576	624	4.40	37,576	908		703
Barbados	439	287,025	660	5.40	18,798	814	11.1	470
Cape Verde	4033	543,767	123.7	4.32	7728	665	8.6	424
Comoros	1861	850,886	457	2.44	2799	554	7.1	453
Fiji Islands	18,274	926,276	46	9.11	10,251	724	6.9	367
French Polynesia	4167	275,918	78	6.16	–	–		–
Grenada	348	111,454	318	1.80	16,604	779	2.9	–
Guam	540	168,801	299	5.79	35,600	901		360
Maldives	300	557,426	1102	8.97	23,343	740	15.0	313
New Caledonia	18,576	271,407	14.5	9.44	34,780	813		–
Northern Marianas	464	51,659	113	1.24	24,500	–		–
Samoa	2842	202,506	70	1.19	5962	715	6.5	387
Seychelles	459	98,462	214	2.92	30,486	801	3.1	321
Solomon Islands	28,400	652,857	18	1.479	2307	567	4.7	371
St Kitts & Nevis	261	52,441	164	1.758	18,714	779	7.6	–
St Lucia	617	184,401	299	2.48	13,708	759	8.5	512

(continued)

Table 13.1 (continued)

1	2	3	4	5	6	7	8	9
St Vincent Grenadines	389	110,211	307	1.37	12,431	738	4.5	–
Timor East	15,007	1,340,513	78	5.3	4031	606	9.1	287
U.S. Virgin Islands	346	105,870	297	4.58	36,350	894	–	–
Islands with double and triple digit billion dollar (B$) GDP ECONOMIES								
Bahamas	13,878	385,637	25	12.8	34,102	805	7.7	570
Bahrain	785	1,569,446	1913	78.76	52,129	852	20	–
Cuba	109,884	11,193,470	102	254.8	22,237	783	10.6	380
Dominican Republic	48,671	10,878,246	220	216	20,625	756	3.0	437
Haiti	27,750	11,439,646	382	33.9	2962	510	1.5	411
Jamaica	10,991	2,726,667	266	26.98	9434	734	9.0	350
Mauritius	2040	1,265,475	618	31.70	25,029	804	7.3	368
Papua N Guinea	462,840	8,935,000	15	32.38	3764	555	3.5	509
Puerto Rico	9104	3,285,874	350.8	112	35,943	845		550
Singapore	728	5,685,800	7804	600	102,742	938	31.0	459
Trinidad-Tobago	5131	1,366,725	264	45.14	32,648	796	9.1	403

1-Name of Island, 2-Approximate Area in km^2, 3-Population, 4-Density (Population/Area), 5-GDP (PPP), Gross Domestic Product (Purchasing Power Parity) which takes into account the relative cost of local goods, services and inflation rates of the country, and is a much more robust and accurate measurement than nominal GDP, 6-Per-Capita GDP Per capita gross domestic product is a metric that breaks down a country's economic output per person and is calculated by dividing the GDP of a country by its population, 7-HDI (Human Development index in thousand points × 1000; (0 is bad, 1000 is outstanding), 8-Public expenditure in health and education as a percentage share of GDP in 2014

Note Data are for 2014, except for Cape Verde, Fiji, for education (2013), 9-GINI Coefficient × 1000, a measure of unequal wealth distribution—0 most equal, 1000 most unequal. M$/B$ = Million/Billion dollars

Source UN-OHRLLS (2015), World Bank (2016), FAO (2020a)

13.2 Ocean Potential and Small Islands

The economic value possible from the global ocean has shown a huge jump since the beginning of this century. For instance, the volume of container shipping and energy generated by offshore wind has increased by about 4 times and 400-fold, respectively. The volume of international telecommunications has been amplified by laying about 600,000 submarine cables on the seafloor. Likewise, the volume of farmed seafood has grown by 5% (on average) each year, and more than 13,000 marine genetic sequences have been patented in the past two decades. During the same period, several oil and gas deposits were discovered offshore and around 1.29 million square kilometers of the seabed have been approved by the International

Table 13.2 Some critical data of five small islands from three oceans. Fish data in metric tons

Islands	1	2	3	4	5	6
Singapore	7,346	6,112	2.5	Steel	Solar	100
Seychelles	127,128	<500	0.1	–	Wind	96
Bahamas	11,633	8	8.6	Salt	Solar	99
Solomon Islands	77,027	10,582	0.2	Bauxite	Wind	68
Kiribati	176,474	3,652	11.8	–	Solar	72
	7	8	9	10	11	12
Singapore	84.44	14,673	38.00	390.3	359	100
Seychelles	23.70	362	0.15	0.824	1.4	100
Bahamas	111.62	1,633	1.47	0.4428	3.2	95
Solomon Islands	330.87	27.9	0.13	0.569	0.601	34
Kiribati	43.94	7.1				48

1-Capture Fisheries in tons in 2016, 2-Aquaculture production in 2016, 3-Marine Protected Areas per cent of country's Territorial area, 4-Major mineral resource, 5-Major renewable energy type (2018a, b), 6-People (%) Access to Drinking Water, 7-Gross value-added to respective GDP in 2018 in million US $ contributed by three areas—Agriculture, Hunting and Fisheries, 8-Tourist arrivals × 1,000 in 2018 (World Tourism Organization 2018), 9-TEU Twenty-foot equivalent unit in million in 2019. TEUs are a unit of cargo capacity, often used for container ships and container ports, 10-Export in USD in 2016, 11-Import in USD in 2016, 12-People (%) Access to Basic Sanitation

Source World Bank (2016), UN-DESA, World Bank and United Nations Department of Economic and Social Affairs (2017), FAO (2018), UNCTAD (2019)

Seabed Authority to various countries for mineral exploration and mining (Virdin et al. 2021).

Unfortunately, small islands have failed to take full advantage of such momentous global economic growth (Tables 13.1 and 13.2). With a total population of about 65 million and average annual growth in the population of 1.3%, the average GDP of small islands has been only 13.7 billion US dollars (B$) in 2011. Many small islands remain poor, as 26.5% of their inhabitants earn less than 1.25 USD per day. The average GDP is skewed, however, with some islands having extremely high GDPs, such as Singapore 222.7 B$, Cuba 254.8 B$, Dominican Republic 216 B$ and Puerto Rico 112 B$. The lowest GDPs are from Niue (10 million USD, M$), Tuvalu 39 M$, Montserrat 63 M$, and Nauru 160 M$. This difference in economic capabilities affects the ease of doing business (EDB), which varies drastically among small islands with, for example, Singapore, Mauritius and Bahrain obtaining, respectively, global rankings of 1st, 23rd and 38th (UNCTAD 2019; World Bank 2020).

The Earth Summit in Rio de Janeiro in 1992, its review meeting in 2012 (Rio 20+), and the Barbados Program of Action (BPOA) took note of the skewed GDP of small islands and stressed the shared opportunities for small islands and the creation of a new sense of ownership (OECD-World Bank 2016). These events recognized that human health, the health of the planet, and future food security depend on how the various components of the ocean are treated (Table 13.3). Such components include capture fisheries, mariculture, aquaculture, tourism, biotechnology and bio-prospecting, renewable energy, desalination, maritime transport, shipping, shipbuilding, ports, waste disposal management, and employment generation. It seems one of the best approaches to bring about 'development coupled with sustainability' in these unique islands is to follow a blue economy paradigm (Pauli 2010).

The economic growth from ecosystem services that include food, freshwater, fuel, and fiber could be the cornerstone for small islands, depending on how quickly and effectively an island can adapt to changing natural conditions. In addition to these provisioning amenities, ecosystem services also include regulating climate change, water quality, and disease spread; protecting the coast, generating power, and promoting cultural services such as recreation, tourism, heritage and aesthetics. We briefly examine below the potential of such natural resources and services for small islands. Also, we touch upon the areas where the intervention of science and technology could help build a blue economy architecture.

Table 13.3 The four aspects of the blue economy (after Walsh et al. 2020; Mukhopadhyay et al. 2021)

STRENGTHS An industry-driven economy A sustainable economy Offers food security Imparts environmental resilience Balance ethical human growth An economy based on circularity, resilience, and inter-dependence	CHALLENGES Impacts of natural disasters: cyclones, tsunamis, storm surges Impacts of climate change: sea-level rise, erosion, pollution Low economic growth, high debt Limited fiscal space, low savings Maritime insecurity, IUUF, piracy
OPPORTUNITIES Fisheries Aquaculture Ecosystem-based tourism Renewable energy Navigation, transport and trade Blue bonds, CES, EF, CRI Funds & expertise from Diaspora Climate fund from a global body	WAY FORWARD Awareness of stakeholders Shift to Ecosystem-driven BE from industry-driven BE Infrastructure-ports, jetties, roads Policy and governance Institution making Private sector participation Inter-island collaboration Integrate TLK to STI through IoT

BE-Blue Economy, CES-Cost for Ecosystem Services (payments for services provided by mangroves, wetlands, seaweeds to filter saline-water as well as sequester carbon; for protection and management costs of blue carbon resources), CRI-Coastal Risk Insurance (subsidized insurance premiums may be used as a reward for environmental compliance, e.g., loss of income in fisheries from coral reef degradation or performance shortcomings of any newly adopted technology), EF-Effective Financing (public funding may be tied to the effective outcome of social, environmental and people-oriented governance), IoT-Internet of Things, IUUF-Illegal, Unreported, Unregulated Fishing, STI-Science-Technology-Innovation, TLK-Traditional Local Knowledge

13.2.1 Fisheries (See Also Chap. 4)

Marine and coastal capture fisheries and aquaculture provide valuable sources of nutrition, about 18% of global animal proteins and essential micronutrients (FAO, IFAD, UNICEF, WFP and WHO, 2020). Fish accounts for 16.6% of animal protein supply and 6.5% of the protein consumed by humans (FAO 2016; Guptha 2018). Global per capita annual fish consumption increased from 9.9 kg in the 1960s to 20.3 kg in 2017. Fish consumption in smaller islands accounts for 50–90% of animal protein in human diets, as much as 3–4 times higher than the global average per capita. In small islands, there is a huge demand for fish, particularly tuna, both for limited domestic use and more so for export to developed countries, which is expected to increase manifold in the future (FAO 2016, 2020a; Table 13.2). For small islands especially, capture fisheries contribute as much as 5–10% of their GDP. Among the islands, Kiribati captures a record amount of fish from the ocean (176,474 metric tons annually) followed by the Maldives (129,191 metric tons) and Seychelles (127,128 metric tons).

Besides capture fisheries, aquaculture contributes enormously to the health and economy of small islands. As far as aquaculture production of fishes is concerned, the Solomon Islands show a high with 10,582 metric tons in 2016, followed by Singapore (6,112 metric tons; FAO 2020a). It has been estimated that aquaculture development could increase total fish production in the Caribbean islands by about 30% within the next 10 years if essential investments are made (FAO 2020a). The same could be true for some Pacific islands. Despite the importance of capture fisheries and aquaculture for food security, trade, and employment, these activities still suffer from significant inefficiencies, often due to a lack of skills, technology and infrastructure, which every small island needs to address critically (World Bank 2016).

In this regard, the traditional knowledge on fishing and ecological management of fishery resources in many island countries, especially in the Pacific Ocean and the Caribbean Sea, may come in handy to adopt modern management strategies. Traditional fishing involves small-scale, commercial or subsistence fishing practices using traditional techniques such as rod and tackle, arrows and harpoons, and throw nets and drag nets. Although the relationships between traditional ecological knowledge, population needs and uses of the environment are still strong in these islands, the narratives have changed since the 1860s. An unquantifiable loss of indigenous knowledge occurred since then as newer technology has often resulted in the abandoning of traditional knowledge and associated sociocultural values, causing avoidable damage to the management of resources and biodiversity (Joannes and Hviding 2000).

In this context, the addition of some islands in the Pacific to the UNESCO World Heritage List in July 2008 recognized traditional knowledge as a tool for innovative management of coral reef fisheries and ecosystems. It suggested a strong linkage between culture and fisheries sustainability. Similarly, the integrated marine policy framework of The Bahamas (2013), the Mauritius Oceans Economy Roadmap (2013), the Eastern Caribbean Regional Oceans Policy (2013), and the Ecuador Green

Export Review focus on governance and the legal alignment of various laws and agencies to ensure sustainable utilization of marine resources, including fisheries, energy and tourism (UNCTAD 2014, 2019).

13.2.2 *Blue Carbon (See Also Chap. 3)*

Some of the key coastal habitats of island nations—including seagrass, seaweed, coral reefs, mangroves, saltmarsh and wetlands—offer huge potential as blue carbon resources. Besides protecting beaches from erosion, flooding, cyclones, and storm surges, these resources also act to absorb nutrients from land, especially from agriculture. They store atmospheric carbon dioxide in the form of organic carbon in biomass and sediment. They fix carbon at higher rates and store up to three to five times the amounts of carbon stored by an equivalent area of tropical land-based forests (NOAA, Coastal Blue Carbon, www.noaa.gov). These environments also act as breeding grounds and nurseries for fisheries, having strong biodiversity values. They offer opportunities for sustainable human uses such as ecotourism and recreational fishing and generate employment opportunities.

According to the Rio de Janeiro-based Convention on Biological Diversity (CBD), islands are home to one-third of the planet's conservation hotspots (www.cbd.int, CBD 2010). The isolation of smaller islands and their small population size have permitted the evolution of unique native plants and animals, with large numbers of endemic species in their waters (also see Sect. 13.3.1.3).

It is suggested that 10% of the world's food could eventually come from seaweeds (World Bank 2020). With no genetic modification, some of these species have a higher temperature tolerance. Dead seaweed can sequester carbon in seafloor sediments. In areas where poor land-use practices are continuing, seaweed can take up excess nutrient runoff from land, acting as a bio-filter. Seaweed can be cultured using aquaculture, producing species that can be used as food for humans and some shellfish, and can provide marine natural products for industrial use (Alemañ et al. 2019; Eggertsen and Halling 2021; Msuya et al. 2022).

The degradation of blue carbon ecosystems around the world is largely driven by human activities. Common drivers are aquaculture, agriculture, mangrove forest exploitation, terrestrial and marine sources of pollution, and industrial and urban coastal development. Cultivating blue carbon inside marine protected areas (MPAs) could restore these habitats and biodiversity (Attri and Bohler-Muller 2018). As blue carbon sequesters atmospheric carbon, blue carbon production can also be developed into a viable market product for carbon trading. Globally, coastal ecosystems contribute a mean of 190.67 ± 30 B$ every year to blue carbon wealth (Bertram et al. 2021). Australia, Indonesia and Cuba are generating the largest positive net blue wealth for the world, with Australia alone generating annually a positive net benefit of 22.8 ± 3.8 B$ billion through sequestration and storage of carbon in its coastal ecosystem (Bertram et al. 2021).

13.2.3 Mineral Resources (See Also Chap. 8)

The increasing demand for minerals and metals has led to the exploration of seabed mineral resources. These resources include massive polymetallic sulfides around hydrothermal vents along mid-ocean ridges and subduction zones, cobalt-rich crusts on the flanks of seamounts, manganese (polymetallic) nodules on the abyssal plains, and methane in the form of gas hydrates on continental slopes and rises.

The Dominican Republic has rich mineral assemblages of bauxite (containing aluminum), gold, gypsum, copper, nickel, salt, silver, and zinc. These are found in its coastal areas and within its EEZ. In addition, Fiji and the Solomon Islands have good reserves of bauxite and gold (FAO 2020a). The export earnings of Papua New Guinea (PNG), which is richly endowed with natural resources, derived from petroleum and gas (36%), gold (23.3%), forest raw wood (5.78%), palm oil (3.45%) and processed fish (1.95%, UNCTAD 2019).

However, mining of seabed resources is expected to disturb the unique assemblages of marine species associated with these habitats and make them vulnerable (Sharma et al. 2001; Mukhopadhyay et al. 2008), besides generating a plume of undissolved sediment to create large-scale seabed pollution. Exploring and mining seabed mineral resources and mitigating probable environmental impact is beyond the capability of any small islands, in terms of finance, logistics, and available skill, so utilizing seabed mineral resources is an uncertain economic prospect for the majority of the small islands.

13.2.4 Energy (See Also Chap. 7)

Islands are generally blessed with enormous potential of generating energy from renewable resources. The production of renewable energy is becoming a major component of the blue economy as it is non-polluting, sustainable and relatively inexpensive after installation of energy-generating infrastructure. Renewable resources include energy/electricity obtained from biomass (biological material), bagasse (biomass remaining from sugar cane, sorghum, and agave after extraction), biogas and bio-energy (a type of biofuel produced from the biological breakdown of organic matter), geothermal (from heat stored beneath Earth's surface), hydropower (from energy moving with surface water flow), ocean thermal energy conversion (using the temperature difference between deep and shallow water depth), solar panels (photovoltaic energy using solar cells that convert sunlight directly into energy), solar thermal (mirrors or lenses that concentrate sunlight into temperature collectors for conversion to energy), solid waste (from household and/or industrial waste to create energy [methane] in the way of heat or electricity), tidal (by converting the energy of tides into electricity), waves (by converting the power of surface waves to energy), and wind power (through conversion of wind power to electricity through wind turbines).

Despite enormous potential, only two islands currently generate more than 80% of their energy needs from renewables, while another six island countries met 40–79% of their needs from renewables in 2016–2017 (IRENA 2018b). Another group of eight islands draw 20–39% of their energy needs from renewables, while an additional 14 islands meet 20% of their energy needs from renewables. The Dominican Republic has taken a lead in generating power from almost all viable renewable sources: solar, bio, wind and hydro. Singapore is also well placed to generate power from solar and bioenergy sources, but other islands fall behind in this sphere despite the immense potential. Fiji has a high potential for hydro-energy.

The South Pacific island of Tokelau (10 km^2 land area with population of 1,500, a dependent territory of New Zealand) is meeting close to 100% of its energy needs through renewables, including by powering generators with locally produced coconut biofuel. One of the world's most ambitious energy transition projects is in Barbados, the leading producer of solar water heaters in the Caribbean region. Barbados is committed to powering the country with 100% renewable energy sources and reaching zero carbon emissions by 2030 (Guerra 2017). Other small islands have also set ambitious renewable energy targets, with Samoa, the Cook Islands, Cabo Verde, Fiji, Saint Vincent and the Grenadines, and Vanuatu aiming to increase the share of renewables in their energy mixes to 60–100% (IRENA 2018a, b). In fact, given the enormous potential of renewable energy, small islands could benefit by collaborating among themselves, and also with the European Union, the United States, other major economies and global corporate agencies (Guerra 2017).

13.2.5 Tourism (See Also Chap. 6)

Tourism is essential to the economic survival of many small states and is a key sector in their national development plans. Global tourist numbers increased by 5% in 2014 to almost 1.2 billion, but arrivals to small states grew at the faster rate of 9% to roughly 19 million.

The tourism sector is a key source of income for island countries, contributing more than 20% of GDP to almost two-thirds of small island nations. The tourism sector in the Maldives contributes 65% to its national GDP. The other island nations in which tourism has been a top contributor to GDP are Seychelles (35%), Antigua and Barbuda (30%), and St Lucia and Vanuatu (both 29%). The tourism sector remains a moderate contributor to GDP in Fiji (22%), Cape Verde (19%), Dominica, Samoa, and Mauritius (all 17%), and St Vincent, Jamaica, and Grenada (all close to 16%). However, tourism contributes only 0.5% to Papua New Guinea's economy (UN World Tourism Organization 2016). Caribbean small states have recovered from the decline in receipts caused by the 2008 financial crisis and the sector now accounts for 41% of total revenues (World Bank 2016).

The number of visitors does not always reflect the importance of tourism to national economies, but the number of tourists is correlated with some of the environmental and social costs of tourism (see also Chaps. 2 and 6). For example, Singapore tops the list of islands in terms of the number of tourists with 14.6 million in 2018. Compared to this, the Dominican Republic had 6.5 million, the Bahamas has 1.6 million and the Maldives had 1.5 million tourists visiting in 2018 (Table 13.2). In 2019, the Dominion Republic earned 7,468,000 USD and Bahrain earned 4,126,000 USD from international tourists visiting their islands. Data demonstrates that it is not the size of the country that matters, rather the facilities, safety and comfort provided by the country (UNCTAD 2019; World Bank 2020).

Cruise tourism is a fast-growing sector and accounts for 50% of the global market share by vessel calls and passenger count. However, cruise tourism in the Caribbean region has been characterized by high volumes and low value. In 2013, for example, the value of receipts from the average tourist visiting the Caribbean was 1,284 USD compared to 1,522 USD for the Pacific Islands (World Bank 2016). The tourism sector has also recovered from the drop in foreign direct investment, with green-field[1] investments reaching 475 million USD in 2012, indicating the growth potential of this key subset of the blue economy for small states (UNCTAD 2019).

Ecotourism and recreational fishing are increasingly stimulated by expanding blue carbon (seagrasses and mangroves) within MPAs. The Fiji islands in the Pacific Ocean and, to some extent, Seychelles in the Indian Ocean, have accomplished ecotourism. These islands have developed large marine tourism potential by combining tourist resort development with traditional coastal fishing villages. Aquaculture sites and traditional cultures have been combined with various marine tourism activities such as snorkeling, diving, fishing, sailing and surfing. The serene geographic isolation and other diverse regional characteristics among the small islands provide a large potential for the development of marine tourism (OECD-World Bank 2016). Ethical tourism, which sets ecological and infrastructure standards, is a growing sector and can advance environmental sustainability in small states.

13.2.6 Maritime Transport

As of now, maritime transport remains a small contribution to the blue economies of most small islands because of their geographic locations and the difficulties of building major port facilities on atolls or volcanic islands. However, since more than 50% of the global population is concentrated in coastal areas, and over 90% of global trade is sea-borne, maritime transport could play an important role in the economies of comparatively larger islands in the future given their reliance on imports and openness to international trade (e.g., Singapore, Mauritius, Male, Fiji).

Consequently, one of the major components for the success of the blue economy is to have good port and harbor facilities, including optimum cargo handling capacity. In addition, ship repairing (if not manufacturing) and registering facilities could not only help island countries' economies, but could also contribute notably to their GDPs and generate large-scale employment. Singapore has capitalized on this fact

[1] "Greenfield investment" is a type of foreign direct investment.

and is thus rated as having some of the best port and harbor facilities in the world (Table 13.2; UN-OHRLLS 2013, 2015).

An analysis of market behavior suggests that the maritime trade from Pacific and A-C (Atlantic Ocean-Caribbean Sea) islands, although increased by 6% between 2004 and 2015, remained low compared to I-C islands (India Ocean-China Sea; World Bank 2016). If the COVID-19 pandemic continues, consumer prices could be 1.5% higher in 2023. The rise is expected to be 7.5% in small islands, and 2.2% in the least developing countries (LDCs) overall (UNCTAD 2021).

The facility to register international ships can increase government revenues, but also adds some legal liabilities for the way the registered ships are operated. Presently, such registration is led by Caribbean small states, but this is expected given the high number of vessels passing through the Panama Canal (UNCTAD 2019). Commonwealth small states have a disproportionately high share of merchant fleets registered in their countries, accounting for above 7% of total fleets since 2011. Importantly, however, there is significant untapped economic potential in upstream value chains in financial and logistical services, which these countries can better leverage. The economic contribution of maritime transport and its potential to drive growth in small states is therefore significant but remains underexploited.

13.2.7 Biotechnology (See Also Chap. 3)

Marine biotechnology involves the use of marine living organisms for industrial and other purposes. It includes the discovery and synthesis of novel chemical compounds and the exploitation of their pharmacological properties. Biotechnology may improve sustainable food supplies, human health, energy security and environmental remediation, and make a significant contribution to green growth in many industrial sectors (Mukhopadhyay et al. 2021).

Many countries and institutions have active research programs to test the potential of marine natural products for human medicine applications (Carroll et al. 2021). Specific examples of biotechnological methods and products may include the use of marine microbes, particularly bacteria, in making drugs and chemicals. On the energy front, algal biofuels appear to offer promising prospects. Within the last two years, billions of dollars have been invested into algae culture and algal farming around the world.

Marine genetic resources provide the raw material for improving the production of more and better food, either directly or through providing better feed for livestock. The access and benefit-sharing (ABS) provisions of the Convention on Biological Diversity (CBD) were designed to ensure that the physical access to genetic resources is facilitated and that the benefit obtained from their use are shared equitably with the providers. The International Treaty on Plant Genetic Resources for Food and Agriculture of FAO (ITPGRFA) was adopted in 2001 to encompass all existing legal provisions to promote global food security through conservation and the promotion of sustainable agricultural practices. The Treaty was the first legally binding international instrument for ABS.

Hence, the legal provisions are particularly important for small states, given their likely reliance on international technological and scientific know-how—and possibly on foreign firms—to exploit these resources to receive their share of economic benefits and ensure long-term environmental and resource sustainability (UNCTAD 2019).

13.3 Threats to Small Islands

The two major threats to the blue economy paradigm of small islands come through (1) natural climate change (see Chap. 12), and (2) human activities. These threats make small islands vulnerable. Climate change threats include the rise in sea temperature and sea level, increased ocean acidification, and increased frequency of major natural storms. All these owe to the unbridled emission of carbon into the atmosphere by humankind since the 1850s as a result of industrial development (Box 13.1).

The second threat comes from safety and security deficits in the islands, and other human activities (Mukhopadhyay et al. 2021). This includes the dependence of island inhabitants on energy, food, trade and tourism and the difficulties in obtaining these resources due to the isolated nature of many small islands. Energy accounts for the highest share of imports to small islands, which are almost entirely dependent on fossil fuel imports for electricity generation and transport (IRENA 2018a, b). Also, about half of the small islands import more than 80% of their food requirement. Trade accounts for more than 71% of small islands' GDPs. The economy of many small islands are also hugely dependent on tourism, and they experience difficulties in managing and responding to shocks (e.g., the COVID-19 pandemic) given the lack of diversity in their economies (UN-DESA, World Bank and United Nations Department of Economic and Social Affairs 2017). However, both types of threats, natural and human-made, could be mitigated to a great extent following the use of STI.

13.3.1 Climate Change Impacts (See Also Chap. 12)

Ninety per cent of the small islands are located in the tropics, leading to frequent impacts from extreme weather events (Box 13.1). Many are affected seasonally by tropical storms, cyclones and hurricanes. Climate variability, droughts and flooding are also features of their weather patterns. The El Niño-Southern Oscillation and other periodic events produce significant alterations in rainfall (UNFCCC 2005).

Most small islands are severely affected by ocean acidification, rising ocean temperatures, and pollution. The smaller islands are especially vulnerable to sea-level rise and extreme weather events. Rising sea levels will submerge territory, will cause significant saltwater intrusion in coastal aquifers and lands, and will increase erosion, threatening settlements and infrastructure that support livelihoods. One impact of such vulnerability has been the hesitancy of large companies to invest in development projects of these islands. As a result, small islands are constantly playing a balancing act among the population, resources, and environment (UNFCCC 2005; UN-DESA 2018).

Box 13.1 Extreme events scenario for small islands and sustainable ecosystem action

Despite emitting the least amount of carbon to the atmosphere, small islands are more environmentally vulnerable (46.7%) than the non-island nations (31.6%; World Bank, 2016). Trinidad and Tobago emitted the highest (Mt CO_2 = metric tons of carbon dioxide equivalent) among the small islands followed by Singapore, Cuba, (about 30 Mt CO_2 each), Bahrain, and the Dominican Republic (close to 20 Mt CO_2). Among the small islands, the least developed islands are more vulnerable (52.4%) than those islands having moderate-upper economies (44.7%; www.ferdi.fr/en/node/). Between 2000 and 2015, small island countries cumulatively faced damage of 17% to their GDP amounting to 22,621 M$ to natural disasters. In contrast, the lower-middle, upper-middle and high income non-island countries lost only 7% (156,438 M$), 6% (453,034 M$) and 3% (1,181,470 M$) of their GDP, respectively. Although the actual monetary loss of the non-island nations may be higher than the small islands, their loss remains only a tiny part of their large GDPs (OECD-World Bank, 2016).

Realizing the importance of environmental sustainability of blue economies, Seychelles records the largest share of territory as a marine protected area (MPA, ~40%), followed by Trinidad and Tobago, Belize and Guam (all between 25 and 30%), and Niue, Dominican Republic and Kiribati (all between 20 and 25%). The extent of MPAs can be correlated directly with fish harvests, for example, Kiribati captures 0.176 million tons of fish, one of the highest among the small islands. Seychelles, Solomon Islands and the Bahamas follow closely in capture fishes from coastal and open seas (also see Table 13.2). More and more islands are slowly extending existing MPAs or initiating new ones to maintain an environmental balance (FAO 2020a).

As far as the generating energy from renewable sources is concerned, Singapore has taken a big lead over the other islands. In 2017, it produced about 300 megawatts of power from renewable sources (International Renewable Energy Association 2018).

Source After UN-Ohrlls (2013, 2015), OECD-World Bank (2016), Patil et al. (2016), FAO (2020a)

Small islands have already started feeling the effects of climate change, hindering their growth and development, and posing an existential threat in some cases. Adaptation can reduce the impacts of climate change, but the economic cost of adaptation is high in small islands relative to the size of their economies. Transformation to low-carbon economies implies new patterns of investment, for which international cooperation is vital. Hence, an optimum integration of climate adaptation, mitigation and development approaches could help small islands. We briefly describe the impact of such environmental challenges.

13.3.1.1 Coastal Flooding

The Special Report on the Ocean and Cryosphere in a Changing Climate finds that global mean sea levels will most likely rise between 290 and 1,100 mm by the end of this century (or about 15 mm per year; IPCC 2021). The Regional Fact Sheet for small islands ascertains that the observed warming (high confidence) in the small islands has been attributed to human influence (medium confidence; IPCC 2021). Warming will continue in the Twenty-first Century for all future emissions and global warming scenarios, further increasing heat extremes and heat stress (high confidence). Sea levels will very likely continue to rise around small islands, more so with higher emissions and over longer periods (high confidence). Such rises in sea level—coupled with storm surges and waves—will exacerbate coastal inundation and the potential for increased saltwater intrusion into aquifers (high confidence; IPCC 2021). Small Islands will face more intense, but generally fewer, tropical cyclones, except in the central north Pacific, where frequency will increase (medium confidence at a global warming level of 2 °C and above) (IPCC 2021).

Despite contributing the least to the global pool of carbon emissions, small islands face high threats from global warming and climate change that result from the emissions of other countries (Box 13.1). On average, small islands emit just 1.5% as much GHGs as industrial countries do. The total aggregated reported emissions from small islands are extremely low, 258.5 million tons of carbon dioxide equivalent in 1994. The top three islands contributing to the global pool of carbon dioxide (in million tons [MT]) in 2005 were Singapore (26.8), Cuba (23.5), and the Dominican Republic (15.0); of methane: Cuba (9.35), Belize (5.56) and Barbados (1.79); and of nitrous oxide: Jamaica (106.4), Cuba (5.25) and Papua New Guinea (3.78) (UNFCCC 2020).

The rise in sea level poses one of the most widely recognized climate change threats to low-lying coastal areas of small islands and atolls. Sea level rises will cause shorelines to retreat along the sandy coasts of most small islands. Yet, the potential risk and response have not always been adequately integrated into adaptation planning. Though the climate of small islands will continue to change in diverse ways, compiling climate information for these islands is a challenging task due to a lack of observational facilities (IPCC 2021).

With the projected increase in sea levels by the year 2100 (IPCC 2014, 2021), low-lying coastal areas and atolls are under threats of flooding, erosion, and degradation of fresh groundwater resources. In this regard, areas with less than five meters elevation are at greatest risk, particularly in the islands of the Maldives, the Marshall Islands, Kiribati, Tokelau and Tuvalu. A rise in sea level would elevate the water table, further reducing drainage in coastal areas. As the people of these islands mainly depend on groundwater and rainwater as sources of fresh water, inundation and consequent saltwater intrusion into the fresh water, agricultural land and infrastructure areas would devastate the economies of the low-lying areas (see also Chap. 5). Loss of a significant percentage of land to rising sea level will result in loss of infrastructure, homes, jobs, and communities for people in low-lying areas (Mukhopadhyay et al. 2018).

The extreme weather events and sea-level rise triggered by climate change not only result in loss of land and employment but also affect the tourism on which small islands' economies are heavily dependent (UN-OHRLLS 2015).

13.3.1.2 Coastal Erosion

Islands are constantly impacted by physical forces from the surrounding sea.[2] Material is constantly either being deposited or carried away from shorelines by ocean waves and currents. Such movement will be intensified by sea-level rise. Irregular island topography, geological instabilities and resulting landslides, volcanism, earthquakes, tsunamis, and heavy cyclonic rainfall increase the erosion of soil. Physical alterations and destruction of marine and coastal habitats and landscapes due to coastal development, deforestation, and mining cause large-scale coastal erosion. The expense of protective structures to control erosion of shorelines is a continuing economic drain on countries. If sea levels rise as predicted, coastal erosion will become a widespread phenomenon for all islands. Coral reefs are the first line of defense against coastal erosion for many tropical islands, so priority should be given to protecting reefs (see Chap. 2).

Small islands generally use similar adaptive measures to cope with coastal erosion due to the relative similarity in their geography. A common example is the use of seawalls against coastal erosion and extreme weather events (Petzold and Magnan 2019). The low elevations and extreme susceptibility to sea-level rise of many islands frequently result in the migration of people as the only means to adapt to climate change. As this comes at the cost of losing homes, and cultural and heritage sites, it is imperative to ensure that all migration decisions are carefully conducted, with minimal loss of cultural amenities (Kelman 2015).

Land is a limited and precious commodity for islands, so islanders are emotionally attached to the land. Hence, small islands must undertake efficient, optimum and comprehensive planning and careful allocation of land to the most appropriate use or combination of uses. Coastal and Marine Spatial Planning (CMSP) appears to be a must for the islands to optimize their land use (Table 13.3; Ozkan 2018; Mukhopadhyay et al. 2021), using appropriate techniques of farming. We discuss the CMSP approach a little later.

---

[2] https://gdrc.org/oceans/sin-problems.html, accessed 1 March 2022.

13.3.1.3 Impact on Flora

The blue carbon resources (mangroves, seagrass, seaweeds) of small islands are threatened by various human activities and climate change-related processes. For example, invasion of foreign species through ballast water released from visiting (and passing) ships increases the pressure on native species. Due to a shortage of land, the mangrove forests in small islands are cleared for agriculture, and for infrastructure development such as the construction of roads, housing, tourist accommodations, and harbors. Mangrove forests are also lost through harvest for sale and due to rising temperatures.

The loss of mangroves and wetlands due to human activities and a rise in sea level would result in the loss of a carbon sink. Subsequent release of sequestered carbon dioxide into the atmosphere would further increase both oceanic and atmospheric temperatures and increase acidification of the ocean. The loss of mangroves also removes the protective barrier around islands against the fury of cyclones and storms. The increasing loss of mangroves and seagrass due to eutrophication (excessive input of nitrogen and phosphorus as fertilizer runoff from land), human destruction of habitat, and overfishing would cause great harm to the maintenance of coasts (Wilson 2017).

13.3.1.4 Impacts on Rainfall and Ocean Acidification

Islands are more dependent on freshwater from rain than developing countries in continents. Changes in rainfall due to climate change can reduce freshwater supplies and the recharge of aquifers that protect against saltwater intrusion. Another direct impact of climate change could be the decrease in the abundance of calcareous organisms (corals, sponges, etc.) due to ocean acidification and a rise in water temperature (see Chap. 11). This would reduce biogenic sand production leading to the loss of beaches and other coastal areas (UNFCCC 2005, 2020).

13.3.1.5 Cumulative Impacts of Climate Change on Small Islands

As small islands face a disproportionate threat from extreme climatic phenomena, they are on average more environmentally vulnerable (46.7%) than other countries (31.6%; Box 13.1). The least developed among the small islands are more vulnerable (52.4%) than islands with moderate-upper economies (44.7%; Ferdi EVI Data). To put these data in perspective, the OECD-World Bank (2016) showed that during the fifteen years between 2000 and 2015, small island countries cumulatively faced damage of 17% of their GDP amounting to 22,621 M$, from natural disasters. In contrast, the lower-middle, upper-middle and high-income countries lost only 7% (156,438 M$), 6% (453,034 M$), and 3% (1,181,470 M$) of the GDP respectively, although their monetary losses are higher than the small islands in absolute terms (World Bank 2016).

13.3.2 Anthropogenic Activities

The locations of small island nations and regional geopolitics can have a telling effect on peace, harmony and good governance, the three most important pre-requisite conditions for the all-around development of any island. However, most island nations are ill-equipped to respond to any sea-borne calamity, pollution (plastic, tar balls) and armed intrusion or piracy.

13.3.2.1 Poaching and Overexploitation

Human activities at times pose a grave concern for the animals on the land and ocean of island territories. 61% of the global loss of animal species to extinction has occurred on islands (FAO 2020a) mostly due to poaching, habitat loss and predation from introduced species on the land portion of island territories. Due to their isolated locations, many islands host endemic marine species that can also be driven extinct by over-harvesting, pollution, the introduction of exotic species, and other human causes.

The principal concern of the enormous EEZ area of the small islands is to maintain their ability to provide coastal fish resources, including the management of highly migratory species, principally tuna. Any damage to blue carbon vegetation and coral reefs can cause a variety of stresses on fish populations including pollution and siltation. Modern boats and fishing techniques have driven giant clams, manatees, and sea turtles to local extinction or serious depletion. Human impacts not only changed essential patterns of water circulation and salinity but also the availability of fish, creating a serious protein deficiency among island populations. Over-exploitation of fishes and IUU (illegal, unreported and unregulated) fishing are also causing great harm to the ecological balance of marine ecosystems. It is estimated that approximately 57% of fish stocks worldwide are fully exploited and another 35% are over-exploited (FAO 2016). IUU fishing is responsible for roughly 11–26 million tons of fish caught annually, equivalent to 10–22 B$ of unlawful or undocumented revenue. As small islands are heavily reliant on fisheries for sustenance and their economies, the migration of fish away from the tropics to cooler waters as a result of climate change could severely impact food security in tropical islands (Cheung et al. 2013). Moreover, many-fold acceleration in human activities is also depleting fish populations and is threatening whales, dolphins, and other critical species in the process.

13.3.2.2 Pollution (See Also Chap. 9)

A host of human activities impact the resources and service industries of small islands by polluting their coastal areas and surrounding waters. Globally, illegal dumping of oily waste contributes more than 800,000 tons of fuel oil sludge to the ocean every year. Dumping is mostly done in the open sea, but sometimes close to islands since most islands lack the means to detect and combat such illegal discards. In addition, leaking offshore oil rigs and pipes create a constant source of pollution that is hard to measure and mitigate. Oil companies, chemical, industrial and agriculture polluters, major developers, and deep-sea fishing corporations are the major contributors of pollution to the sea.

In addition, pollution from terrestrial wastes (domestic, human, mining, and industrial), radioactivity, and invasive species are major concerns of small islands. Some small islands in the Pacific Ocean face an atypical challenge: radioactivity from past nuclear weapons testing. Many of these islands are located in the western Pacific region (including Bikini Atoll of the Marshall Islands) and have experienced radioactivity from nuclear testing activities of the United States, the United Kingdom and France. Some people have been contaminated, and a few islands still have dangerous residual levels of radioactivity from such explosions, even though the last nuclear weapon test was conducted about 30 years ago.[3]

The safe disposal of domestic wastes—particularly human wastes and urban sewage—have become a widespread environmental problem, affecting almost all island nations. Although a few countries do have adequate waste collection and treatment facilities (e.g., Singapore, Bahrain, Cuba, Mauritius, the Maldives), such facilities in most other islands are either lacking, at a rudimentary state, or not properly maintained. Similarly, old car bodies, dismantled heavy equipment, bottles, and cans are putting tremendous pressure on disposal sites created either in coastal swamps or wetlands that affect adjacent ocean areas. Added to this are the toxic chemicals and pesticides (used widely to control mosquitos, other pests in agriculture) and microplastics that enter streams and coastal ocean areas, which can negatively affect all organisms, including humans (UN-DESA, World Bank and United Nations Department of Economic and Social Affairs 2017).

Although islands not located along major shipping routes may remain safe from hydrocarbon pollution, drifting tar balls can be a problem for some islands. Industrial activities are not widespread in small islands, except for some food processing and mineral extraction activities. Yet, wastes from these two industries can cause localized industrial pollution on small islands. Invasive alien marine species, released through ballast water from ships and attached to the hulls of ships, are a serious threat to small island blue economies. These alien species can introduce diseases, act as competitors and predators to indigenous species (which have evolved in relative isolation) and can thus be devastating. As this threat reaches small islands from the outside, it should be countered by strict maritime surveillance under UNCLOS provisions (Thaman 2018).

For several small islands in the Pacific Ocean, mining of minerals remains the most significant economic activity, even though mining is accompanied by serious environmental problems. The disposal of wastes, tailings and processing wastes from land-based mines, the pollution of rivers in mined areas, loss of natural habitat and destruction of land with agricultural potential are very real threats in small islands

[3] https://gdrc.org/oceans/sin-problems.html, accessed 1 March 2022.

(Petzold and Magnan 2019) The coastal regions of Papua New Guinea have been designated for offshore mining. Ensuring a continuous supply of sand and gravel for construction purposes without creating serious environmental problems is a major challenge to these islands. Any removal of sand from beaches leads to coastal erosion and loss of beaches, which are important for tourism and recreation purposes. Fishery resources can be disturbed and damaged during the dredging of coral and sand from coastal waters (UN-DESA 2008; UNEP 2019).

13.4 An STI Roadmap to Establish the Blue Economy

With the global blue economy potential predicted to rise to 3 trillion USD (T$) by 2030, a vast opportunity for STI intervention in this sector is emerging globally. For instance, the STI interventions in keeping the shipping industry cyber-secured, in reducing coastal erosion, in accurately identifying preferred fishing zones, in expanding aquaculture and coastal tourism, in tracing the source of pollution (largely microplastic) and devising mitigations, in generating increased energy from renewable sources (blue energy), and in augmenting the supply of potable water are being considered with great interest (OECD-World Bank 2016; World Bank 2020).

A summary of the previous three sections makes the case stronger for small islands to be given special consideration while implementing blue economies. Their limited landmasses force the islands to rely more on resources from the coast and ocean. However, their truncated infrastructures, weak economies, and limited human resources make it impossible to realize the benefits of their resources. Yet, islands can be seen as testbeds of STI approaches for the future world, as a sustainable blue economy has to be based on clean technologies that will ensure the economic and social needs of people without damaging the planet (MENAFN-OECS 2021).

The strength, challenges, opportunities and way forward of the blue economy architecture for small islands are summarized in Table 13.3. To mitigate the enormous challenges of small islands, it is now increasingly acknowledged that an integrated package of science, technology, innovation, management skills, and a comprehensive understanding of the island environment and its communities is essential. Scientific research and technological development could come in handy in dealing with many of the threats more effectively. Given the lack of skilled people and scientific infrastructure in many small islands, the essential requirement has to remain to achieve a dynamic balance among natural resources, socio-economic development, and the environment, the three-pronged goals mentioned in Chap. 1.

A detailed stepwise strategic roadmap to establish blue economies powered by STI in any given small island is presented in Table 13.4. This approach recognizes the intrinsic relations between humans and nature, and between development and the environment to establish a sustainable growth model (World Bank 2017; Mukhopadhyay et al. 2018, 2021). Considering their locations and geography, the roadmap to establish blue economies for small islands may include providing social and economic benefits for current and future generations; restoring, protecting, and maintaining the diversity, productivity, resilience, and the inherent value of marine ecosystems; and using clean technologies for renewable energy and circular economy (reduce, reuse, and recycle).

It also must be remembered that not all small islands have similar or comparable economic strengths. Small islands can be divided into four categories (Table 13.1). About 29% of small islands have high gross national income (GNI), while another 33% of islands are in the upper-middle-income group. Among the rest, 31% of islands have a lower-middle income, while 7% record a low income. Singapore has the highest GNI (222.7 B$), whereas Tuvalu has the lowest (31.4 M$; World Bank 2017).

Hence a roadmap for islands with varied levels of economies may have several stages, as the implementation of blue economies depends largely on the economic strength of each island, and how effectively they can manage their challenges and make the best use of their opportunities. A template of components required to establish a blue economy for an island is given in Table 13.4 (see together with Table 13.3) and may be classified into three stages:

1. Planning and Prioritization: Setting goals, objectives, identifying study area; data evaluation, CMSP, acquisition, data gaps, content and quality; ecosystem characterization of socioeconomic, oceanographic, and biological habitats.
2. Resources and Services: Mainly three areas: biological resources, renewable energy, and tourism.
3. Governance: maritime security and extreme events; pollution and waste management; blue carbon; capacity building, outreach, awareness; funding and finance.

13.4.1 Planning and Prioritization

Planning the transition to a blue economy paradigm is the first stage of a possible roadmap. It includes working out a strong and implementable legal framework consistent with various international and regional legal instruments, such as the UN Convention on the Law of the Sea, the Convention on Biological Diversity, the International Convention for the Control and Management of Ships' Ballast Water and Sediments, and the International Convention on the Control of Harmful Anti-fouling Systems while taking into account national security and strategic geopolitics input (Ojaveer et al. 2018).

For example, to counter biological pollution, islands must stop or reduce the introduction and consequent spread of invasive species by carefully examining all individuals, cargo, and ballast water coming into the island region through air and sea. Strict implementation of the above conventions and other similar guidelines such as the FAO's Code of Conduct for Responsible Fisheries could help small islands reduce the threat and devastation of bio-invasion and other pollutants (FAO 2009).

However, most small islands—except a few such as Singapore, Barbados, Mauritius, and Seychelles—lag far behind in taking advantage of STI to develop their blue economies (Halais 2019). Stimulated by the input from a national dialogue,

Table 13.4 Roadmap for blue economy architecture in small islands

Preamble
Recognizing the intrinsic relations between humans and nature, and between development and the environment, an STI-backed roadmap for blue economy must provide social and economic benefits for current and future generations, and restore, protect, and maintain the diversity, productivity, resilience, and the inherent value of marine ecosystems using clean technologies, renewable energy and circular economy
Planning and prioritizing
• Frame appropriate policies and develop a strong and implementable legal framework amenable to UNCLOS • Consider national security, geography, and strategic geopolitics. Subscribe to the extreme events warning system • Undertake honest exercise to precisely value the potential of natural oceanic resources within the EEZ • Use appropriate technology (satellite, aircraft, drone, RS-GIS, AI) to develop coastal and marine spatial plans (CMSP), LULC and ICZM. These may help resolve conflicts over ocean space and enact long-term change • A few islands in the same area may collaborate or seek help from a nearby major country to complete the survey • Use CMSP to prioritize natural resources based on accurate valuation, available logistics and human resources • Prioritise expansion of fisheries, tourism, renewable energy, desalination, minerals, hydrocarbon, and blue carbon
Resources and services
Fisheries
Modernize technology to increase fish catch to sustainable levels, use satellite chlorophyll data to pinpoint potential fishery zones Modernize mariculture, cage culture, aquaculture, and tuna and shrimp culture Use biotechnology to process, package and export fish
Eco-Tourism, Marine Protected Areas, Ecosystem Resources
• Form travel and tourism partnerships among island countries • Form marine parks to give impetus to tourism and adventure sports, and recreation • Apply appropriate taxes to tourist services • Create jobs in tourism-related service industries and contribute to socio-economic growth • "Home stays" may be encouraged, rather than constructing big hotels. Home stays would directly benefit islanders
Energy and Water from Ocean
• Use S&T to generate power (and potable water through desalination) from currents, tides, winds, waves, algae, solar insolation, and OTEC • Conduct more research to solve the concern that OTEC disturbs coastal biology by mixing warm surface water with nutrient-rich cold water from the deep • Encourage research on efficient renewable energy generating technology
Agriculture
As the coastal area in small islands extends much into the land, encourage the use of scientific methods to conserve soil health, optimize the use of water, identify the appropriate crop/seed, and minimize the pollution levels

(continued)

Table 13.4 (continued)

• Collaborate with other global leaders to employ modern biotechnology to produce value-based high-quality foods • Encourage Aquaponics, food production systems that couple aquaculture with hydroponics, whereby the nutrient-rich aquaculture water is fed to hydroponically grown plants, involving nitrifying bacteria for converting ammonia into nitrates
Blue Carbon
Scientifically rehabilitate mangroves, seaweeds, and seagrass beds, which absorb not only atmospheric carbon, but also act as nursery grounds for fish production and coastal protection. The World Bank suggests that 10% of the world's food could eventually come from seaweed, so some coastal areas may be devoted to seaweed mariculture
• Strictly implement ICZM provisions to protect coast and blue carbon systems and reduce ocean acidification and eutrophication
Minerals and Building Material
• Collaborate with leading nations to explore EEZs to pinpoint mineral resources and hydrocarbons • The contiguous EEZ of various nations could be surveyed together • Washed up broken corals may be used for building, but only the excess (after a study on what can be harvested)
Medicine from Sea, and for Aquatic Disease
Study in detail the traditional and local knowledge and information relating to marine natural products. Integrate such knowledge with modern methods. Conduct studies on bioactive molecules available in seawater and organisms to make medicines
• Collaborate with other technologically advanced countries to develop the marine pharmaceutical industry • Share information with others on aquatic disease and aquatic animal health • Ports, Shipping, Navigation, Trade & Commerce • Develop infrastructure to enhance shipyards. Increase TEU and capabilities to handle more cargo • Act as a hub of international shipping activities to enhance trade and investments • Deploy sailboats, some faster boats for inter-island traffic, and some speed boats for emergency evacuations
Governance
Participative Management
• Take islanders and all stakeholders into confidence before initiating any activity and avoid lack of communication • Find out the carrying capacity of the island in terms of fish catch and tourist footfalls at a given time • Maritime Security and Extreme Events • Collaborate in the region to thwart threats from armed intervention, terrorism, and piracy • Enforce MARPOL against oil spills, pollution, ballast water invasion, algal blooms, and hypoxia • Construct rehabilitation shelters to save people from extreme events: inundation, cyclones, tsunamis, sea-level rise; develop SOPs

(continued)

Table 13.4 (continued)

Pollution and Waste Management
• Use S&T and good town planning for adequate solid-waste collection and treatment facilities • Use S&T to reduce toxic chemicals, pesticides and micro-plastics that enter the sea as pollution • Control wastes from fish- and food-processing plants, and effluents from mineral extraction plants • Use UN laws (monitored by satellite GPS) to stop ballast water release by foreign ships and stop the introduction of invasive alien species into coastal waters of islands • Set up integrated waste management. Develop eco-friendly mechanisms to transform waste → wealth → reuse → safe disposal of industrial by-products and wastewater
Capacity Building, Outreach, Awareness, Ethics-Values
• Conduct training and re-training for Coast Guard: IMO III, IMOOPRC level II and level III training • Conduct workshops and develop university extension services on pollution management • Make people aware of coastal protection, coastal zone regulations, policy and legal issues, and the role of blue carbon
Funding and Finance
• Introduce blue bonds and Cost for Ecosystem Services (CES) approaches • Undertake Effective Financing (EF) and Coastal Risk Insurance (CRI)

Compiled from IPCC (2014, 2021), FAO (2020b), UN-DESA, World Bank and United Nations Department of Economic and Social Affairs (2017), Mukhopadhyay et al. (2018, 2021), Walsh et al. (2020)

Mauritius launched its ocean economy road map in 2013. The plan was to strengthen sectors such as tourism, seaports, and fishing, and develop emerging sectors such as aquaculture, marine biotechnology, and renewable energy. Its northern neighbor—Seychelles—also initiated spatial planning in 2014 for the sustainable management and health of its enormous EEZ.

After planning for transition to a blue economy, the STI must be used further by small islands to create accurate valuations of their natural and human resources. While having a large EEZ is good for a small island in terms of more living and non-living resources, such an enormous area also presents maritime security challenges and difficulty in mapping and monitoring. Small islands may not have sufficient resources, facilities and trained human resources to monitor and guard their EEZs. In such a situation, neighboring small islands may cooperate to formulate a maritime security policy for the region and tailor their requirements to protect their blue economies (Hastings 2009; Malcolm 2017).

Small islands must use the best available science, data, and technology (satellite, aircraft, and drone) to shape management decisions, based on coastal and marine spatial plans (CMSP) encompassing the land, coast, and ocean area to the extent of their EEZ (Ozkan 2018; Table 13.2). The protection of landmass has become more important as the threats from sea level rise, cyclones/hurricanes and storm surges increase. A strategic approach that combines local knowledge and scientific innovation is needed to build resilience to extreme events and external shocks, and to reduce risks from natural disasters. A few nearby islands may collaborate while help may be sought from a major developed country nearby to complete the CMSP. Such a plan can also help resolve conflicts over ocean space, and enact long-term change. Once the legal framework and CMSP are established, the island may accurately value the potential of natural oceanic resources within its EEZ.

The job of prioritizing areas for development depends on their strength and need, and the pace of mitigation (and adaptation) of impacts from climate change. The island nation intending to establish a blue economy must prioritize specific sectors for immediate-, short- and long-term development in at least three major sectors: biological resources, ecosystem-based tourism, and renewable energy-desalination.

13.4.2 Resources and Services

As pointed out earlier, small islands could prioritize the development of three main areas: biological resources (fisheries, mariculture, aquaculture, biotechnology, food processing), ecosystem-based tourism (MPA, conservation, exploring nature), and renewable energy (generating energy from wind-wave-tide-solar insolation, and desalination).

13.4.2.1 Biological Resources

The world's fish stocks are not only under threat from intensive legal fishing activities; they are also at risk from IUU fishing. Advanced satellite-based alert and navigation systems could considerably reduce IUU fishing activities. Besides helping islands to invest in precision aquaculture and mariculture activities, S&T intervention could also encourage islands to develop finished products for both domestic use and export instead of exporting raw products (Table 13.4). A well-regulated regional trade agreement among neighboring small islands for the import and export of fish could be highly beneficial (FAO 2020a). Overfishing can be reduced by ensuring that over-fished stocks are restored by reduced fishing to produce maximum sustainable yield (MSY), thus improving food and economic security (Ye et al. 2013). In this regard, the United Nations Fish Stocks Agreement could be useful. The utilization of fishery by-products in obtaining enzymes for fish silage, feed production, manufacture of pharmaceuticals, and anti-microbial substances could reduce waste as well as enhance the economic prospects of fisheries (Biancarosa et al. 2019).

The dispersed, diverse and dynamic nature of the fishery sector is always a challenge for small-scale island fisheries (SSF). Governing fisheries in small islands thus must integrate three aspects: its economic potential, ecological sustainability and social impacts. The third part is largely forgotten and such failure could damage the ability of small islands to implement the blue economy paradigm. The high-profile dialogue and policy decisions on the future for capture and culture fisheries are normally covered by economic and ecological research, whereas fisheries' impact on food and nutrition security, livelihoods and social justice are largely relegated to secondary importance. This approach must change. The role of traditional methods of fisheries—which are strongly rooted in society and the well-being of islanders—must be given equal importance. The social impact of SSF is huge. It contributes to enriching the livelihoods of millions of women and men, offers food security to around four billion consumers globally, and acts as a key source of micro-nutrients and protein for over a billion low-income consumers. The role of SSF must be recognized and given due importance (Cohen et al. 2019).

Puniwani et al. (2014) proposed a GIS-based tool to select an aquaculture site after integrating a range of physical, environmental, and social factors Such S&T intervention could further ensure that aquaculture species are selected more appropriately, such as by stocking filter-feeding carp in multispecies polyculture farming systems. This would enhance fish productivity and also ensure water quality. Bivalves can also be employed as effluent treatment systems. It is important that any aquaculture developed focuses on species that do not require the fishing and processing of other species to create the fish feed.

13.4.2.2 Ecosystem-Based Tourism

Small islands are the natural reserves and bastions for ecological sustainability. Island ecosystems must be treated in a manner that contributes financially to national economies in a sustainable fashion without being environmentally unsustainable. Small islands cannot afford any ecological blunders given their scales, limited adaptive capacities, and relative fragility (Cheer 2020). With the limited alternatives for economic growth available in small islands, tourism often becomes the second major component of island blue economies, after fisheries. It is now increasingly realized that the success of eco-tourism requires the preservation of island ecosystems and biodiversity. Setting up MPAs and marine parks, and protecting and expanding mangrove, seaweed, seagrass and coral reef areas to protect the coastline and nurture fish population and its diversity must be a priority. Implementing this approach, the Cook Islands in 2017 turned the country's entire EEZ, covering 15 inhabited islands and equivalent to 1.9 million square kilometers, into the world's largest multiple-use marine park and protected area (World Bank 2020).

To be successful, the tourism industry in small islands must be monitored and assessed following the established guiding indicators of the International Network of Sustainable Tourism Observatories (INSTO) framed in 2004 (UNWTO 2016). Emphasis is focused on the systematic collection and analysis of empirical data at regular intervals, followed by tracking and close monitoring of such data. To develop sustainable tourism in a given island, data and information from nine supporting and enabling areas, including public satisfaction, carrying capacity, contribution to GDP, employment generation, energy management, waste management, wastewater management, solid-waste management, and governance are required.

Important questions that an island must have answered before it establishes tourism as a blue economy activity is to estimate the optimal ratios of islanders to tourists, the spatial dispersal pattern of tourists, and the attitudes of the island community toward tourists and tourism. As tourism flourishes, islanders sometimes feel unhappy due to the weakening of family relations, security, community cohesion, cultural endangerment, a sense of self-belonging, or due to an increase in crimes and economic inequality. The government needs to quickly collect the answers to these issues.

Island governments may regulate tourist visits and spread them evenly throughout the year, depending on the availability of services and utilities on an island. They also must ensure the security of employment for the islanders through the various seasons. Governments may also decide to close tourism for a brief period every year for recovery and regeneration following peak periods. Small islands are particularly vulnerable to hyper-eutrophication (following agricultural run-off and tourism-related pollution), and the impacts can render permanent damage, especially to fragile reef ecosystems that are important for subsistence fishing and tourism (Cheer 2020).

Data on the macro- and micro-economic impacts of tourists on island life, such as the nature of spending by tourists, ease of currency exchange, inflation, availability of good hotels and intra-island transport should be monitored. Islanders need to develop skills and capabilities to take on new positions in tourism-related initiatives. This may include skill-based competencies in language, information technology, culinary, hospitality, and in managing accommodation and inter-island tours. Governments must develop strategies to bridge skills gaps and provide necessary funds for training (UNWTO 2016).

Managing the generation of electricity is an extremely important job for the government. A clear dataset must be developed regarding how much energy is generated currently, estimating future needs with different levels of tourism, potential energy sources, and the initiatives that can be taken to harness renewable energy either via wind, wave, OTEC or solar (see next section). Tourism needs clean potable water, and managing such a resource has always been a challenging proposition. The government must know the status of water scarcity or abundance on the island and should be prepared for any water-emergency situations. Balancing the competing priorities of the needs of residents and the requirements of the tourism sector poses management challenges for government. The feasibility of installing OTEC plant(s) for both the generations of electricity and clean potable water may be worked out (World Bank 2020). The scarcity of potable water for drinking and agriculture is also a serious issue in some small island nations. Water shortage, which has the potential to impact sustainable development and human migration, could be addressed by S&T-powered rainwater harvesting, efficient water and land management, and water recycling using low-cost wastewater treatment facilities. This could include the creation of artificial wetlands and the installation of OTEC plants (IRENA 2014). Energy to support all these facilities in the future could come from renewable sources.

Wastewater management is a major issue for any island nation. The ecological changes, if any, at the outfall points of wastewater into the sea need to be studied and documented. Additionally, island governments must have strong regulatory and enforcement systems to ensure tourism operators comply with the existing wastewater management regime. To ensure effective management of solid waste, both the residents and tourism stakeholders need to be consulted and involved. The type of support (logistic, procedural, technical, and financial) needed for any necessary upgrading of waste management facilities must be ascertained by the government.

Small islands are increasingly becoming prime tourism destinations. While public satisfaction and acceptance of the tourism industry are a must, one must also look into the other eight aspects listed above (UNWTO 2016). Governance misadventures occur when the tourism industry is not harmonized with islanders' interests. Disharmony can have far-reaching consequences that must be avoided. In this regard, the government must involve local stakeholders in the development of the tourism industry. Eco-tourism may hence take over from purely economy-based tourism.

13.4.2.3 Renewable Energy

Small islands often rely heavily on imported fossil fuels, spending an ever-larger proportion of their GDP on energy imports. However, low-carbon, climate-resilient renewable technologies have the advantage of providing cheap energy and making these islands more sustainable. For example, the successful solar water heaters adopted by Barbados, an island with abundant sunshine, now boasts over 50,000 installations and claimed to have saved consumers as much as 137 M$ since the early 1970s (Guerra 2017; REN21 2017). The success in Barbados could be replicated elsewhere.

S&T involvement in generating renewable energy from wind, current, wave, tide, and sunlight is required. In 2020, 275 Gigawatts of global energy was sourced from renewable sources. Of this, 45% came from hydropower, 28% from nuclear, 13% from wind, 6% from solar and 5% from biofuel (Inger et al. 2009). Although not much of the above came from small islands, Ocean Thermal Energy Conversion (OTEC) could be utilized particularly by small islands located in the tropics. The chemical potential of the salinity gradient from the convergence of freshwater and saltwater could be used to generate energy. However, although the OTEC plant in Hawaii has used the cold deep water to grow a variety of cold-water species in the tropics, this technology generally has not yet been very successful for energy generation.

The ocean can serve fundamental human needs, support climate change mitigation, drive economic growth, and also generate energy from renewable sources. In the future, bioenergy through the fermentation of marine biomass such as algae and seaweed is slated to be produced in large quantities (Borthwick 2016; Guerra 2017; IRENA 2018a, b).

Coastal communities, in small islands, are increasingly looking to the ocean to develop resilient energy, food, and water systems. Some of the marine energy devices could be integrated into coastal infrastructures, such as piers, jetties, groins, and breakwaters, providing the dual benefit of shoreline protection and power generation. Other emergency needs, such as water desalination, treatment, and supply, and long-term critical challenges like food insecurity could be alleviated by marine energy-powered aquaculture.[4] While diversification in STI-powered economic activities of

[4] https://www.energy.gov/eere/water/goals-powering-blue-economy, accessed 1 March 2022.

small islands is a must, the islands must also be careful to avoid short-cuts to attain higher GDPs quickly by hosting unethical and unsavory offshore finance and tax-haven activities (Hampton and Jeyacheya 2020).

13.4.3 Governance

The blue economy is now a rapidly growing powerhouse of the world economy and is predicted to grow from 1.5 trillion USD in 2015 to 3 trillion USD by 2030, growing at twice the rate of the rest of the global economy (OECD-World Bank 2016). In addition, the ocean is responsible for 31% of global CO2 absorption (leading to ocean acidification) and has so far absorbed 90% of the excess heat in the climate system. If climate change is an undeniable threat to our environment, our health, and our economy, good and effective governance could play an important role in fostering better climate change mitigation and establishing a sustainable blue economy.

A roadmap to establish blue economies in small islands is given in Table 13.4, wherein the emphasis is to have a clearly defined national priority, social context and resource base before a small island could aspire for a sustainable and inclusive ethical blue economy regime. A CMSP, land use-land cover (LULC) survey and integrated coastal zone management (ICZM) can enhance the identification, prioritization, protection and use of resources. Investment in science and technology-powered adaptation and mitigation activities could create a pipeline of opportunities to build sustainable blue economies in a way that benefits both present and future communities. S&T-backed state-of-the-art weather forecasting systems can reduce the impact of extreme climatic disturbances, such as cyclones, tsunamis, storm surges, flooding, and drought. Science and technology can also be applied to control carbon emissions and reinforce blue carbon resources.

While a blue economy paradigm normally has several components, the three major issues that concern the small islands have been (a) fisheries and biotechnological research products, (b) ecosystem-based tourism, and (c) generation of energy from renewable sources (see Sect. 4.2). Based on two decades of data on fisheries and tourism (1996–2016), the size of the blue economy positively depends on the gross fixed capital formation and access to electricity and communication technology. In addition, the size of the blue economy responds positively to sustainable and effective ocean management and governance policies. The inherent transparency and traceability of blockchain technology could effectively eliminate IUU fishing and unethical seafood from the supply chain, and empower seafood buyers and consumers to make well-informed commercial choices based on demonstrable information (see Chap. 4). It seems that more investment, better access to electricity, and better export opportunities determine the profit in the fisheries sector (Bhattacharya and Dash 2020).

Similarly, the tourism industry and hospitality facilities depend hugely on the development and function of robust supply chains, powered by professional information and communication technology. This approach also called for higher investment in physical capital in terms of transport, storage, and the promotion of ICT by island governments (World Bank 2020). A strong and efficient supply chain, ample refrigerated transport and warehousing facilities can ensure the easy and timely availability of resources (fisheries as well as tourism-related material) to the islanders.

The growth of fisheries, aquaculture (including hi-tech fish-food research and processing facilities), blue carbon components, and responsible tourism can be further pursued in an integrated way in a few targeted pilot areas. Such initiatives may include the promotion of tuna fisheries and culturing of shrimp, pearl oysters, and seaweeds, processing and marketing of salt from salt ponds, rice-fish farming, and mangrove forests on one side, and building of eco-tourism and industrial estates on the other could be undertaken by small islands. Necessary infrastructure to support these activities in the form of ports, harbors, jetties, roads and energy-generating units may be developed in phases (Tables 13.3 and 13.4; World Bank 2020). Also, S&T could help integrate aquaculture with agriculture (for example, aquaponics), which is highly relevant for small islands as it addresses issues of resource scarcity, especially potable water. For many small islands, particularly from the Caribbean Sea and the Pacific Ocean, public–private partnerships can explore aquaponics for food security.[5]

Pollution has a direct bearing on fish production and the tourism industry and therefore must be given due consideration. The increasing use of persistent organic pesticides (POP) in small islands endangers human health, fragile ecosystems, biodiversity, and freshwater quality. Unfortunately, most of the smaller islands are ill-equipped to deal with any major accidents emerging either from POP, oil spills, tar balls, micro-plastics, alien invasive species, waste disposal and freshwater contamination. Improper management of these threats could further generate serious water pollution, both of freshwater supplies (rivers, groundwater and even rainwater catchments), and of coastal waters around beaches, reefs and lagoons that are important for tourism, recreation and fishing. Accordingly, some islands have created legal structures and authorities for managing chemicals throughout the islands. An increase in population, socio-economic development, and lifestyle change is heightening the quantity of human and industrial waste that pollutes the ocean (Mukhopadhyay et al. 2021). A low-flying helicopter and drone can detect the source and movement of tar balls. Also, regular testing and monitoring of coastal waters could be an effective tool against POP pollution.

Extensive research by the International Blue Carbon Initiative (BCI) has resulted in a manual to estimate blue carbon stocks and emission factors in mangroves, tidal salt marshes, wetlands and seagrass (Howard et al. 2014). A team of 34 experts in the fields of coastal carbon measurement, remote sensing, and climate policy produced this manual to standardize protocols for sampling methods, laboratory measurements, and analysis of blue carbon stocks and fluxes. Small islands could use this manual to produce robust blue carbon data.

Small islands could also agree to be a part of the Global Ocean Observing System, and benefit from its analyzed data and information delivery system, especially about

---

[5] https://www.aquanet.com/caribbean, accessed 1 March 2022.

forecasting extreme weather conditions (cyclones, storm surge, coastal flooding, and ocean acidification) (see Chap. 14). It is estimated that climate change may cause an average annual loss of 0.75% global GDP by 2030, varying from 0.50 to 6.5% in the Pacific islands, and 5% in the case of the A-C (Atlantic-Caribbean) islands (World Bank 2020). S&T can play a major role to counter this loss by helping to identify the CO2-optimal maritime shipping and navigational lanes based on ocean state and ocean circulation (Hodgson et al. 2019).

Small islands could strengthen the circular economy principles to reduce, recycle, reuse waste, and invest in the protection of ecosystems (Pauli 2010). Small islands may further collaborate among themselves and also with larger nations to strengthen mutual economy (an economy that depends on each other's resources). For instance, islands with high levels of production from fisheries and aquaculture could form a trade agreement akin to the European Union in which the excess products from one island are merchandised with other islands under a specific concession. This would reduce the pressure on fisheries on each island and serve to improve the economy of the region. Similarly, Singapore, as a very wealthy nation but low on mineral resources, could trade resources with islands that have large mineral reserves. Such mutual exchanges of products could strengthen the economy of all concerned islands. Such collaboration would need market integration and deeper economic partnership among the islands and should encourage Public–Private-Partnership (PPP) as a force multiplier following ethical and UNCLOS guidelines (UNWTO 2016; UN-DESA, World Bank and United Nations Department of Economic and Social Affairs 2017). Islands should see themselves as not only a consumer, but also a producer and exporter of their goods and services.

We have earlier discussed three major activity areas where small islands must focus: fisheries, tourism and renewable energy. The measures that could help small islands to achieve success in these three areas, and also to effectively counter climate change impact are (a) climate finance, (b) STI support, and (c) capacity building (UNFCCC 2020). In 2018, Seychelles launched its strategic framework and roadmap for its blue economy and initiated the world's first sovereign blue bond, raising 15 M$ from international investors to finance Seychelles' blue economy projects. This initiative included the expansion of marine protected areas and the improvement of the sustainable management of the nation's fisheries. In addition, the Commonwealth Secretariat, through its Blue Charter signed in 2018, helped several islands to prepare a strategic framework for the blue economy. The Secretariat also encouraged cooperation among its members to fulfil their commitments for the sustainable development of the ocean (Halais 2019). Indonesia has implemented such an integrated approach very appropriately in its Lombok Island, which can be replicated in other small islands.

Since 1970, it is estimated that small islands have lost 153 M$ to climate-related events (World Bank 2020). This opens up again the age-old debate between the environments versus jobs, which has always been wrongly compared. Not investing in the blue economy architecture is a much bigger economic threat to island countries than continuing the destructive practices that have brought the islands (and the world) to the brink of climate catastrophe. Every dollar invested in the sustainable ocean economy can yield at least five dollars in return (Virdin et al. 2021). Moreover, small island countries tend to share similar sustainable development goals (SDGs) and challenges, such as growing populations, limited resources, remoteness, susceptibility to natural hazards, vulnerability to external shocks, excessive dependence on international trade and fragile environments. The growth of small islands is further held back by the high cost of communication, energy, transportation and administration due to their small sizes (Mead 2021).

STI is essential for successful and effective planning, prioritization, and appropriate actions that are the essential components of good governance. Some of the challenging tasks for the governments of small islands are to reform policies to enhance public sector capacity, align economic interests with long-term sustainability, promote conditions that sustainably encourage business growth, and undertake large-scale capacity building and skill development. Encouragement may be given to public–private collaboration, participative management and strategic partnerships towards poverty alleviation, employment, and food security. Governments of small islands must act to reduce waste, add value, and increase market access (Table 13.4). Such actions may attract capital from public, commercial, philanthropic and private agencies to invest in projects that create jobs, grow local economies and create affirmative social impacts. In this regard integrating local traditional knowledge with modern S&T could be a potent combination to maintain a balance among humans, economy, environment, and development (World Bank 2017; Virdin et al. 2021).

Resource surveillance within vast island EEZs is a challenging task. An S&T-based approach could use artificial intelligence to accomplish the job. Reducing the cost of desalination of seawater would also require the continued application of new S&T innovations. Mass production of electrochemically treated wastewater to clean solar-powered toilets would need solid S&T support (Mead 2021). S&T inputs powered by professional and efficient information and communication technology could build up good, transparent, accountable, and accessible governments to ensure that government and citizens share development goals and approaches. On the industry front, generating state-of-the-art scientific knowledge, predictive analytics, technical assistance and ICT could help both the wealth creators and employment generators.

Building human capacity to deal with the challenges coming from the change in climate and human activities is the third most important requirement for the small islands to establish blue economies (see Chap. 15). A network of S&T cooperation among small islands could be developed to strengthen their education, health and research sectors. An increase in the number of tertiary education (postgraduate and R&D) programs, upgrading academic excellence and fostering ties and linkages with the productive sectors are a few areas that small islands must work on. In collaboration with UNESCO, the World Bank, UNFCCC, and UNEP and with a few major nations, this S&T-R&D network must continue cooperation in assessing the STI situation in small islands. The proposed network could take the form of a Small Islands Science & Technology Council (UNDP 2011; UNEP 2019). NGOs may be engaged to encourage science communication practices through formal education, as well as public debate and media engagement, workshops, and training courses.

In this regard, the scope and activities of the International Scientific Council for Island Development (INSULA) may be expanded to include the creation of a database on the rich traditional knowledge on fisheries, fishery products, food security and medicine. Building and enhancing human capacity in the areas of capture fisheries, mariculture, aquaculture, tourism, biotechnology, mineral extraction, renewable energy, desalination, maritime transport, shipping, shipbuilding, ports, and waste disposal management can be achieved through rewarding international collaboration in science, education, research, innovation and technology. Global bodies could initiate individual study grants and group training, strengthen institutions, and spread educational and learning materials through seminars and meetings (World Bank 2017). For example, the Cariscience scheme of UNESCO to enhance the quality of graduates, postgraduate and researchers has been successful in the Caribbean islands.

In summary, while an effective intervention of science and technology could contribute immensely to helping the economy of small islands, these islands may achieve sustained growth and balanced development by enhancing skill, increasing cooperation, and improving connectivity. Deepening cultural linkages among the people in the region—backed by soft diplomacy and S&T cooperation—could transform island nations as a frontier of human understanding, peace, and harmony. In this regard, a comprehensive integrated strategy is required, in absence of which even a plethora of activities and large investments may not bear fruit. For instance, optimum funding (blue and green bonds, "debt for nature" swaps or debt restructuring), STI support and capacity building must be in place to maintain a balance among environmental sustainability (least use of pesticide, supporting clean energy, reducing plastic) social sustainability (supporting employees, helping communities, encouraging health), and economic sustainability (providing fair employment, encouraging local business).

Acknowledgements We thank the Editors (Ed Urban and Venugopalan Ittekkot) for reviewing the manuscript and suggesting improvements. Sridhar D. Iyer also made several recommendations.

References

Alemañ AE, Robledob D, Hayashia L (2019) Development of seaweed cultivation in Latin America: current trends and future prospects. Phycologia 58(5):462–471

Attri VN, Bohler-Muller N (2018) The blue economy handbook of the Indian Ocean region, Edited volume. Africa Institute of South Africa, p 496

Bertram C, Quaas M, Reusch TBH et al (2021) The blue carbon wealth of nations. Nat Clim Chang 11:704–709

Bhattacharya P, Dash AK (2020) Drivers of blue economy in Asia and Pacific island countries: an empirical investigation of tourism and fisheries sectors. ADBI Working Paper 1161. Asian Development Bank Institute, Tokyo, p 26. www.adb.org/publications/drivers-blue-economy-Asia-pacific-island-countries

Biancarosa I et al (2019) Replacing a fish meal with insect meal in the diet of Atlantic salmon (*Salmo salar*) does not impact the amount of contaminants in the feed and it lowers accumulation of arsenic in the fillet. Food Additi Contam Part A Chem Anal Control Exposure Risk Assess 36(8):1191–1205

Borthwick AGL (2016) Marine renewable energy seascape, engineering. Elsevier Ltd 2(1):69–78

Carroll AR, Copp BR, Davis RA et al (2021) Marine natural products. Nat Prod Rep 38:362

Cheer J M (2020) Tourism on small islands: the urgency for sustainability indicators. In: The 21st century maritime silk road islands economic cooperation forum: annual report on global islands 2019, Island Studies Press, pp 131–154

Cheung WW, Watson R, Pauly D (2013) Signature of ocean warming in global fisheries catch. Nature 497(7449):365–368

CBD (Convention on Biological Diversity). 2010. Report on the implementation of the programme of work on marine and coastal biological diversity. Document UNEP/CBD/SBSTTA/14/INF/2 for the fourteenth meeting of the Subsidiary Body on Scientific, Technical and Technological Advice. Nairobi, 10–21 May. www.cbd.int

Cohen PJ et al (2019) Securing a just space for small-scale fisheries in the blue economy. Front Mar Sci, 18 April 2019. https://doi.org/10.3389/fmars.2019.00171

Eggertsen M, Halling C (2021) Knowledge gaps and management recommendations for future paths of sustainable seaweed farming in the Western Indian Ocean. Ambio 50:60–73

FAO (2009) Analysis of the implementation and impact of the FAO code of conduct for responsible fisheries since 1995. Food & Agriculture Organization. Available at: www.fao.org. Accessed 9 Nov 2020.

FAO (2016) The state of world fisheries and aquaculture contributing to food security and nutrition. Food & Agriculture Organisation, Rome, p 200

FAO (2018) The state of food security and nutrition in the world 2018. Building climate resilience for food security and nutrition. Rome, Food and Agricultural Organization, of the United Nations. Jointly prepared by FAO, IFAD, UNICEF, WFP and WHO. Licence: CC BY-NC-SA 3.0 IG, p 202

FAO (2020a) The state of food security and nutrition in the world 2018. Building climate resilience for food security and nutrition. Rome, Food and Agricultural Organization, of the United Nations. Jointly prepared by FAO, IFAD, UNICEF, WFP and WHO. Licence: CC BY-NC-SA 3.0 IG, p 320

FAO (2020b) The state of food security and nutrition in the world: transforming food systems for affordable healthy diets. https://doi.org/10.4060/ca9692en

Ferdi-EVI, Economic Vulnerability Index (database), Fondation pour les études et recherches sur le développement international, Clermont Ferrand, France. http://byind.ferdi.fr/en/indicator/evi/results/0bad6ab7965ccca0e81a70ddbe010754ff774aa4

Guerra F (2017) Mapping offshore renewable energy governance. Mar Policy 9:21–33.https://doi.org/10.1016/j.marpol.2017.12.006

Guptha MV (2018) Contribution of aquaculture to global food security. Ref Module Food Sci. https://doi.org/10.1016/B978-0-08-100596-5.22361-5

Halais F (2019) How small islands can harness the ocean economy? www.devex.com

Hampton MP, Jeyacheya J (2020) Tourism-dependent small islands, inclusive growth, and the blue economy. One Earth 2:8–10

Hastings JV (2009) Geographies of state failure and sophistication in maritime piracy hijackings. Polit Geogr 28(4):213–223. https://doi.org/10.1016/j.polgeo.2009.05.006

Hodgson EE, Essington TE, Samhouri JF et al (2019) Integrated risk assessment for the blue economy. Front Mar Sci 6:609. https://doi.org/10.3389/fmars.2019.00609

Howard J, Hoyt S, Isensee K et al (2014) Coastal blue carbon: methods for assessing carbon stocks and emissions factors in mangroves, tidal salt marshes, and seagrass meadows. Conservation International, Intergovernmental Oceanographic Commission of UNESCO, International Union for Conservation of Nature, Arlington, Virginia, USA

Inger R, Attrill MJ, Bearhop S et al (2009) Marine renewable energy: potential benefits to biodiversity? An urgent call for research. J Appl Ecol 46(6):1145–1153

IPCC (2014) Climate Change 2014 synthesis report summary for policymakers, IPCC 5th Assessment Report. https://www.ipcc.ch/site/assets/uploads/2018/02/AR5_SYR_FINAL_SPM.pdf. Accessed 21 July 2019

IPCC (2021) Intergovernmental Panel on Climate Change. Assessment Report 6, Climate change: the physical science basis. https://www.ipcc.ch/report/ar6/wg1/

IRENA (2014) Ocean thermal energy conversion technology brief. International Renewable Energy Agency, Abu Dhabi, United Arab Emirates

IRENA (2018a) Offshore innovation widens renewable energy options. Available at: www.irena.org. Accessed 3 Mar 2021.

IRENA (2018b) Renewable energy benefits leveraging local capacity for offshore wind. Available at: www.irena.org. Accessed 3 Mar 2021. ISBN 9780749483968, Kogan Page publisher

Joannes RE, Hviding E (2000) Traditional knowledge possessed by the fishers of Marovo Lagoon, Solomon Islands, concerning fish aggregating behaviour. Tradit Mar Resour Manage Knowl Inf Bull 12:22–28

Kelman I (2015) Difficult decisions: migration from small island developing states under climate change. Earth's Future 3(4):133–142

Malcolm JA (2017) Sustainability as maritime security: a small island developing state perspective? Global Pol 8(2):237–245. https://doi.org/10.1111/1758-5899.12446

MENAFN, Organization of Eastern Caribbean States (OECS) (2021) To validate coastal and marine spatial plans. https://menafn.com/1101606708/OECS

Mead L (2021) Small islands, large oceans: voices on the frontlines of climate change: still only one earth: lessons from 50 years of UN sustainable development policy. www.iisd.org

Msuya FE, Bolton J, Pascal F et al (2022) Seaweed farming in Africa: current status and future potential. J Appl Phycol. https://doi.org/10.1007/s10811-021-02676-w

Mukhopadhyay R, Ghosh AK, Iyer SD (2008) The Indian Ocean nodule field: geology and resource potential, 1st edn, Elsevier BV, p 292

Mukhopadhyay R, Karisiddaiah SM, Mukhopadhyay J (2018) Climate change: alternate governance policy for South Asia. Elsevier Inc., p 173

Mukhopadhyay R, Loveson VL, Iyer SD et al (2021) Blue economy of the Indian Ocean: resource economics, strategic vision, and ethical governance. CRC Press, Taylor & Francis, p 297

O'Rourke R. (2018) Maritime territorial and exclusive economic zone (EEZ) disputes involving China: issues for congress, China: conditions, issues and U.S. relations, pp 1–108

OECD-World Bank (2016) Climate and disaster resilience financing in small island developing states. OECD Publishing, Paris. https://doi.org/10.1787/9789264266919-en

Ojaveer H, Galil BS, Carlton JT et al (2018). Historical baselines in marine bio-invasions: implications for policy and management. PLoS ONE 13(8):e0202383. https://doi.org/10.1371/journal.pone.0202383.t001

Ozkan O (2018) Coastal and marine spatial planning. Int J Adv Res Rev 3(12):1–12

Patil PG, Virdin J, Diez SM et al (2016) Toward a blue economy: a promise for sustainable growth in the Caribbean; An overview. The World Bank, Washington DC

Pauli G (2010) Blue economy-10 years, 100 innovations, 100 million jobs. Paradigm Publications, p 336
Petzold J, Magnan AK (2019) Climate change: thinking small islands beyond Small Island Developing States (SIDS). Clim Change 152:145–165. https://doi.org/10.1007/s10584-018-2363-3
Puniwani N, Canale L, Hawa M et al (2014) Development of a GIS-based tool for aquaculture siting. Int J Geo-Inf 3(2):800–816
REN21 (2017) Renewable energy Global Status Report 2017, REN21 Secretariat, Paris
Sharma R, Nath BN, Parthiban G et al (2001) Sediment redistribution during simulated benthic disturbance and its implication on deep seabed mining. Deep-Sea Res II 48:3363–3380
Thaman R (2018) The 2016 Fiji ant-mealybug bioinvasion. Suva, Fiji. Available at: http://piat.org.nz/uploads/PIAT_content/pdfs/Thaman2018compressed.pdf. Accessed 9 Nov 2020
UN (2012) United Nations conference on sustainable development Rio+20. Available at: https://sustainabledevelopment.un.org/rio20. Accessed 11 Oct 2020
UN (2018) Sustainable development goal 6 synthesis report 2018 on water and sanitation, United Nations. https://doi.org/10.1126/science.278.5339.827
UNCLOS (1982) United Nations Convention on the Law of the Sea, 10 December 1982, p 208
UNCTAD (2014) Small Island Developing States: challenges in transport and trade logistics, note by UNCTAD Secretariat, United Nations Convention on Trade and Development, Geneva. https://unctad.org/system/files/official-document/cimem7d8_en.pdf
UNCTAD (2019) Annual report. https://unctad.org/annualreport/2019/Pages/index.html
UNCTAD (2021) Review of maritime transport 2021 (unctad.org)
UN-DESA (2008) The millennium development goals report. United Nations, New York
UN-DESA, World Bank and United Nations Department of Economic and Social Affairs (2017) The potential of the blue economy: increasing long-term benefits of the sustainable use of marine resources for small island developing states and coastal least developed countries, World Bank, Washington DC. http://www.climateactionprogramme.org/images/uploads/documents/World_Bank.pdf
UN-DESA (2018) United Nations—Department of Economic and Social Affairs. The Sustainable Development Goals Report. https://www.un.org/development/desa/publications/the-sustainable-development-goals-report-2018.html
UNDP (2011) Oceans at Rio + 20 how well are we doing in meeting the commitments from the 1992 Earth Summit and the 2002 World. Marine Policy, p 62
UNEP (2019) Taking the fight to the frontline: island states unite to end pollution. Available at: https://www.unenvironment.org/news-and-stories/press-release/taking-fight-frontline-island-states-unite-end-pollution. Accessed 9 Nov 2020
UNFCCC (2005) Climate change—small island developing states, issued by the Climate Change Secretariat (UNFCCC), Bonn, Germany, p 32. ISBN: 92–9219–012–1, 32
UNFCCC (2020) United Nation Framework Convention on Climate Change, United Nations Climate Change, Annual Report, p 74. www.unfccc.int/annualreport/
UN-OHRLLS (2013) Small Island Developing States: Small Islands Bigger Stakes. http://unohrlls.org/custom-content/uploads/2013/09/Small-Island-Developing-States-Factsheet-2013-.pdf
UN-OHRLLS (2015) Small Island Developing States in Numbers: Climate Change Edition 2015
UNWTO (2016) Rules for the operation and management for the UNWTO- International Sustainable Tourism Observatories (INSTO). United Nations World Tourism Organization, Madrid. http://statistics.unwto.org/; www.pwc.com/papuanewguinea. Republic of Papua New Guinea
Virdin J, Österblom H, Jouffray JB (2021) 100 Companies account for more than half of the "Blue Economy". www.maritime-executive.com
Walsh M, Robertson D, Mehta A (2020) The role of ccean finance in transitioning to a blue economy in Asia and the Pacific. Asian Development Bank. www.development.asia
Wilson R (2017) Impacts of climate change on mangrove ecosystems in the coastal and marine environments of Caribbean Small Island Developing States (SIDS). Carib Mar Clim Change Rep Card Sci Rev 2017:60–82

World Bank (2016) Toward a blue economy: a promise for sustainable growth in the Caribbean. Available at: http://www.copyright.com/. Accessed 10 Nov 2020

World Bank (2017) The potential of the blue economy: increasing long-term benefits of the sustainable use of marine resources for small island developing states and coastal least developed countries. World Bank and United Nations Department of Economic and Social Affairs. World Bank, Washington DC, p 50

World Bank (2020) Small states forum. www.worldbank.org/en/country/smallstates/overview

Ye Y, Cochrane K, Bianchi G et al (2013) Rebuilding global fisheries: the World Summit Goal, costs and benefits. Fish Fisheries 14(2):174–185. https://doi.org/10.1111/j.1467-2979.2012.00460.x

Chapter 14
The Role of Sustained Ocean Observations to the Society and Blue Economy

Juliet Hermes, R. Venkatesen, Tamaryn Morris, Emma Heslop, Vedachalam Narayanaswamy, Jerome Aucan, and Bernardino S. Malauene

Abstract The ocean's contributions to humanity exceeds the products available from it, by absorbing more than 90% of the heat resulting from anthropogenic greenhouse gas emissions. The ocean plays a major role in the global cycles of oxygen, carbon dioxide, nitrous oxide and other gases and rebalances the heat differential between poles and the equator, governing the climate to maintain life on our planet. The need to sustainably observe all areas of the ocean—as well as its unlimited potential for renewable ocean energy—are providing inspiration for new technological innovations. However, it is becoming more evident from recent scientific findings that ocean health is more at risk than previously thought, because different pressures add up and contribute to rapid and unpredictable changes in ocean ecosystems. With

J. Hermes (✉) · T. Morris
South African Environmental Observation Network, Cape Town, South Africa
e-mail: jc.hermes@saeon.nrf.ac.za

J. Hermes
Oceanography Department, University of Cape Town, Cape Town, South Africa

J. Hermes · B. S. Malauene
Nelson Mandela University, Gqeberha, South Africa

R. Venkatesen · V. Narayanaswamy
Ministry of Earth Sciences, National Institute of Ocean Technology, Chennai, India

T. Morris (✉)
South African Weather Services, Marine Unit, Cape Town, South Africa
e-mail: tamaryn.morris@weathersa.co.za

E. Heslop
IOC/UNESCO GOOS Office, Paris, France
e-mail: e.heslop@unesco.org

J. Aucan
Pacific Community Center for Ocean Science, The Pacific Community, Nouméa, New Caledonia
e-mail: jeromea@spc.int

B. S. Malauene
Instituto Oceanográfico de Moçambique, Maputo, Mozambique

E. R. Urban Jr. and V. Ittekkot (eds.), *Blue Economy*,
https://doi.org/10.1007/978-981-19-5065-0_14

renewed, revitalized, and changing global scenarios and the United Nations declaring this decade as the UN Decade of Ocean Sciences for Sustainable Development, countries are moving up the ocean in their national policy agendas. Coastal countries, especially small island developing states, are advocating for socially equitable and environmentally sustainable growth. This will require systematic in-situ ocean data collection to understand today's ocean and for forecasts, disaster risk reduction and early warning systems for coastal society and infrastructure and for the assessment and management of ocean resources. This chapter discusses in detail the need for and importance of ocean observations linked to the blue economy, using case studies to understand how under-resourced countries are facing the complex challenges of ocean observing.

14.1 Introduction

The ocean encompasses the majority of Earth's surface and is home to most of its biomass. Ocean dynamics play a major role in every aspect of our planet's climate. The ocean plays a critical function in the prosperity and future of our civilization—in controlling weather and climate (including climate change), and as a source of natural resources and empowering coastal communities and industry (e.g., tourism, fisheries, transport, mining and renewable energy). Observations of the ocean are the backbone for many operational services and industries (e.g., near-real or real-time data, weather forecasts, cyclone warnings, storm surge alerts, monsoon predictions, tsunami warnings and harmful algal bloom detection). Observations are also vital for research and development, including validation of satellite data and parameterizing key processes for models and verifying model simulations. The accumulation of climate-relevant time-series parameters such as surface ocean currents and sea surface temperatures, support the progress of climate sciences. Different phenomena in the ocean require different spatial and time scales of observations, with some changing hourly (e.g., tides, wind breezes) and others over periods of weeks (e.g., mesoscale eddies). A few aspects of the ocean environment, such as the El Niño and La Niña oscillations, require study and monitoring of subtle signatures over decadal periods of time. These phenomena interact ceaselessly and these interactions challenge in-situ instrumentation and ocean science to accurately distinguish between process and event types.

Ocean observations are vital, but not simple to undertake and can be very costly. The ocean is a harsh, difficult-to-observe environment and hence designing and deploying observing instruments requires specialized technology and a range of engineering approaches. Observing systems need to be operated over extended periods of time and increasingly autonomously, considering the vastness of the ocean and remoteness of many locations that are important to observe.

Ocean observing techniques have advanced rapidly in the last few years, although not globally, with many developing countries still not having observing systems. However, an intense need remains globally for information about present trends and allowing prediction of future trends, drawing from past observations. Practical experience gained in data collection, calibration, sampling, instrument use and assimilation in modelling are not available in a single source for reference.

Development of blue economies requires observation systems that are adequate to monitor the status and trends of ocean ecosystems, detect environmental degradation, and value the products and services available from the ocean. The international ocean science community, within the context of assessing societal need and value, as well as feasibility and readiness, has identified Essential Ocean Variables (EOVs; see Box 14.1) that should form the basis for ocean observations. In addition, the main observational needs for capacity development should be focused on improving the observation of EOVs globally, as these are not only useful for science and for prediction capacity, but also are at a level simple enough to inform policy.

This chapter highlights the role of ocean observations as a foundational infrastructure to address many of the issues raised elsewhere within this book, supporting establishment of sustainable blue economies.

14.2 Evolution of Ocean Observing Systems

The beginning of the systematic study of Earth and its planetary environment can be attributed to the framework of international cooperation from July 1957 to December 1958 during the International Geophysical Year (IGY). Over the late Twentieth and early Twenty-first centuries, various global programs—such as the Tropical Ocean Global Atmosphere program (TOGA), the World Ocean Circulation Experiment (WOCE) and the Indian Ocean Air-Sea Interaction Research Initiative–Ocean Mixing Monsoon (ASIRI-OMM) program—were undertaken to understand the status, variability and change in the physical state of the ocean.

The Global Ocean Observing System (GOOS), developed in 1991, is a permanent program coordinating the functioning of a long-term, sustained ocean observing system serving societal needs for climate, operational services and ocean health (see Box 14.2 for more details on GOOS). The GOOS Observations Coordination Group (OCG) coordinates twelve (three of which are emerging) ocean observing networks sustained across the globe (see below). These global networks, comprised of precision in-situ meteorological and oceanographic sensors, provide real-time and delayed-mode coastal and offshore observations and ensure that their data are findable, accessible, interoperable and reusable (following FAIR data principles), through quality control, standards and best practice. OceanOPS—the joint WMO-IOC/UNESCO support center for oceanography and marine meteorology observation programs—provides core network and technical support for metadata and system visualization. OceanOPS (i) monitors and reports on the status of the global observing system and networks; (ii) uses its central role to support efficient observing system operations; (iii) ensures the transmission and timely exchange of high-quality metadata; and (iv) assists free and unrestricted data delivery across operational services, climate and ocean health. One of the methods GOOS OCG uses to inform its stakeholders, ocean observing networks, industry and funders of the status of the ocean observing networks, is through an annual report card (www.ocean-ops.org/reportcard). This outward-facing review, designed to be understood by policy makers and investors in the ocean observing system, is motivated by an increased awareness and importance of the ocean for sustainable development, climate change trends analysis, the integration of atmospheric and ocean observing systems, and the need to guide policy development. The report card also highlights key issues in each edition, such as the COVID-19 pandemic in 2020 and the subsequent impacts on ocean observing systems, and the decline in dissolved oxygen within the ocean and what this means for humans and marine animals alike. The value of ocean observations on our livelihoods cannot be overstated, and continued and enhanced communications in this regard should be encouraged globally.

Categories of EOVs: GOOS began defining essential variables across disciplines; however, as authors of the FOO specifically pointed out, a large part of the current global ocean observing system is driven by climate observing requirements. The reality is that there are more societal and scientific drivers for ocean observations than climate (and weather). Guided by the FOO, discussions about additional scientific questions and societal benefits that require sustained ocean observations were the first step in the EOV definition process. GOOS expert panels identify EOVs based on two criteria; the first being the impact that sustained monitoring of a variable will have on the understanding of ocean health, the climate or operational ocean service. The second criterion is the feasibility of monitoring a variable at a global scale using proven scientific methods, while also considering criteria of cost and ethics, among others. This resulted in essentially three tiers of EOVs: fully ready, pilot and future. A variable of high importance, but without as yet proven observing infrastructure, is either considered pilot (if there are efforts to improve and prove observing capability) or future (if there is as yet insufficient effort on observing capability), with the list evolving as variables move up from future or pilot to fully ready. Societal need and value might soon have a stronger role in the evolving context that motivate adding to the EOV list. In addition, apart from proven scientific methods, other criteria, such as cost (limiting global scale of some high impact observations) or even ethics, are a means of increasing the readiness level of an existing EOV, but also for adding new EOVs.

Box 14.1 Evolution of the Essential Ocean Variables

The development of Essential Ocean Variables (EOVs, including physical, biological and biogeochemical parameters, Miloslavich et al. 2018; Tanhua et al. 2019) and Essential Climate Variables (ECVs, Bojinski et al. 2014), fostered the establishment of globally coordinated networks that are platform- and method-independent (e.g., SOCONET for Inorganic Carbon, GOMON for

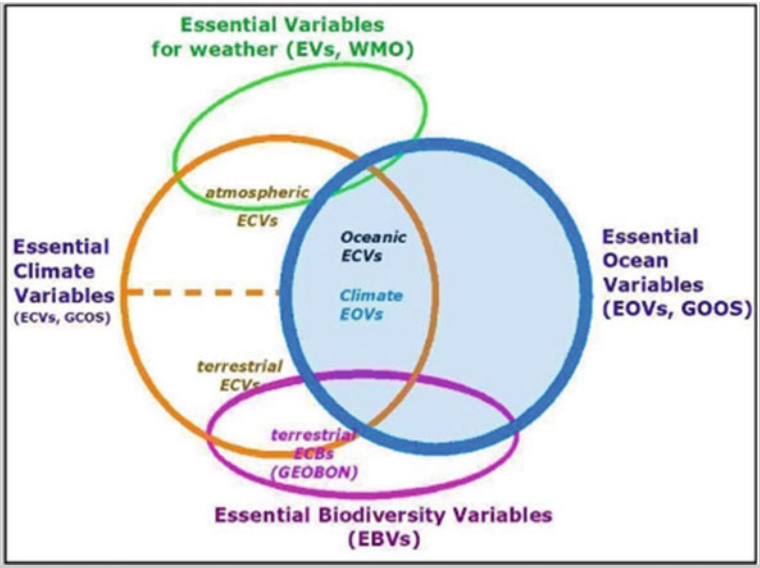
Macroalgal Canopy Cover and Composition) or focused on addressing multidisciplinary phenomena requiring many EOV observations, such as ocean acidification (GOA-ON) and air-sea fluxes (Integrated Surface Ocean Observing System Task Team in development). GCOS provides enhanced coordination across expert panels for ocean, land and atmosphere; in this way, EOVs and their evolution are not isolated disciplinary "stove piped" efforts.

Monitoring the influence of the ocean on the weather patterns and global climate requires sustained and precise measurements of ocean physical parameters, including sea-surface and subsurface temperatures, seawater salinity, dissolved oxygen and near-ocean meteorological parameters such as surface wind speed and direction, barometric pressure, air temperature, air pressure, relative humidity, solar radiation, wave and precipitation, which are used for analyzing heat flux, ocean circulation, monsoon, ocean state, and climate change, and to provide reliable oceanographic services.

The measurement of dissolved carbon, inorganic carbon, nutrients, nitrous oxide, ocean colour, sound, particulate matter, carbon isotopes and transient tracers for characterizing the physical and chemical environment, primary production, ecosystem structure, habitat, spatial distribution and diversity of biomass, energy transfer and the influence of the anthropogenic pressures is essential for studying ocean ecosystems. Enhanced models are required for biogeochemical modelling to understand climate change, nutrient availability and distribution of food webs.

The influence of the cryosphere on ocean biogeochemical cycles, biological productivity and rise in sea levels require analyzing ice-shelf dynamics, paleoclimate, long-term mass balance, energy balance and hydrological balance. These studies require the measurement of salinity, temperature, dissolved oxygen, photosynthetically active radiation (PAR), fluorescence, turbidity, nitrate, water currents and ambient noise.

Conceptual Overlap of Essential Ocean Variables in a Venn diagram. Essential Variables defined by the WMO for weather forecasting inspired the Essential Climate Variables later defined by the Global Climate Observing System (GCOS). The concept has been adopted for Essential Biodiversity Variables on land by the Group on Earth Observations Biodiversity Observing Network (GEOBON). The Framework for Ocean Observing processes defined ocean observing EOVs. Overlap among these groups is shown, which argues for the need to adopt a consistent approach (after Lindstrom et al. 2012).



Concept of EOV

The concept of the ECV was developed by the UNFCC/IPCC during the late 1990s to focus resources on the collection of minimal sets necessary to understand climate variability needed for climate change negotiations. The EOV concept arose from ECVs, following OceanObs'09 and the development of a Framework for Ocean Observations (Lindstrom et al. 2012). The Global Ocean Observing System (GOOS) is engaged in the process of refining, prioritizing and expanding EOVs. Considering ocean biogeochemical processes and their potential role in global warming, GOOS has extended the suite of EOVs to include biogeochemical and biological variables (EBVs) (GOOS Biogeochemistry Panel 2013; Fig. 14.2). The EOVs proposed by the deep ocean observing strategy (DOOS) consider physical parameters such as ocean bottom pressure, seafloor fluxes, ocean turbulence and biogeochemical parameters including seafloor respiration, seafloor organic matter, seafloor fluid, gas effluxes and micro-plastic litter.

The EOV list spans a spectrum of disciplines from physical and biochemical to those representing biological and ecosystem variables, and more recently, also human impact on the ocean (see Table 14.1). The development of EOVs is overseen by one or more of the GOOS Expert Panels that curate EOV Specification Sheets describing societal and scientific requirements, current observing capacity and management of relevant data and information products.[1]

[1] See https://www.goosocean.org/index.php?option=com_content&view=article&layout=edit&id=283&Itemid=441, accessed 11 March 2022.

Table 14.1 Essential Ocean Variable (EOVs)

Physics	Biochemistry	Biology and ecosystems
Sea state	Oxygen	Phytoplankton biomass and diversity
Ocean surface stress	Nutrients	Zooplankton biomass and diversity
Sea ice	Inorganic carbon	Fish abundance and distribution
Sea surface height	Transient tracers	Marine turtles, birds, mammal abundance and distribution
Sea surface temperature	Particulate matter	Hard coral cover and composition
Subsurface temperature	Nitrous oxide	Seagrass cover and composition
Surface currents	Stable carbon isotopes	Macroalgal canopy cover and composition
Subsurface currents	Dissolved organic carbon	Mangrove cover and composition
Sea surface salinity		Microbe biomass and diversity (emerging)
Subsurface salinity		Invertebrate abundance and distribution (emerging)
Ocean surface heat flux		
Cross-disciplinary (including human impact)		
	Ocean colour	Ocean sound
	Marine debris (emerging)	

Source https://www.goosocean.org/index.php?option=com_content&view=article&layout=edit&id=283&Itemid=441

Recognizing changing requirements for ocean observations, as well as innovation and technological progress, which together alter our perception of impact and feasibility of a given measurement to be measured sustainably and comparably on a global scale, GOOS has been reviewing proposals for new, so-called "emerging EOVs". Adding a new EOV requires establishing coordination (and often communication) oversight, services provided by GOOS Expert Panels jointly with relevant coordinated observing networks, and increasingly, in partnership with external groups of experts, projects or programs (e.g., International Ocean Colour Coordinating Group for the Ocean Colour EOV; International Quiet Ocean Experiment for the Ocean Sound EOV; and a plethora of organizations for the Marine [Plastics] Debris EOV). By adopting a new EOV, GOOS commits to building a global network and community of data providers in areas where this was fragmented or non-existent, and gradually increasing the readiness level from concept to pilot to mature.

Ocean observations, such as meteorological data from ships of opportunity or surface drifters and ocean data, such as temperature and salinity profiles from instruments such as eXpendable BathyThermographs (XBTs), Argo floats and CTDs or observations from moored data, are made available to the Global Telecommunication System (GTS), established by the WMO. These data are assimilated into coupled climate models (atmosphere, ocean, land/soil, sea-ice) used for Numerical Weather

Prediction (NWP) such as by the European Centre for Medium-Range Weather Forecast (ECMWF). These observational data are used to determine the near-real time atmospheric state and are compared to short-range (or real-time) forecasts, and the results are used to update medium-range forecasts for dissemination. Although not always highlighted in weather forecasts, ocean data are an essential component of weather and climate predictions. Marine meteorological and sea surface temperature (SST) data are currently shared by in-situ observation platforms (moored, drifting or profiling) through the GTS. In addition, most ocean observing networks have established Data Acquisition Centers (DACs), and in some cases Global Data Acquisition Centers (GDACs), whereby all quality-controlled datasets are archived and made available to users. These datasets are assimilated into global ocean models and coupled-climate models for hindcast and forecast purposes, and they are used by researchers and students for research projects. Additionally, datasets are used by decision-makers to interpret the current state of their countries' ocean domain, and by educators for capacity development purposes.

The aim for data acquired by ocean observing networks overseen by the GOOS OCG is to be freely and openly available to all users without restriction. OceansOPS aims to have all metadata available, although complex issues remain in sharing data within EEZs. These networks are described further:

14.3 Existing In-Situ Observing Networks

14.3.1 Data Buoy Cooperation Panel (DBCP)

The DBCP coordinates two surface buoy systems, namely autonomous drifting buoys and moored surface buoys. The objective of these systems is the continuous acquisition of ocean–atmosphere data in remote regions (by means of free-floating autonomous buoys) and regions of importance (e.g., in terms of moored buoys in coastal regions within countries' EEZs). Data originating from drifting buoys and moored surface buoys are assimilated into coupled-climate models and are used for weather forecasting purposes, in addition to other research and operational purposes. See https://www.ocean-ops.org/DBCP/.

14.3.2 Argo Program

The first Argo floats were launched in 2000 and standard floats are capable of operating to 2,000 m depth and sampling physical properties (temperature, salinity, and pressure). More recently, Deep Argo floats have been launched, with full ocean depth capacity (4,000–6,000 m) and Biogeochemical Argo floats are being deployed with a suite of sensors including dissolved oxygen, nitrate, pH, chlorophyll a, suspended particles and downwelling irradiance. Argo data are used for a variety of applications, including state-of-the-ocean assessments such as steric sea level rise and ocean heat content, ingestion into the GTS, for research and educational training purposes, and assimilation into global circulation models. See https://argo.ucsd.edu/ and https://biogeochemical-argo.org/index.php.

14.3.3 Ship Observations Team (SOT)

SOT is constituted of three smaller groupings: (1) the Voluntary Observing Ship Scheme (VOS), (2) the Automated Shipboard Aerological Program (ASAP) and (3) the Ships of Opportunity Programme (SOOP). A wide range of vessels are recruited for the program to ensure that data are acquired not only from conventional shipping routes, but also from remote regions by means of research vessels and yachts. Data from VOS, ASAP and the XBT component of SOOP are ingested within the GTS for weather forecasting purposes. Data from additional underway observing platforms under the SOOP are acquired from thermosalinographs (TSG) measuring temperature and salinity, partial pressure of carbon dioxide instruments (P_{CO2}) and Continuous Plankton Recorders (CPR) obtaining data on both phyto- and zooplankton species distributions. These data are available in delayed mode in most cases at this stage. See https://www.ocean-ops.org/sot/.

14.3.4 OceanSITES

OceanSITES is concerned with high-resolution, high-quality observations of the full depth of the ocean at moored locations globally (mostly physical data, but with plans to expand to biogeochemical observations). Moorings linked to OceanSITES are found in the open ocean (thus not coastal stations linked to specific regional objectives) and are long term in relation to their deployment duration, so as to provide a series of reference stations for studies relating to global climate change. Data from OceanSITES are essential for understanding climate change in the ocean, but can also lead to improved forecasting of ENSO, as well as tropical cyclones. See http://www.oceansites.org/.

14.3.5 The OceanGliders Program

The OceanGliders program provides a mechanism for observing from the open ocean to the coast to understand processes occurring across this boundary as well as providing long-term observations. Gliders operate autonomously, acquiring data in regions that are difficult to study using vessels of opportunity or research vessels dedicated to inshore or fisheries resource surveys. Due to the innovative designs of ocean gliders, different sensor payloads can be incorporated, depending on the objectives of the survey, thus acquiring data for physical, biogeochemical and ocean sound variables. Data from gliders can thus be used to inform fisheries management and understand ecosystem health, understand boundary currents and for scientific studies of rapid upper ocean evolution as well as high-value profile data for assimilation in both operational and research forecast models. See https://www.oceangliders.org/.

14.3.6 Global Ocean Ship-Based Hydrographic Investigations Program (GO-SHIP)

Despite the advances in technology, particularly related to observations with autonomous instrumentation, the best way to collect high-resolution, high-quality ocean profile data, especially over a range of disciplines (physical, biogeochemical, biological) is by ship-borne overside instrument deployments to the full depth of the water column. Data from GO-SHIP are aimed at understanding the impacts of interannual and decadal variability in the ocean, as well as long-term climate change, which can be used to better inform the coupled models used by the Intergovernmental Panel on Climate Change (IPCC) to forecast the climate into the future. The recently published SCOR Working Group 154 Report (2020)—recommending how best to sample plankton using discrete samples from Niskin bottles, rosette-mounted sensors and with flow-through systems onboard vessels undertaking GO-SHIP cruises—is important for teams seeking to measure EOVs related to phyto- and zooplankton, as well as microbial abundance and distribution. See https://www.go-ship.org/

14.3.7 Global Sea Level Observing System (GLOSS)

The Global Sea Level Observing System (GLOSS) is a network of global sea level stations collecting high-quality sea level observations used for a wide variety of purposes. These include research into sea level change and ocean circulation, providing information to protect coastal communities in terms of storm surges, tsunami and flood warnings, use in tide tables for port and fishing operations, and for providing sea-level datum data for countries' EEZs. See https://www.gloss-sealevel.org/gloss-core-network.

14.3.8 HF Radar Network

HF Radars are land-based stations that measure ocean surface roughness from coastal radar transmitters and receivers. From these data, ocean surface waves and currents can be distinguished at a high resolution. Coastal radar data are particularly valuable around ports and regions along the coast where shipping is concentrated, but are also used for ecosystem health studies, pollution monitoring and validation of satellite products as well as assimilation into ocean forecast models. Only a few countries have thus far rolled out coastal radar systems but an aim of the network is to deploy stations in more regions and countries globally. See http://global-hfradar.org/index.html.

14.3.9 Animal Borne Ocean Sensors (ANIBOS)

ANIBOS is an emerging network and makes available to the global community data acquired through sensors attached to marine mammals, turtles, fish and birds, also known as bio-logging. These tagged animals are usually those occurring in data-sparse tropical and polar regions. Biologging data are not only related to physical (e.g., temperature, salinity), biogeochemical (e.g., oxygen) and meteorological (e.g., wind speed and direction) parameters, but also data on animal foraging routes and behavior. See https://anibos.com/about/.

14.4 Satellite Observations

Though not a program or specific network per se, satellite observations provide vital information for understanding ocean state and complement ocean observing in-situ networks, as well as being utilized to calibrate and evaluate ocean models and as a key input for data assimilation into forecast models. The remote sensing community has an approach to planning and coordination under CEOS (Committee on Earth Observation Satellites) that evaluates the future coverage of a given variable and works across nations to ensure coverage by future satellite launches. The spatial and temporal coverage of Essential Climate Variable (ECV) measurements for ocean surface variables have been greatly enhanced by satellite remote sensing. Satellite-based data allow for global mapping of physical variables such as sea surface temperature, salinity, ocean surface topography, winds, currents, sea ice, and waves, as well as biological properties such as chlorophyll concentration, phytoplankton content and net primary production. Satellite observations achieve spatial coverage that is not possible by in-situ observations. However, satellite observations, for instance for ocean color, can be limited and not realistic near the coast or in validation of shallow

Fig. 14.1 Schematic diagram of GOOS components (*Source* IOC 2019)

water surfaces. Satellite observations are also limited to the ocean surface and in-situ observations and models are always needed to observe the water column to the bottom of the ocean. This limitation can challenge the application of satellite data in some places. Thus, a combination of satellite-based data and in-situ observations and numerical models allows for a coherent global mapping of the ocean.

Through enhanced technology, funding and collaborations, driven by the increasing knowledge of the importance of our ocean, ocean observations have progressed significantly in the past few decades; however, many challenges remain. For example, observations of biological and ecological parameters need significant development to reach the same level as the global climate and operational forecast observing capability. In addition, we need to integrate from open ocean to coasts and expand coastal observations, by improving support of nations developing ocean observing capability, particularly those with large EEZs compared to their GDPs. It is also essential to ensure that observations reach service providers that provide accessible information required by the users in society, from reinsurance, to shipping, resource management, coastal planning, and even citizens viewing a weather forecast in their native language. Observational data collected by non-governmental organizations and private companies or industries also need to be incorporated in national/regional observing systems.

Box 14.2 The Global Ocean Observing System (GOOS)

GOOS was established in March 1991 by UNESCO's Intergovernmental Oceanographic Commission (IOC), and is co-sponsored by the IOC, WMO, the United Nations Environment Programme (UNEP) and the International Science Council (ISC). The implementation of GOOS and other observing systems are key to creating and maintaining sustainable blue economy activities; the following is a summary of how GOOS operates. Since its inception, GOOS has created an extensive global system, based on contributions from a large number of organizations and nations, from which countries and people worldwide benefit. In its first decades, GOOS coordinated the development of a system designed to support climate science, and to serve as the observational backbone for operational forecast systems. The Ocean Obs'09 conference, coupled with growing concerns about the health of ocean and demand for information products to help nations manage their ocean economies, sparked the development of the visionary Framework for Ocean Observing (FOO, Lindstrom et al. 2012). GOOS has since led the implementation of this framework by the ocean observing community, with the goal of serving users across climate, operational services and ocean health, increasingly with a focus on coastal areas and regional seas.

The GOOS Strategy 2030 (http://www.goosocean.org/2030Strategy) envisions a fully integrated global observing system ranging across the value chain that extends from observations, through data management systems, scientific analysis and forecast, to end users via information, data and decision-making services. The eleven Strategic Objectives of the 2030 Strategy provide guidance on priorities for the development of a more user-focused and integrated system, and for the core work of GOOS itself.

GOOS Regional Alliances (GRAs) are coalitions of nations and/or institutions that share GOOS principles and goals. GRAs were introduced to integrate national needs into regional systems and to deliver these at a global level. The mission of GOOS within the 2030 Strategy is '*To lead the ocean observing community and create the partnerships to grow an integrated, responsive and sustained observing system*' (Fig. 14.1).

14.5 Emerging Ocean Observation Methods

Aware of the limits of existing methods and instruments for collecting marine data, such as networks requiring observers to be at sea for long periods of time or limitations within technical observing teams in terms of capacity and skills, policymakers and scientists continue to seek more, and more reliable, data regarding ocean conditions and climate change. They also seek new and better data regarding natural disasters, particularly in the wake of the Asian tsunami resulting from the 2004 Sumatra–Andaman earthquake and more recently the east Japan tsunami resulting from the 2011 Tohoku earthquake. In addition, the frequency of extreme events such as marine heat waves and tropical cyclones are increasing, as is the severity of their impacts on marine life, coastal communities and economy (see Chap. 12). These extreme events result in loss of human life, coastal and marine biodiversity and resources, and infrastructures, challenging well-being and economic development. Strategic technologies that will greatly enhance the capability of in-situ observations using multiple platforms should be immune to bio-fouling, capable of self-calibration during extended deployment periods, and be equipped with artificial intelligence-enabled low-power sensors capable of sending real-time or near-real-time measurements to open databases. Recent technological advances—both in observing but also in the communication and decision support tools—have made cyclone forecasting and problems associated with cyclones such as intense rainfall, storm surges, strong winds and coastal inundation or floods more accurate in terms of magnitude, timing and place of occurrence, resulting in reduction in loss of lives, and reducing the costs involved in evacuations of people (Mohanty et al. 2015).

More challenging is to determine the best way for the observing system to adopt new observing methods that are more affordable, easier to deploy, and open the doors to more nations and users, but that do not achieve the accuracy, stability, and reliability of the premium sensors and instruments. For example, adding inexpensive temperature sensors to lobster traps has engaged a segment of the fishing community and helped track poleward shifts in oceanic temperature that are accompanied by poleward shifts in lobster populations. There is a need to evaluate what is needed, not by technology or platform, but by variable and need, to understand the value of the additional observations.

To maintain long-term observing records, it is necessary to establish the comparability of new observing methods with older/existing ones. Observing methodology transition requires great care and documentation (Trenberth et al. 2002). At the same time, we need to be able to evaluate the observation needs and it is up to national and other investors to decide what technology is best. This may depend on many factors (e.g., capacity, etc.), but some checking is required to ensure the new technology can meet quality standards.

14.5.1 Marine Telecommunication Cables

Traditionally, the commercial telecommunications and scientific applications of submarine fiber-optic cables have operated independently. Submarine cables carry an overwhelming, and growing, percentage of the world's voice, data, and Internet traffic (up to 95% of the global traffic). Scientists also operate submarine cables to power, and transmit data from, marine observatories, in some cases using retired submarine cables previously used for commercial telecommunications. Recent technological developments and scientific imperatives have generated significant interest in multipurpose submarine cables that would transport commercial telecommunications traffic while also gathering and transmitting real-time data regarding ocean temperature, salinity, and water pressure by using scientific sensors.

Deep ocean temperature and pressure measurements can improve estimates of ocean circulation and heat content. Cable-based pressure and seismic-acceleration sensors can improve tsunami warning times and earthquake parameters (fault slip length, slip angle etc.).[2] The resulting data would address the long-term need for sustained climate-quality data from the under-sampled ocean, particularly in deep ocean areas far from land. The need for the same is driven by the themes of OceanObs'19 (e.g., the "Blue Economy" and "Ocean Discovery," particularly in the deep ocean) and the United Nations' Sustainable Development Goals (SDG 13—Climate and SDG 14—Oceans).

Deploying oceanographic sensors on new undersea telecommunication cables is a promising solution for obtaining the extensive, longitudinal, real-time data that are critical for understanding and managing urgent environmental issues such as climate change and tsunami hazard mitigation. The Science Monitoring And Reliable Telecommunications (SMART) subsea cables initiative is a solution to integrate sensors into future undersea telecommunications cables (Howe et al. 2019). SMART sensors would "piggyback" on the power and communications infrastructure of a million kilometers of undersea fiber optic cable and 20,000 repeaters, creating the potential for seafloor-based global ocean observing at a modest incremental cost. Initial sensors would measure temperature, pressure, and seismic acceleration. These cables are repaired, replaced, or expanded on 10- to 20-year cycles, meaning that every year tens of thousands of kilometers of new cables are being laid. By developing new connectivity projects through the SMART cables program, the ocean science community need only raise the incremental cost of the added sensor packages, resulting in globe-spanning sensor coverage at a fraction of the cost of alternative systems.

SMART cables as a new technology could provide valuable data for developing countries, assuming that local technicians can be shown how it will be used for big systems that will, in return, provide them useful data. In particular, SMART cables will be more useful for tsunami warnings, as they allow for a faster warning time than tide gauges.

14.5.2 Emerging Autonomous Ocean Observing Systems

Existing autonomous ocean observation systems making observations over a wide range of temporal and spatial scales, measuring salinity, temperature, nitrate, pressure, oxygen, biomass, and many other parameters have shown that there are many complex levels of dynamics in the ocean from global to meso and local scales, each coupled in non-linear ways. In order to cater to the complex strategic requirements, future autonomous ocean observation systems should be designed to be more affordable, modular, capable and easier to operate. Creative new types of platforms that are compact, low power, with calibrated and stable sensors are under development to expand autonomous observations.

[2] https://www.itu.int/dms_pub/itu-t/oth/4B/04/T4B040000160001PDFE.pdf.

Various mobile platforms—including Autonomous Underwater Vehicles (AUVs), gliders, Remotely Operated Vehicles (ROV) and hadal landers enable comprehensive data collection in specific locations. AUVs enable data collection in an increased spatial domain. The developments until now have resulted in AUVs with excellent performance in terms of vehicle endurance, precise navigation, reliable acoustic telemetry, high-resolution bathymetry/imagery, collision avoidance and excellent reliability. Strategic requirements will require higher spatiotemporal capabilities, energy efficiency, agility and improved maneuverability. The demanding requirements can be illustrated by the challenging need to understand the impacts of Gulf of Mexico Deep Water Horizon oil spill on the ocean in 2010, the Polar challenge by the World Ocean Council involving a 2,000 km continuous under-ice mission in the Arctic and Antarctica, and the ongoing Seabed 2030 project aimed to create a full global seafloor map by 2030 with a 100 m resolution.

The key technologies required for next-generation AUVs for ocean observations include the following:

- Intelligent autonomy for the AUV to sense, interpret, and act upon changes in the environment and the vehicle itself, which requires intelligent decision-making capabilities in navigation, energy management and system error handling.
- Swarm capability involving multiple AUVs that takes inspiration from the spatial self-organizing, navigation behavior and collective decision-making behavior of social animals.
- Subsea homing and docking to enable leveraging the submerged endurance capability of AUVs for long-term operations and reducing operational costs and hazards.
- Bio-inspired design to innovate vehicle designs that emulate the performance of animals, particularly in instances where animal performance exceeds existing technology associated with AUV propulsion, sensing, control and navigation.

In addition to emerging technologies, low-cost technology solutions and innovative methods of getting more observations into the global system are gaining traction. For example, making use of sailing yachts, particularly those involved with long-distance races crossing ocean basins not often covered by shipping vessels, are ideal mechanisms for deployment of Argo floats and satellite-tracked drifters, but also to host automatic weather stations and underway oceanographic sensors. Another key vessel type being engaged more frequently is that of fishing vessels, including the smaller types that don't transit far from their countries' coastlines. These vessels could be providing very valuable data from coastal regions from onboard meteorological and oceanographic sensors, but also from CTDs deployed on fishing nets.

The need for low-cost, easy-to-use sensors is particularly relevant for countries with limited funding for observations. For global coastal observing systems to be sustainable and impactful it is essential that the same set of minimum variables are observed with consistent accuracy worldwide. This need has very much come to the forefront in recent years and is beginning to be addressed through GOOS, as well as

Coast Predict (https://www.coastpredict.org/). A dedicated working group—Open-MODS—Open Access Marine Observation Devices,[3] funded through the Partnership for Observation of the Global Ocean (POGO), was tasked "to devise ocean sensors and monitoring devices, globally available to all and not just to a privileged few." A significant advance in coastal observing systems is now possible given recent technological advances in both the instruments and data communications (Marcelli et al. 2021).

14.5.3 Leveraging Private Sector Data Collection Initiatives

Private sector organizations are becoming increasingly involved in ocean observing; either through the collection of data for their own needs, or through the development and operation of ocean observing technologies. Improved data sharing is essential between, for example, oil and gas industry and public and research institutes. South Africa (through Operation Phakisa) has instituted the South African Marine and Exploration Forum (SAMREF, https://samref.saeon.ac.za/) to identify and take advantage of opportunities provided by oil and gas exploration activities and platforms, and to facilitate new collaborative offshore studies. By developing a demonstration project with private partners, there is potential to prove enhanced value through better forecasts, as has been discussed with Project Azul (in Brazil, see case studies). Such efforts are needed to build an environment of mutual trust. Another major private sector contributor is the shipping industry, which is already involved in the observing system through Voluntary Observing Ships (for meteorological observations) and Ships of Opportunity (for near-surface ocean observations) programs (see above). The shipping industry values corporate social interaction. There is a need to work with the industry to encourage the inclusion of observation packages as part of ship build specifications, rather than retrofitting with observing equipment later (see https://scor-int.org/Publications/OceanScope_Final_report.pdf).

In addition, emerging commercial networks may be key to ocean observations in the future. SOFAR Ocean (https://www.sofarocean.com) has developed drifting wave and meteorological parameter buoys which are available commercially but are also deployed through opportunistic means to validate their state-of-the-art global wave forecast model. Their business model allows for data acquired by their buoys to be used for marine research purposes, but products developed from their high-resolution global wave forecast model, such as those required by shipping fleets for safe passage, are what brings them revenue, allowing for continued infrastructure development as needs arise.

Autonomous surface vehicles (ASVs), such as Saildrone (https://www.saildrone.com) acquire observations of the atmosphere and near-surface ocean parameters, but are piloted autonomously. Not only is the size and look of the Saildrone different

[3] https://pogo-ocean.org/innovation-in-ocean-observing/activities/openmods-open-access-marine-observation-devices/.

from other ASVs, but their business model does not allow for external purchase of the platforms. Instead, users hire individual Saildrone platforms and services, fully inclusive of shipping, launching and recovery, operation, maintenance, data processing and dissemination to the preferred data portal for a single fee. This takes away the need of each organization to have its own set of engineers, technicians and data scientists to remotely operate autonomous instruments at sea. Saildrone is open to deployment of different sensors on its ASVs, with joint sponsorship of missions by different organizations.

The principals of private–public partnerships, in particular in developing countries, can support advances in ocean observing independent of financial constraints, that can be achieved through stakeholder engagement and dialogue without depending on government funding. While these types of new technologies and business models don't necessarily comply with the GOOS mandate of freely available and accessible data for all, discussions between GOOS and new technology teams are ongoing. Such technological developments and possibilities for academic research are growing exponentially. However, it is important to understand the validation and accuracy of new technology driven through private sector partnerships, with the sustained observing system welcoming new methods, but also validating new measurements to establish their provenance. This is a roll that the WMO/IOC Regional Marine Instrument Centre (RMICS) could play.

14.6 Case Studies: Role of Sustained Ocean Observations in Society

To have a full understanding of the role of sustained ocean observations in society, this chapter highlights several case studies from developing countries looking at the successes and difficulties encountered.

14.6.1 Government Buy-In of the Importance of Ocean Observations Ensures Their Sustainability—A Case Study from South Africa

14.6.1.1 Development

The development of a national Oceans and Coastal Information Management System (OCIMS, https://www.ocims.gov.za/) was prioritized as part of the South African Government's Operation Phakisa Initiative 6: "Unlocking the economic potential of South Africa's Oceans".[4] Operation Phakisa (meaning 'hurry') is an initiative of the

[4] https://www.environment.gov.za/white_paper_national_environmental_management_ocean_no37692.

South African government that was designed to fast track the implementation of solutions to critical development issues, as highlighted in the National Development Plan 2030, such as poverty, unemployment and inequality. The Government recognized the vast value of the ocean areas surrounding South Africa and the need to utilize ocean resources sustainably.

14.6.1.2 Stakeholder Engagement

In the beginning phases of OCIMS, a lot of work was devoted to establishing the system, getting stakeholder buy-in and developing partnerships. The tools were then rolled out in phases. A particularly successful dynamic tool is the ship-tracking decision support tool, which is very important for surveillance. Using vessel monitoring systems as well as Synthetic Aperture Radar (SAR) data, activity of vessels can be monitored, including ship movements around marine protected areas; highly suspicious activity can be identified and targeted. Approved stakeholders are alerted whenever there is unusual activity. The end users of this tool are the South African Maritime Safety Authority for safety and security, and other state security enforcement agencies. The Harmful Algal Bloom (HAB) tool has helped drastically reduce the loss to the aquaculture industry from HABs (for a discussion of HABs, see Chap. 10). Given the focus on 'ops at sea', a tool is being introduced to automatically identify the optimal search area for sea rescue in support of the National Sea Rescue Institute.

14.6.1.3 Challenges, Successes and the Future

As OCIMS is a government-run program, reports are made to the Deputy Director General and the Minister of the Department of Forestry, Fisheries and Environment, as part of the ocean economy portfolio, given that OCIMS is also intended to boost economic development. By providing knowledge and basic information for people to use by making value-added products available, economic growth is driven.

The success of OCIMS is largely due to active engagement of stakeholders. Each decision support tool has a technical advisory group in charge of managing stakeholder engagement to ensure that stakeholders drive the development of the support tool. Many of the stakeholders and partners are also end users, and this is a strength of OCIMS; it builds on collaboration and partnership, helping to mitigate the high costs of, for example, data.

However, there is a lack of real-time in-situ observations for the program. At the moment, the system relies on satellite imagery, but in-situ observations are key to validate the satellite observations and to derive proxies from satellite observations. For daily operations, HF radar and autonomous platforms would be very useful. In addition, real-time buoys would allow wave, weather and current measurements a little off the coast to be used to validate regional models. For the system to be successful, it is essential that open data policies are enacted.

14.6.2 Enhancing Projects by Ensuring Community Understanding—Case Studies from the South Pacific

14.6.2.1 Development

The South Pacific Community (SPC), an international development organization owned and governed by its 26 country and territory members, has several different successful programs focusing on using marine observations to inform society. Described here is the Climate and Oceans Support Program in the Pacific (COSPPac), an Australian Government-funded program. The Pacific Sea Level and Geodetic Monitoring project operates under COSPPac and is a continuation of the 20-year South Pacific Sea Level and Climate Monitoring Project.

SPC has recognized the need for integrated ocean sciences across its divisions and created the Pacific Community Centre for Ocean Sciences (PCCOS), which aims to help Pacific Island governments and communities easily access the ocean science and expertise they need to make informed decisions and to protect and sustainably manage ocean resources (see also Chap. 13).

Recent actions led by PCCOS are showing the possibilities and benefits of in-country collaborations between met services and fisheries agencies. The latter are often in charge of deploying anchored fish aggregator devices (FADs) nearshore to provide local fishers with access to pelagic resources. These FADs can be coupled with small-size wave buoys by leveraging the nautical capabilities of fisheries agencies and the instrumentation capacity of met services. This approach would allow a sharp increase in the number of coastal wave buoys around Pacific islands.

14.6.2.2 Stakeholder Engagement

In countries with limited capacity, meteorology (met) offices are often the most appropriate organization to raise ocean visibility, either by upskilling met officers or by creating an ocean post in the met office. But, with a growing need for improved ocean policies, it is important that different sectors providing ocean services work together. For example, met services may forecast waves, but the Navy and the hydrographic offices are also key participants and stakeholders. Creating multi-sectorial ocean policies is one way to bring together providers and users of ocean data. This is how COSPPac evolved through upscaling of met services and ensuring that products get to stakeholders; this is a major achievement of COSPPac.

In-country workshops have been facilitated since 2015 between the weather services and their stakeholders to identify how they can interact more effectively. This includes a field trip to tide gauges and introducing the local contact person to answer questions about ocean conditions. It is also important to link the observations to issues people care about on a day-to-day basis. For example, tide gauges are not only important for tsunami warnings, but also in the longer term to show how sea level is rising, which makes coastal villages more susceptible to storms that occur every year.

14.6.2.3 Challenges, Successes, and the Future

Vandalism and lack of buy-in from communities has been a major issue, driven by lack of co-development and clear communication. In the Solomon Islands, a tide gauge was installed and communities were told that it was to warn against tsunamis. When a tsunami hit, the communities had expected the tide gauge itself to emit a siren and when there wasn't one, they were frustrated. The need to explain the tide gauge's contribution to an early warning system had been overlooked. Following this, videos were created showing the benefits of sea level gauges and more emphasis was placed on downscaling the application of data, making it more visible, creating data products and telling stories about the data products. A big piece of the change has been making visible the benefits of ocean data through efforts such as the creation of a real-time tidal display for anyone, not just for the benefit of the local met service, and signage in local languages explaining the importance of the tide gauge.

In 2016, Australia (funded through Green Climate Funding) transitioned technical maintenance that was carried out by experts from Australia to regional people within the Pacific islands, creating cost savings and enhanced sustainability. Having technical maintenance capacity at the regional level has had a two-fold positive effect during the COVID-19 pandemic. Since Australian technicians were unable to travel, the development of local technical expertise has been expedited and tide gauges are now being maintained by in-country people. In addition, regional technical skills have had to develop further as additional responsibilities that were previously performed by Australian technicians needed to be managed by Pacific Islanders. This has been a phased approach, building regional capacity and then building capacity at national levels.

Traditional knowledge on ocean observations can provide valuable information in its own right and contribute to validating and updating tailored marine information, strengthening a community's ability to adapt to climate change. Within COSSPac there has been a focus on validating traditional knowledge with climate indices, with the marine component being integrated through work with the Secretariat for the Pacific Regional Environment Programme (SPREP) to establish traditional databases. The approach is focused on recognizing traditional knowledge and including a page on local knowledge in the tide calendars, either a generic sheet or nation-specific sheets. However, SPC, SPREP and the national met offices are working hard to not only expand communities' knowledge and understanding of marine science, but also growing the traditional knowledge base.

User communities are generally aware of the tides. In Kiribati, tides have a special importance, and the officials there use the tide calendars to look at where the high tide through the year reaches a threshold of over 2 m (identified through local knowledge), a critical level for coastal inundation. From this they make their own page highlighting these times of the year and share it with the communities on the beaches that will get flooded. In Samoa, port authorities rely on the calendar to know when big ships can access ports.

14.6.3 Global Monitoring in Ghana

14.6.3.1 Development

The Global Monitoring for Environment and Security (GMES)[5] and Africa program aims to promote sustainable management of natural resources by improving decision-making processes through effectively integrating Earth Observation (EO) data, technologies and services in support of socio-economic development in Africa. Specifically, the program seeks to improve African policy-makers' and planners' capacities to design, implement, and monitor national, regional and continental policies and to promote sustainable management of natural resources through the use of EO data and derived information. The Regional Marine Centre (RMC) at the University of Ghana implements Marine and Coastal Areas Management in western Africa project under the GMES and Africa program.

The implementation of the GMES and Africa program by the RMC evolved from a series of EO programs beginning with a simple research activity involving tracking of local artisanal fishing boats fitted with locally constructed corner reflectors in collaboration with the U.S. Navy in 2008. Thereafter, the University of Ghana—in partnership with institutions from the UK, South Africa, Tanzania and Egypt—implemented the Europe Africa Marine Network (EAMNET) program. The EAMNET program involved the use of satellite data to monitor the surface temperature and chlorophyll of the ocean by accessing data with a simple antenna and a set of computers without the Internet, in order to eliminate the challenge of limited Internet access. Capacity of students was developed to use these data for the generation of various products, including potential fishing zone maps. This attracted the attention of the ECOWAS (Economic Community of West African States) Commission and, through a competitive process, the University of Ghana (UG) was selected to coordinate the Monitoring for Environment and Security in Africa (MESA) program. Under MESA, UG developed three EO services, namely (1) provision of potential fishing zone charts overlaid with vessel traffic, (2) monitoring and forecasting oceanographic variables, and (3) forecast of ocean conditions disseminated as SMS alerts. As the MESA project metamorphosed into the GMES and Africa program, two new services were incorporated: (4) generation of coastal vulnerability indices and (5) mapping of coastal ecosystems/habitats.

[5] Geoportal: https://geoportal.gmes.ug.edu.gh/. Youtube Channel: UG-GMES_Regional Marine Centre.

14.6.3.2 Stakeholder Engagement

A variety of sectors use the GMES and Africa program data for (1) research and studies, (2) policy and decision making, and (3) individual decision making. The research section consists of universities, individual scientists and students. The second category includes government institutions such as ministries, departments and agencies, for example, fisheries ministries, navies and coast guards, environment ministries, etc. The third category of users mainly comprises artisanal fishers, coastal communities, and private entities. Although a variety of training is offered for data use, it may not be targeted enough and given the attention it deserves in order for data and products to be used widely.

14.6.3.3 Challenges, Success and Way Forward

Ongoing Learning to Integrate Indigenous Knowledge

The main barrier overcome so far, although not completely, is the uptake of information from EO products by the local fishing communities for decision making in addition to their local knowledge. Additionally, some ministries, departments and agencies of government such as the navy, fisheries ministries and meteorological agencies have also adopted the use of marine EO products in their daily activities.

Before the use of ocean condition SMS alerts were introduced to fishermen, it was important to understand how they observed the ocean in order to tell the "weather" at sea. An example was that early in the morning a fisherman will wake up and feel the temperature of the ocean with his/her feet. Combining this temperature information with observations of the physical behavior of the ocean, the fisherman predicts the ocean state before going to sea. In addition, the position of the moon is used to indicate calm conditions and bumper harvest.

14.6.4 Public–Private Partnership Leads to Improved Knowledge of the Ocean in Brazil

14.6.4.1 Development

A successful case study on public–private partnerships is the Project Azul, implemented in Brazil for the development of an ocean observing system for the Santos Basin region (www.projetoazul.eco.br, MacKenzie et al. 2019). This project consists of a partnership between the Laboratory of Computational Methods in Engineering of the Federal University of Rio de Janeiro, and an ocean technology company, Prooceano, in Rio de Janeiro. Both partners had well-defined roles, wherein the university was responsible for numerical modeling and data assimilation while

Prooceano was responsible for the observations and data analysis. In order to understand the oceanography of the Santos Basin region, data were collected from 60 surface drifters, 36 Lagrangian floats, and 5 underwater gliders during the pilot stage of the project (2012–2016). Critically, the data contributed to a dynamic representation of the region and was assimilated into a regional ocean model, additionally being evaluated against drift trajectories and non-assimilated model products. In 2017, and lasting five years, the second phase of the Azul Project began, with an increase in observational capability linked to instrumented anchor lines and an autonomous surface vehicle. Much of the improvements of the second phase are linked to model products: the implementation of a wave-forecast model, increased capabilities related to data assimilation techniques and increased resolution of the regional ocean model. An additional improvement is linked to the optimization of autonomous vehicle tracks to acquire data needed for the benefit of the regional and coastal models (MacKenzie et al. 2019).

14.6.4.2 Stakeholder Engagement

This project demonstrated the collective responsibility in the ocean observation value chain between the Federal University of Rio de Janeiro and Prooceano, with well-defined resource sharing responsibilities and future plans to move forward to further enhance the benefit of the successful collaboration. Public investment in research and development by oil companies in Brazil is encouraged by the National Petroleum Agency, suggesting an investment of 1% of their exploration budgets. This successful model of Project Azul could be adopted by other countries to utilize local resources and to build capacity.

14.6.4.3 Challenges, Successes and the Future

A major issue facing many developing countries after they have acquired specific equipment is that the maintenance (calibration and repairs, etc.) of the equipment has to be conducted overseas. At the beginning of the project, all glider maintenance was conducted outside Brazil. During the project, part of the team had the opportunity to acquire knowledge and technical licenses to proceed with part of the maintenance, breaking down a large barrier to using such equipment locally.

Historically, the main oceanographic observation efforts in Brazil were conducted by the Brazilian Navy to meet their own data requirements. Most of these data are represented by temperature and salinity observations acquired from Nansen and Niskin bottles (very old approaches) and CTD casts (newer ones). All of these datasets are publicly available for the community on the National Oceanographic Data Bank. There are other regional datasets acquired, mostly by oil companies in Brazil, but unfortunately, most of these data are not publicly available. Project Azul has made a visible difference to this approach.

Key skills development outcomes of the project are linked to student development, from undergraduate to doctoral level, peer-reviewed articles and publications, but also the development of both professionals and academics in operational oceanography. Successful relationships were established with international universities and scientific organizations, developing cooperation around operational ocean modeling and data assimilation. While much of the data and the analysis is still being interpreted, the overall understanding of the oceanographic dynamics of the southeastern Brazilian region has increased. An example is the successful linkage of fisheries and oceanography whereby some fisheries communities located along the Brazilian coast use some oceanographic observations and their generated information in order to support their daily activities.

14.6.5 Societal Benefits of the Ocean Observation Systems—A Case Study from the Indian Ocean

14.6.5.1 Development

The Indian Ocean basin, surrounded by 22 countries, is one of the most densely populated regions in the world. The economy of many of these rim countries is agrarian and depends on the seasonal monsoons, with many others depending on fisheries for their livelihood. Several studies have documented the warming of the Indian Ocean and its impacts on monsoon rains (Saji et al. 1999; Webster et al. 1999; Roxy et al. 2016), sea level rise (Han et al. 2014), and changes in fisheries and marine ecosystems. The intensity of extreme weather events is also increasing due to the warming of the Indian Ocean. The Indian Ocean, apart from its direct impact on weather and climate of rim countries, also influences ocean-atmospheric interaction processes such as Madden–Julian Oscillation (MJO), Indian Ocean Dipole (IOD) and El-Niño Southern Oscillation (ENSO) in the Pacific Ocean (Izumo et al. 2010; Luo et al. 2010). These features demonstrate the need for an ocean observing network to provide sustained high-quality oceanographic and marine meteorological measurements.

The Indian Ocean Observing System (IndOOS) consists of five in-situ observing networks: moored buoys, Argo floats, surface drifters, XBT network, and tide gauges. The observations, especially temperature and salinity from Argo floats, moored buoys maintained by National Institute of Ocean Technology, Chennai (NIOT; www.niot.res.in/niot1/oos_intro.php), and Research Moored Array for African–Asian–Australian Monsoon Analysis and Prediction (RAMA; McPhaden et al. 2009; www.pmel.noaa.gov/gtmb), are used for assimilation in the High-Resolution Operational Ocean Forecast and Reanalysis System (Francis et al. 2020). The model output, along with remote sensing products, are also used to forecast Potential Fishing Zone (PFZ) advisories for fishing communities (Francis et al. 2020). The fish catch in the PFZ is observed to be 3–4 times higher compared to the non-PFZ area (Nammalwar et al. 2013). In addition, the time-series observations from this network of data buoys provide valuable information on important meteorological observations, particularly during the cyclone period supported by the Indian Meteorological Department, to predict the track and intensity of cyclones.

The moored buoy network in the Northern Indian Ocean commenced in 1996 under the National Data Buoy program of NIOT. The first-generation data buoys were equipped with sensors to measure surface meteorological and oceanographic (met-ocean) parameters. Technological advancement within a decade led to the development of next-generation buoys, which are capable of measuring the met-ocean, surface and subsurface parameters up to 500 m water depth. These buoys are fitted with sensors to measure parameters such as sea level, air temperature, relative humidity, downwelling short-wave and long-wave radiation, wind direction, wind speed, precipitation and directional wave parameters apart from sea temperature and salinity at discrete levels up to 500 m depth and current profiles up to 150 m water depth. The met-ocean parameters are transmitted in real time to NIOT every three hours and the high-frequency datasets are retrieved while servicing the buoy system. OOS-NIOT is presently maintaining a 19-buoy network, along with specifically deployed CAL-VAL (CALibration & VALidation) buoys for the validation of satellite data. During cyclone passage, the moored buoys trigger rapid mode transmission for real-time data transmission in shorter intervals to closely monitor cyclone tracks.

The Bay of Bengal witnessed two intense pre-monsoon cyclones in 2019 (Fani, Category 4) and 2020 (Amphan, Category 5). Super cyclone Amphan made landfall in West Bengal with sustained wind speeds of 155–165 km per hour, claimed 86 lives, and caused widespread devastation. Even though remote sensing platforms provide the spatial patterns of ocean-atmospheric variables, the temporal resolution is very low compared to observations from the buoys. Remote sensing platforms cannot measure the subsurface temperature, which is very essential for estimating the ocean heat content, which fuels the cyclones. The high-frequency subsurface temperature observations from moored buoys and Argo floats are extremely useful for the accurate estimation of ocean heat content and in understanding the role of the ocean in the intensification of tropical cyclones (https://india.mongabay.com/2020/06/leverage-improved-forecast-to-deal-with-disasters/).

14.6.5.2 Stakeholder Engagement

The CLIVAR/IOC-GOOS Indian Ocean Regional Panel led a 3-year international review of the IndOOS by more than 60 scientific experts, highlighting the need for an enhanced observing network that can better meet societal challenges, and provide more reliable forecasts (Beal et al. 2020). A key action in achieving this is bringing together the IndOOS Resources Forum (IRF), which is made up of key directors from ocean institutes around the world who fund observing programs. There needs to be good interaction between IORP and IOGOOS/IRF in order to inform them of what IORP has learned about IndOOS and how this can be passed on to the relevant countries to help sustain these observations.

14.6.5.3 Challenges, Successes and the Future

Challenges experienced are similar to other regional observing systems, although these can be exacerbated further in developing countries: cost, longevity of the buoy system to remain at sea, battery life, sensor performance, drift and ability to work in a hostile environment. Through sharing experiences during meetings, such as the GOOS regional alliances, publications, newsletters and many web portals, as well as through international bodies (e.g., the OCG observing networks, the Ocean Best Practices System), industry interaction and the active roles of technical societies such as Marine Technology Society/Institute of Electrical and Electronics Engineers, many of these challenges have been resolved.

Early warnings and preparedness made possible by the observing system helped to save many lives during the tropical cyclones in the recent decade.[6] Several studies (Mathew et al. 2018; Chaudhuri et al. 2019; Navaneeth et al. 2019; Venkatesan et al. 2020) have used observations from moored buoys to understand the ocean-atmospheric interaction and upper ocean response to cyclones.

The high population density along the coasts of India necessitates a real-time storm surge warning system. Keeping this in view, the Earth System Science Organization (ESSO)—Indian National Centre for Ocean Information Services (INCOIS) has implemented the Storm Surge Early Warning System for Indian coasts using the ADCIRC (Advanced Circulation) model (see Fig. 14.2). ADCIRC is a finite-element based, depth-integrated shallow water model that can be used to model storm surges and for other coastal applications. This warning system utilizes the automated Decision Support System (DSS) based on Geographic Information System (GIS) and database technology. Wind and pressure fields are generated using the Jelesnianski and Taylor dynamic wind model, which makes use of track forecasts from Indian Meteorological Department. After testing of the system during the very severe cyclonic storm Phailin, it was successfully used for other cyclones.

[6] WMO Factsheet *Early warning system saves millions of lives* https://library.wmo.int/doc_num.php?explnum_id=7560.

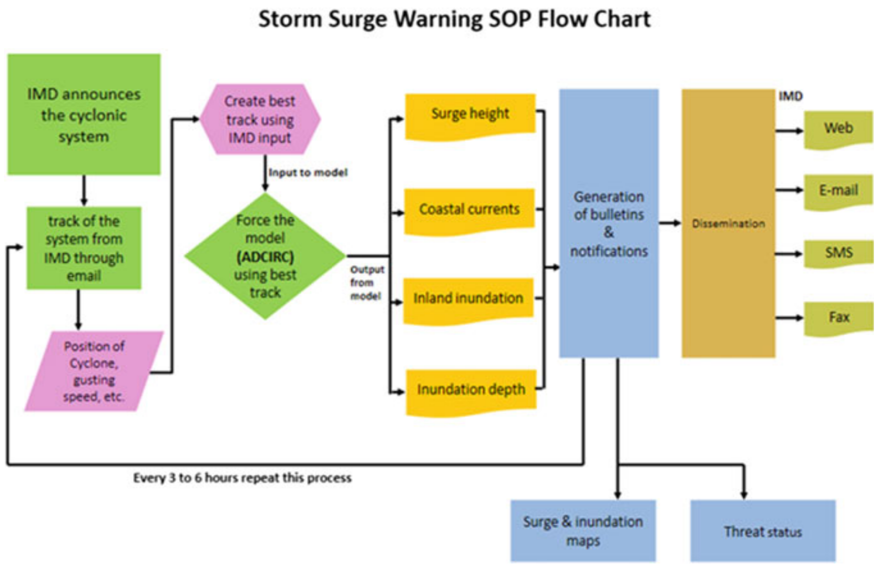


Fig. 14.2 Storm surge warning flow chart developed by the Indian Meteorological Department (IMD)

14.6.6 The Importance of International and National Programs Working Together for Sustainability—Case Studies from the Mozambique Channel

14.6.6.1 Development

The Mozambique Channel, between Mozambique on the Africa mainland and the island of Madagascar, has unique characteristics of ocean circulation in the form of a train of intermittent mesoscale eddies (Sætre and da Silva 1984; de Ruijter et al. 2002; Schouten et al. 2003; Halo et al. 2014); a continuous and permanent western boundary current is absent. While cyclonic eddies can also occur, anticyclonic eddies dominate and are the largest (>300 km) in diameter. These eddies propagate southwards at about 6 km a day (Schouten et al. 2003), with the majority on the western side of the channel over the Mozambican slope, creating an eddy corridor (Halo et al. 2014), resulting in a favorable route for ships transporting goods and people. Eddies, especially dipoles, can generate high (up to 2 ms^{-1}) velocity boundary currents (Roberts et al. 2014; Ternon et al. 2014), with cross-shelf exchange of biotic and abiotic material between coastal and offshore waters (Tew-Kai and Marsac 2009; Malauene et al. 2014, 2018) with implications on coastal ecosystems and fisheries, thus on blue economies in the region. This eddy field can be considered a key natural laboratory to understand the interaction between eddies and ocean productivity (Tew-Kai and Marsac 2009). Eddy-induced high productivity can support marine species at different trophic levels from plankton and fish to top predators and megafauna (Weimerskirch et al. 2004; Jaquemet et al. 2005) promoting fishing for food security and coastal tourism. These eddies extend deep into the ocean, interacting with the seafloor at more than 2,000 m depth, hence cannot be studied with satellite observations alone, which are limited to the ocean surface. However, observational data needed to improve our knowledge of this unique ecosystem are scarce.

14.6.6.2 Stakeholder Engagement

In the Mozambique Channel, the first and the longest in-situ observations were conducted by the Long-term Ocean Climate Observation (LOCO) program from 2003 to 2009 (Ridderinkhof and de Ruijter 2003; Ullgren et al. 2012), after the experimental phase between 2000 and 2001 (de Ruijter et al. 2002). LOCO was an international program developed by NIOZ Royal Netherlands Institute for Sea Research and Utrecht University in the Netherlands. The array consisted of a series of eight moorings deployed across the narrowest section of the channel at about 17oS between the shelves of Mozambique and Madagascar. Measurements included temperature, salinity, and ocean current data vertically through the water column, with emphasis on the bottom layer. This provided one of the first temporal in-situ demonstrations of the Mozambique Channel eddies and water volume transport in the region.

The Mozambican National Fisheries Research Institute (IIP - currently Instituto Oceanogafico de Mocambique) established a long-term observation station off Pemba in northern Mozambique. This was a collaborative project with the Norwegian Institute of Marine Research and funded by the Norwegian Agency for Development Cooperation. The effort included a single observation point at about 1,000 m depth from 2008 to 2011, designed to support the emerging oil and gas sector in the southern Rovuma Basin off Mozambique. The 3-year time-series observation of deep ocean current, temperature and salinity revealed strong currents and eddy influence near the seafloor (Ullgren et al. 2016), which needs to be taken into account for safety during oil and gas activity well drilling and infrastructure installations.

14.6.6.3 Challenges, Successes and the Future

LOCO was a world-class mooring array that has inspired other long-term ocean observation initiatives in the Western Indian Ocean. The unique data time-series generated by LOCO elucidated the driving mechanisms, nature and dynamics of the Mozambique Channel eddies and the water volume transport in the narrowest section of the channel between Mozambique and Madagascar. Yet, understanding changes and trends in the eddy frequency and volume transport, and ultimately relating these to ecosystem function and services, is demanding. This information is vital to understand how climate change and a warming ocean will impact the eddy field, thus ocean productivity and fisheries, which is currently the main component of the ocean economy in Madagascar and Mozambique. Since the LOCO mooring was terminated in the Mozambique Channel, a big gap remained in terms of monitoring this dynamic system. LOCO had no or poor connection with the governments of Madagascar and Mozambique, or with the national research communities. This illustrates the need for international programs and coastal states to work together to sustain of long-term observations, even beyond project lifetimes. It is also important that international projects work together with coastal countries for transfer of knowledge, particularly in developing countries.

While both the LOCO mooring array and IIP's mooring station were located off the shelf deeper than 200 m, no long-term observations exist on the shelf apart from the network of coastal underwater temperature recorders at approximate 18 m depth. Future activities need to observe these regions.

14.7 Relevance and Benefits—The Importance of Observing the Ocean

Ocean and coastal ecosystems are key parts of the global cycles of several important gasses (e.g., oxygen, carbon dioxide, nitrous oxide), absorb 30% of the carbon emissions and sequester more than 90% of the heat added to the atmosphere from human activities. The ocean is the strategic frontier for a global population that will require 30% more water, 40% more energy and 50% more food by 2030. A healthy ocean and coasts help to mitigate climate change and its impacts, offer food security to vast numbers of coastal communities, support coral reefs and mangrove forests that offer coastal protection for humankind, and secure habitat for marine organisms in different phases of their life histories (e.g., spawning ground for adults and nursery ground for larvae and juveniles).

Human vulnerability depends upon a population's exposure to a hazard, and its capacity to adapt to, or otherwise mitigate against, adverse impacts. Coastal vulnerability can thus be expressed as an index which includes exposure to environmental threats, population density and coping capacity. Effective coastal management at the state, regional or national levels requires the ability to identify areas with high population densities, settlement, private and public infrastructure and housing values that would be adversely affected by increases in storm frequencies, sea levels, or coastal erosion rates, inundation, super tidal range, mean significant wave height, tropical cyclones, dynamic coastal geomorphology and other climatological variables.

In-situ ocean observations are vital for improving the understanding of ocean–atmosphere dynamics, which are essential for operational oceanography, weather prediction, and climate modelling. Monitoring ocean stressors is equally essential due to the increase in the rate of loss of biodiversity, changing population distributions and regime shifts, habitat degradation, acidity of the ocean, and accumulation of plastics and other wastes. Natural assets of the ocean (services and products) need to be managed to support human development in the future. Similarly, tropical ocean areas have to be monitored for events such as cyclones and tsunamis to provide advance warning for protecting life and coastal infrastructure, while polar ocean areas need to be monitored from the perspective of climate change and sea level rise (see also Chap. 12).

Coastal and ocean observations can help advance the blue economy related to coastal resources and reduce coastal threats. Other chapters of this book provide greater detail about the contributions of various blue economy resources and how some environmental challenges threaten blue economies. The benefits associated with ocean observations are difficult to quantify in a meaningful way, but evidence to date suggests that benefits from well-targeted investments in integrated ocean observing systems will justify the costs (Kite-Powell et al. 2003). Several examples are highlighted below:

14.7.1 Climate Prediction, Ocean Analysis and Forecasting

As alluded to throughout this chapter, one of the benefits of ocean observations is ocean analysis, validation, assessment of and assimilation into predictive models (Le Traon et al. 2019). Most modern data assimilation systems include bias correction techniques that rely on in-situ observations (Lellouche et al. 2021). For example, the value of the TAO/TRITON array to ENSO prediction is well known, yet it has been hard to sustain. However, this coupled problem is much more complicated than originally envisioned; for example, predictive skill and potential predictability can change from one decade to another. And models are still not quite up to the task of being able to fully utilize the dramatically improved ocean observing systems we now have to provide better forecasts. So when it comes to continued investment in TAO/ENSO (and subseasonal-to-seasonal prediction), we are still challenged by motivating and justifying observations based only on forecast improvement.

Climate prediction is still not on the priority level that it deserves to be, equal to the priority of weather prediction. Climate variability is large scale and slow in time, which means governments should pay for basin/global scale observing systems, to address slowly evolving ocean conditions at the national/local scale. However, needed investments are usually beyond the capacity of any single agency and nation. A consensus is needed that the global public product requires global cooperation and investment and to achieve this product we need to highlight a more explicit connectivity between ocean observing and Earth modelling and societally motivated prediction activities.

14.7.2 Marine Meteorological Services

While the ocean covers more than 70% of Earth's surface, the natural system is fully coupled between the atmosphere and ocean. The delivery of effective and improved metocean (marine and weather) services depends on both atmospheric and oceanic information. The growth of seamless forecasting systems means that meteorological services need an increasing amount of quality information about ocean conditions (both at the surface and subsurface) and the atmosphere above the ocean to be able to deliver the weather, marine and climate services derived from the use of such prediction systems.

14.7.3 Safety, Shipping and Recreation

The safety and well-being of people worldwide, the economic benefits available from the ocean, and the cultural and recreational opportunities can be linked to ocean observations. Coastal tourism and recreation are valued as a high-revenue earner globally (see Chap. 6). This industry requires attractive, safe and functional recreational beaches, clean coastal waters (Blue Flag beach certification) and healthy coastal ecosystems. Safe shipping around the world also contributes to fewer incidents or accidents at sea, reducing the possibilities of harmful bunker fuel and oil spills over coastal and open ocean regions. Moreover, ocean information and forecasts help in planning and selecting ship navigation routes that avoid bad weather and rough seas, thus minimizing fuel consumption, with less emission of greenhouse gasses by burning fossil fuel.

14.7.4 Hazard Warnings

Multi-hazard early warning systems related to weather and climate events have been established by many countries at the national and regional levels. Many lesser developed coastal nations, some of which are likely to be critically impacted by global climate change, have not yet established such early warning systems. Forecast models are imperative to issuing warnings with lead times of 48–72 h for the safety of lives, livelihoods and infrastructure against extreme weather events such as dangerous waves, storm surge, overtopping and tropical storms, along with marine events such as harmful algal blooms and marine heat waves. These forecast models require robust in-situ coastal observations to increase lead time, and accuracy and location of events, and only through sustained ocean observing infrastructure is this possible.

14.7.5 Marine Ecosystem Services[7]

Compared to the assessment of land ecosystems, there is a large knowledge gap and an underdevelopment of tools to assess coastal and marine environments, even though they have been estimated to contribute about 63% of the total worth in services provided by global ecosystems (Carrasco de la Cruz 2021). 60 % of the global ecosystem services are in decline, many of which are provided by marine and coastal ecosystems. It is important to recognize that continual decline in these ecosystem services is a barrier for achieving SDG targets and growing blue economies. The international community has, over the past decade, become increasingly concerned about many issues involving the ocean and coasts. The issues of concern include depleting fish stocks, destruction of natural marine and coastal habitats, uncontrolled pressure of urbanization and tourism on coastal regions and pollution from maritime and land-based activities. Issues such as the impact of climate change on the ocean and coasts, biodiversity, conservation and sustainable use of the high seas and the exploitation of the seabed, have raised the profile of marine issues even further.

There is an urgent need to increase scientific knowledge, develop research capacity and transfer marine technology, considering the Intergovernmental Oceanographic Commission (IOC) Criteria and Guidelines on the Transfer of Marine Technology (CGTMT), to improve ocean health and to enhance the contribution of marine biodiversity to the development of developing countries, in particular SIDS and least developed countries (SDG 14.A). The present IOC/CGTMT guidelines offer to IOC Member States guidance to implement Part IV of the UN Law of the Sea (UNCLOS). The text adopted states as basic principle that the "transfer of marine technology should be done free of charge or at a reduced rate for the benefit of the recipient state" (IOC/ABELOS 2005). Capacity development is particularly relevant with regard to fisheries research, oceanic aquaculture, and the exploration and exploitation of new marine compounds, as well as marketing of these. Chapter 16 discusses the importance of capacity development to blue economies in greater detail.

14.8 Challenges and Lessons Learned

There are numerous challenges to improving and sustaining ocean observations, the biggest being that they generally require collaborative arrangements, funded largely through research grants, with limited sustained government support, particularly in developing countries. In some cases, where developing countries' governments are involved, they request the observing agencies or institutions to get revenue from the products they develop, thus they are obliged to charge to provide data. This challenges the concept of making the data freely available to the public. An additional important challenge, from an external perspective, is the need to bootstrap some form

[7] A detailed discussion on the definition of ecosystem services within a marine context can be found in Millenium Ecosystem Assessment, 2005: https://www.millenniumassessment.org/en/index.html.

of implementation, proof of concept or value with additional investment, into the growth of the ocean science service enterprises. For example, how do we connect ocean and terrestrial observations to support the coastal zone? Ocean observing needs to be a multi-stakeholder arrangement with enhanced collaboration on data sharing, standards, technology and capacity. Another major challenge is the need for co-development of ocean observing systems, both between countries, but also between physical, natural and social scientists. To address these challenges, it is essential to learn from experience and so this section highlights some reflections from the case studies.

Bureaucracy poses another challenge for the development of ocean observing systems, particularly from regional and international initiatives, with foreign projects avoiding countries with complex licensing procedures. This is worse for countries protective of foreign initiatives, especially as there is often a lack of communication and co-development of the work, with the data often not being given back to the coastal states, perpetuating the protective behavior of these countries.

14.8.1 Governance and Coordination of National Observing Systems

There are many "actors" (funders, implementers, and users) involved in the global ocean observing system. How do we equitably collect and disseminate ocean information to meet the broad range of needs of these actors from a global point of view? One likely avenue for this will be via the UN Decade of Ocean Science for Sustainable Development, as well as the GOOS program looking to co-design (with stakeholder) observing systems, particularly in coastal areas. Within the context of this chapter co-design refers to a multitude of factors—between developed and developing nations; stakeholder engagement; connecting ocean observing to communities that it serves—to modelling and service providers; connecting, through social scientists, to ensure that observing complements local or indigenous knowledge so local management can be empowered. Co-design will ensure that we remain focused on the reasons for collecting the observations.

The increased investment in ocean observing, as well as enhanced capabilities and technologies is impressive and a positive step; however, the global system is not coordinated, with efforts often being duplicated and using less than optimal observing technology. Understanding the key aspects of the ocean economy and the use of ocean observations is essential and needs more data and a deeper knowledge than is currently available. This information should be a key message for enhanced, sustained funding from governments. Under-resourced countries must develop the necessary policies to invest in science and technology so they have the capacity to drive new technology. Oftentimes, experts in the region are forced to adapt to requirements of external funding sources in order to obtain funding. More emphasis should be put in the area of open-source technology development and capacity development. There is a need for more effective system-level management, with planned coordination across the system, and optimal financial and management support levels for many of the efforts (Tanhua et al. 2019).

A major constraint in the global coastal environment is a widespread lack of accurate and timely data at the global level. Although there are regional programs with long-term coastal observations, there is no global coordinating body, aside from the tide gauge network. To establish governance at the national level GOOS, through its 2030 vision, is taking steps to support national focal points and the emergence of national committees.[8] This will strengthen the reach of national needs into global observing, particularly from those countries that are new to GOOS and the roles they play in building capability and access to ocean observing networks. The GOOS 2030 strategic objectives aim to strengthen partnerships, building advocacy and visibility with stakeholders and regularly evaluating the ocean observing system to ensure it is fit-for-purpose for as many users as possible. This requires effective communication and implementation between stakeholders, users and GOOS. We need to ensure there is a cohesive and coordinated agenda for information gathering. A legacy of long-term observing systems is seen as a key outcome of such projects, as well as the research-based observations being widely available for use and reuse following the project, to ensure maximum value for investment.

For governance to be successful it must demonstrate the advantages of improved global engagement at national levels. This would include global coordination and effective governance of open and sustained data mechanisms and systems that focus on expansions for supporting best practices in data discovery, access, and training, sufficient metadata, as well as development of shared/common tools for ocean data access and exploitation. Global networking and coordination should be implemented to minimize regional gaps in all aspects of observing and governance.

In all the case studies described in this chapter, governance and stakeholder relations were a key to their success. In South Africa, the importance of government buy-in for sustainability was highlighted—a top-down approach which was responsive to stakeholder needs. The Pacific Islands focused on a more bottom-up approach driven by stakeholder needs, whereas in Ghana and India a regional approach was successful, and in Brazil a public/private partnership was implemented. However, these are all examples of national efforts with limited links to international programs. In the Mozambique Channel, the lack of connection between the international projects and the governments of Mozambique and Madagascar (on each side of the Channel), resulted in the failure of a long-term mooring array to be maintained when the international project and funding finished. The GOOS 2030 Strategy could effectively stitch together the patchwork of local, national and regional systems, which are beyond the government structure and ensure they are communicating when required. Such engagement would lead to more access and input to the development and implementation of intergovernmental conventions that require ocean observations (Tanhua et al. 2019).

---

[8] https://www.goosocean.org/index.php?option=com_oe&task=viewGroupRecord&groupID=231.

14.8.2 Blue Economy: Role of Weather, Climate and Coastal Hazards

Economic activities related to the ocean account for 70% of world trade, which provides livelihoods for over 6 billion people and is a source of opportunity, investment and growth. It has been predicted that by 2030 the ocean economy could reach over US$3 trillion per annum (Rayner et al. 2019). The accuracy and timeliness of weather forecasting over the past decades has improved and gains have been made in science, observing (both in-situ and satellite), modelling, computing, and communications to bring relevant Twenty-first Century services to the maritime community. Observations are becoming integrated with value-added products such as forecasts, analyses and dissemination of products. However, millions of dollars in goods and thousands of lives are still lost at sea and on land each year due to extreme weather conditions such as cyclones, hurricanes, tsunamis, strong winds, large waves, fog, thunderstorms, sea ice, coastal erosion, sea-level rise and many other natural coastal hazards. Developing countries are often hardest hit by these conditions. Of the 25 largest island nations and territories, ranked by area, less than 10 have established sustained ocean observation networks (https://www.ocean-ops.org/).

Observations should follow well-defined, science-based and international protocols. But, in addition, there is an urgent need to expand not only our observational coverage, but also to improve how marine data are used and transformed into actionable information, creating systematized value chains for society in all areas of the globe. Downstream services are required to customize value-added products to specific users. Work by the Organization for Economic Co-operation and Development (OECD, Jolly et al. 2021) has highlighted the need to unlock the value of marine data by supporting the entire marine data value chain, while promoting the use and reuse of marine data in policies and communicating the benefits.

In strengthening the value cycle across observations, research and services delivery; we need to identify observational needs, but also improve communication of outcomes and benefits of research and other applications to a broad audience, to demonstrate the value of data sharing for all, articulate needs and advocate for improved observations. Improved products and forecasts need to be translated into useful information and communicated appropriately to ensure uptake by stakeholders and policy makers. An OECD study is underway to estimate the economic value of sustained observations globally, including coastal regions, which could be helpful in demonstrating the value of data sharing (Rayner et al. 2019). More evaluations such as this will aid both in communication and understanding the flow of ocean data in national economies. In the future, regulatory pressures on carbon management, global temperature rise, and sea level rise mitigation may rely heavily on knowing and predicting the ocean state. Ocean observations are critical to improving model-based predictive capability, to elucidating the processes not yet included in models, and getting the ocean storage of heat and carbon correct.

14.8.3 Exclusive Economic Zones

The 1982 UN Convention on the Law of the Sea (UNCLOS) was an extraordinary achievement in international treaty-making. The Exclusive Economic Zone (EEZ) concept was established, extending 200 nautical miles beyond a coastal nation's land territory or internal (or archipelagic) waters. Within its EEZ, a coastal state has the right to explore, exploit, conserve, and manage natural resources; establish artificial islands; installations, and structures; conduct marine scientific research and allow other nations to conduct research; and protect and preserve the marine environment. EEZ claims form the basis for most marine pollution control regulation by coastal states, although many coastal states have framed their EEZ claims narrowly in terms of fishing rights. A coastal state may exercise its rights within the EEZ subject to freedoms of navigation, overflight, and laying of submarine cables and pipelines. Although UNCLOS defines EEZ jurisdiction narrowly in relation to natural resources and the environment, it is often construed broadly as a basis for regulating any economic activity within the zone.

Some countries are apprehensive about deploying, permitting, or making freely available ocean measurements in their EEZs for concerns over national security, resource development, or other reasons. This causes challenges for observations in EEZs, ranging from getting access to ports for research ships through to the implications of autonomous vehicles such as Argo floats, drifting into EEZs (Bork et al. 2008). The problem of measuring in EEZs is a longstanding one that complicates the implementation of ocean observing systems, but observations in these regions are crucial from both a scientific and a societal perspective. The global community is working to facilitate these observations. Argo has a formal communication channel and many countries have given formal concurrence for Argo floats within their EEZs and 6 of the BGC variables are now included in this arrangement (Bittig et al. 2019).

It is becoming increasingly evident that nations need to take ownership and collect data and use the observations from their EEZs themselves. The international marine science community needs to be acutely aware of so-called "parachute science" (Stefanoudis et al. 2021) where developed countries undertake research within lesser developed countries' EEZs, but the involvement of local scientists in these projects is limited. Research project applications need to go beyond just skills transfer "tick boxes" in order to obtain approval for funding, but rather should show how the project was conceptualized and co-designed and will be undertaken with scientists from the local marine science community. This implies a shift towards more co-generation of observing systems and knowledge sharing between developed and developing countries. Effective communication and collaboration between scientists from different parts of the world, enhancing collaborations, as well as sharing knowledge and data, technology and equipment should not be something for the distant future. Meaningful engagement that contributes to the global ocean observing system, while aiding developing countries to manage their resources, is necessary. However, there remains a disconnect between the international legal and policy framework and the reality of global ocean science collaboration, capacity development, data sharing and technology transfer. Building capacity through monitoring will build scientific literacy which, in turn, will enable all countries to engage purposefully in the global dialogue. Global networking and coordination need to be implemented to minimize regional gaps in all aspects of observing and governance. Sustained observations require a coordinated, collaborative and culturally appropriate process, incorporating indigenous and local knowledge, with long-term resourcing that meets identified local, national and regional needs. Given the influence this will have on economic stability for the impacted countries, it is essential that the long-term resourcing be, at the least, derived from a combination of international and local sources.

14.8.4 Communicating the Value of the Observing System

While much of the data collected in the ocean are funded from research grants, increasing amounts of data are available in real time through the GTS or Web services. It is important to demonstrate the benefit of data sharing for the things people care about, and also work towards ensuring that the benefits of data sharing are equitable. The Keeling time-series of atmospheric CO_2 is iconic and the ocean would benefit from a similar record, for example sea level or temperature.

Coastal states are particularly engaging in the process to advocate for benefit-sharing arrangements; for instance, in line with the Nagoya Protocol on access to genetic resources and the fair and equitable sharing of benefits arising from their utilization to the Convention on Biological Diversity. Many states are supportive of ocean observations for scientific and operational applications, but they also see the dual use of these observations for applications over which they are much more protective, for example, bioprospecting for potentially lucrative drugs. Communication of benefits—particularly with an emphasis on engagement and participation—is key to demonstrate the benefits of data already available. Information needs to be communicated on how and where observations will make a positive impact on weather and climate forecast systems and multi-hazard early warning systems.

All of the case studies had a strong focus on ensuring that the value of data from observing systems was clear to government managers and policymakers, stakeholders and users. Responsive decision support tools and easily accessible data were shown to be key success factors. Some case studies discussed the need to exploit citizen science data better to increase not only observations, but also citizen's understanding of the ocean. Today's citizen science can become part of tomorrow's traditional knowledge. Linking the two could create linkages between elders and younger people and enhance the understanding and support of ocean observing systems.

An additional benefit of clear communication around the value of observing systems is the prevention of vandalism. Effective data buoy vandalism refers to the intentional interference with, damage to, or theft of observing platforms by human action. It is essential to promote education and outreach and broaden support by community stakeholders, especially to recreational, artisanal, and commercial fishers about the equipment and the importance of the data produced. Proactive engagement at regional and local scales through the development of new partnerships to share lessons learned and generate new ideas for addressing vandalism issues is needed.

The Pacific case study clearly demonstrated the impact of culturally sensitive communications about supporting ocean observations and many developing countries can learn from the methods they have applied to ensure that the information is relevant, leading to local community support and hence protection of the equipment.

14.8.5 Capacity Development and Retention

Key to ensuring sustained ocean observations globally is the human capacity required. When considering future technical breakthroughs, we also need to look at where we can implement human capacity breakthroughs. Capacity here refers to, but is not limited to, technicians, engineers, marine scientists (including oceanographic, environmental, atmospheric and biological disciplines), social scientists, and data scientists. However, it also includes such disciplines as economics, business and project management, information technology, policy and decision making for governance, and artificial intelligence disciplines (including robotics and similar abstract concepts that, when brought together, answer the full value chain of the skills required to maintain and enhance ocean observing systems). Capacity development and training needs to happen in a way that takes into account the needs of the country, as well as its capabilities to ensure that the most fit-for-purpose technology and skillsets are developed. As highlighted in the OCIMS case study from South Africa, the bureaucracy of working in a government system can be constraining, combined with the lack of positions available to work on the system and qualified people to fill them. To address these issues of human capacity, it is essential to develop capacity and invest in people in the long term, in a transformative manner, using partnerships. However, this takes time and a long-term commitment. In addition, OCIMS highlighted the need for more in-situ data; developing countries tend to rely a lot on satellites. It is not just the cost of acquiring the instruments but also of sending them overseas for maintenance. There needs to be more access to innovative, low-cost sensors that can be maintained within the country.

In addition, skill sets need to be retained as best as possible in the regions where they are developed. This is difficult to do where a gifted marine scientist is trained locally, but may complete their studies or gain in-field work experience in a developed country, and they choose to stay in the developed country to earn a better way of life than what they had experienced at home or, when they return to their home country, they are offered administrative or management positions, rather than technical or scientific positions in the fields in which they have been trained. Opportunities should be created and encouraged to attract individuals back to their local regions, in their field of expertise, where possible to ensure growth within their sector of interest, and to go on to train the next generation. There are numerous programs specifically designed for capacity development within ocean observing systems. These include (but are not limited to) the POGO-SCOR fellowships which have been successful as the proposals are co-created between the developing country trainee and the trainer, so there is knowledge sharing in a more sustainable manner. The POGO-Nippon Foundation Centre or Excellence program allows long-term training (>9 months) in all aspects of observing systems and has created a strong alumni network from developing countries. These programs are successful because they are responsive to feedback from the participants. In addition, the IODE Ocean Teacher program continues to run courses as the need arises and supports IOC member nations in developing capacity. Sharing and training in best practices, through initiatives such as the Ocean Best Practices system (https://www.oceanbestpractices.org/) is essential for countries developing their own observing system both for observing and data processing, quality control and archiving. To ensure regional programs have a global reach, there is also a need to offer access to existing Global Data Assembly Centres and help with data submission, as offered by OceanOps.

There are many other different international efforts and within the Ocean Decade, there is a thrust to coordinate better. The key for any of these programs remains sustainability, measuring impact and being responsive to create a positive and sustainable set of skills with an open feedback loop. For a more detailed treatment of capacity development, see Chap. 15.

14.8.6 Expansion of Networks to Include Less Developed Countries (LDC) and Small Island Developing States (SIDS)

Ocean observing networks are largely built up and funded through research grants. In addition, reporting back to funders requires lead researchers to show value for money within their regions of concern, and not always as a global outlook. This is particularly true for networks that are land-based (e.g., GLOSS and HF Radar). And while some ocean observing platforms are free floating by their nature, acquiring data from the global ocean as they drift (e.g., Argo and DBCP), the deployment opportunities to get these instruments to all regions of the global ocean can be very limited. In addition, understanding the benefits of such global observations in national EEZ contexts is not always clear. For example, individual Argo float data may not be that useful, but the global dataset can be used to provide boundary conditions for models and probably be of more direct use for some SIDS which rise straight up from the seabed thousands of meters below. Furthermore, with BGC Argo, the sensors used are essentially the same as those they may use in coastal waters, so a partnership program where deep-water island and coastal states can assist with deployments in return for some capacity building on sensors and data use and scientific partnership could be a way of developing scientific capacity in ocean observations more generally.

Mechanisms need to be developed through engagement with LDCs and SIDS to assist with funding grants and applications to gain access to ocean observing platforms for in-country deployments, and to brain-storm unique ideas for platform deployments at sea using modified fishing vessels, sailing yachts and other recreational ocean craft large enough to carry an automatic weather station and a satellite transmitter. The expansions required for LDCs and SIDS will likely not be through traditional developed country means, but through innovative and unique approaches. To do this, engagements at the grassroots level of researchers and technicians in the field would be a useful exercise, with engagement through intergovernmental task teams to secure and release funding for ocean observing systems be encouraged.

14.9 Opportunities and the Future

14.9.1 Need for Ocean Observations in Developing Countries

There is a need to understand the ocean and atmosphere environment as a whole, in order to address the coastal hazards and climate change-related challenges to be faced in the future and to enhance the livelihood and safety of people and infrastructure. The natural Earth system comprises a fully coupled atmosphere and ocean. The delivery of effective and improved marine and weather services depends on both atmospheric and oceanic information. As such, a short-term approach with a focus on facilitating surface marine meteorological observations in support of safety of life and property at sea needs to be combined with a longer-term approach, and future collaboration developed with the IOC of UNESCO with regard to ocean observation requirements, including in coastal regions, in particular in support of Earth System prediction and hydro-climate services. It is often difficult for developing countries to know where to start with observing programs and resources and information need to be more widely available to provide a starting point relative to the needs for the country (Box 14.3).

Sharing of data, knowledge, capacity, technology, methodologies and infrastructure is the only way to truly achieve a Global Ocean Observing System. Globally, there is a need to **increase investment in observing networks, ensuring that, where possible, there is co-investment from developing countries to ensure sustainability**. It is necessary to share and draw from the successes and failures of regional and global systems, such as highlighted in the case studies within this chapter, towards building a common and interoperable system. However, requirements for ocean observing vary depending on mission, ocean environment and capabilities; best practices for a system in the Atlantic Ocean may not be applicable to the Indian Ocean. Targeted measurement precision can be different for small climate signals in the deep ocean or for near-real time observations in coastal areas. Human and technological capacities, as well as the needs of society, also vary across institutions and countries. There are also lessons to be applied from the way national space agencies operate. New missions go through a rigorous evaluation of the geophysical process to be observed, the error budget of the proposed sensor, and whether the deployed sensor, orbit, QC/QA and duration will meet the science objective. That approach to new networks in the ocean could be taken so that, for example, a global fleet of gliders in support of the GOOS objectives is not deployed until the end-to-end value chain is shown to be reasonably feasible.

There is a need to standardize, integrate and share operational and data management best practices. Coordinated efforts, such as the GOOS/IODE Ocean Best Practices System (www.oceanbestpractices.org), that ensure easy access to trustworthy best practices around collecting EOVs, will ensure that our observations are interoperable, reproducible and reliable. This is a priority that needs to be addressed for all ocean parameters: physical, chemical and biological. This means serious engagement with biologists in an ocean observing system that is fit-for-purpose and that delivers value to society. This requires recognition that many of the observations made are intended to understand impacts of a changing environment on ocean organism and ecosystems.

As highlighted in the case studies, there is a need **for targeted and continuous stakeholder engagement**. Improved ocean observing governance is required to effectively and efficiently address the growing needs of the many stakeholders. There is a need at the local, regional and international levels for coordination of sustained ocean observing. Although we can look to the remote sensing communities and the WMO, the ocean community task is more complex (ocean, disciplines, coast/deep/open) and the community is more fragmented. We also need to be wary of a top-down approach, which stifles innovation and fosters inertia. The vision for the next 10 years, as highlighted in the Global Ocean Observing System 2030 Strategy, is really about building a comprehensive system, based not just on GOOS, but many players, engaging multiple networks in comprehensive observations including biology. It requires listening to those who need the information in order to design the observing system required. In developing countries, this system needs to be fit for purpose, considering not only what observations are needed to develop blue economies, but also the capacity to collect such measurements. And it requires all ocean observers to deliver the right information into hands that understand how to use it.

Maintaining continuity of data records is critical to establish long base lines for assessing natural variability and anthropogenic climate change. It is important to evolve the observing system in light of new scientific understanding by taking advantage of new technologies that are ready for deployment and nurturing those that are not yet ready. **Complementary systems and emerging technologies need to be included in implementation planning activities**. But, care must be taken when changes are made to the observing system by introducing new technologies to replace older measurement systems. The transition should be managed with awareness, with overlapping measurements to ensure the integrity of the record is not compromised by changing techniques.

Building and maintaining ocean observing systems are expensive propositions and data accessibility and discoverability are essential. The social impact requires that the investments made in ocean observations are validated by the widest possible use of the data for research, forecasting, analyses, assessments, and applications. That is only possible if the **data follow the FAIR principles** (Wilkinson et al. 2016). Ocean data are being increasingly used not only by people in oceanography or associated fields, but also outside the research field by non-experts to deliver services and information for decision making, highlighting the societally relevant system that is being built. Therefore, it is important that data systems are easy to use by people building products and that information in the metadata enables accurate post-processing for products and services. These service needs must be built into metrics; this vital need for partnerships down the value chain is fundamental to the GOOS strategy. For example, the data system requirements are ripe for developing strong partnerships with data scientists that will enable collection and serving of data that are usable to a wider user community.

Communication to the ocean and coastal communities is also essential to avoid vandalism of the existing observing system like moored buoys. Increasing the literacy of these communities about the benefits of these system to their daily life is essential. The importance of the ocean to society is becoming clearer; however, how to address the many real challenges we are facing is still not very well understood. Science needs to provide the foundation for that understanding. **Open knowledge sharing, including transparency and acknowledging uncertainties and gaps** is ever more important. In addition, the way in which we observe the ocean needs to be environmentally sound. The ocean observing community would be doing a disservice to itself and its mandate if it uses large amounts of plastic to monitor the ocean or if deployed equipment is continuously left in the ocean without retrieval plans. The value of making observations using autonomous platforms is also growing, with newer technologies being less reliant on vessels to be deployed. These new technologies look **at not just understanding the environmental health of the ocean, but also promoting it**.

A key achievement of the FOO was to identify the classes and priorities of observations to be made, the societal impact versus the technologies' ability to make the needed observations. The FOO requires partnerships between communities to assess observation elements for every EOV, and to expand the quality, scope and relevance of products. But are the EOVs and particularly the biological EOVs robust enough yet? EOVs have been developed to set priorities for observing, but **metrics for measuring the system performance need to be developed**.

The modeling community is heavily dependent on sustained observations in validating, assessing, assimilating and motivating improvements to predictions. Society needs very much to get views of the future in order to react at present to that future; hence, such forecasts have large economic value. Thus, it is necessary to quantify how forecasts are impacted by gaps in observations to strongly motivate where to make new observations. These should be quantified in terms of impact in forecasts, evaluating the observations' impacts on models and thus on their application products and their utility to users. Society is willing to invest considerable funds into climate modelling, for example, but on shorter time scales, future predictions of drought, changes in regional fisheries dependent on future regional ocean conditions and other model-based efforts could have great benefit. **We need a more explicit connectivity between ocean observing and Earth modelling and societally motivated prediction activities**.

In parallel there is a need for continuous validation and model bias correction. Observing system simulation experiments (OSSEs) performed within models to assess the best place for observing systems are vital to provide universal standards for the observational community and decision-makers, with the information that is needed to assess, manage, and maintain GOOS routinely. By so doing, decision-makers are empowered to advocate for the maintenance of GOOS using up to-date evidence and consensus results from numerous models. Systematic evaluations supported by a common standard from the end-user community will ensure the development of future technologies and observing systems that are sustainably implemented and useful to the user community. This approach can support the **routine monitoring and assessment of the observational designs**. A formal way is needed to bring observers and modelers together with sufficient resource support to work at the intersections of ocean observing and model validation and improvement. GOOS, through its Expert Team on Operational Ocean Forecast Systems, as well as the Ocean Decade Ocean Observing Co-design program, could provide such mechanisms.

Sea level and carbon (carbon storage, blue carbon, green carbon, carbon markets, etc.) are all important and a driver for additional ocean knowledge/observations and improved ocean predictions. Much work is underway and there is increasing recognition that **adaptation requires significant effort to inform and explore adaptation practices**. This is now being taken up by the private sector and by government agencies, driving change.

14.9.2 Finally

Climate adaptation, weather prediction, early warning systems, carbon budgets, commercial and tourism activities, coastal cities and communities, renewable energy and marine resource management all rely on accessible data from global, regional and national ocean observations, which are fundamental to achieve sustainable blue economies. The current disparity between the observing systems of developed and developing countries leads to large gaps in the global observing system. A key next step for the global community is to ensure that under-resourced nations are supported in the development of their national observations as well as contributing to global observations.

This chapter has used case studies and literature to highlight the need for improved governance at global levels to ensure that implementation of observing systems is in line with supported by global coordinating infrastructures such as GOOS. Box 14.3 gives some suggestions, but a key recommendation for any nation starting an observing program is to focus on the well-described essential variables (Box 14.1 and Table 14.1) and to reach out both regionally and internationally to ensure that they have access to the best practices[9] and global systems that are there to support observations, In particular the GOOS 2030 vision and the suite of papers from the

[9] https://www.oceanbestpractices.org/.

OceanObs'19 Frontiers of Marine Research[10] provide a great place to start and will be followed up by the work which will arise from OceanObs29.

Box 14.3 Where to start as a developing nation wanting to make observations

- *What are the most critical data for a coastal nation to monitor in terms of operational purposes, not the most advanced research needs?*

There are a number of key parameters that need to be measured, but the question really depends on the coastal nation needs and the stakeholders involved in relation to their blue economies. Also, what are the threats to the coastal nation? A coastal nation impacted by cyclones may require different data to those influenced by upwelling. There needs to be engagement in regional and global observing systems through GOOS and the GOOS regional alliances, but at the same time with the National Meteorological and Hydrological Services (NMHS) and WMO. Local measurements which can be used to ground truth satellites and validate models, or even feed into data assimilation are essential globally and also to make global products more relevant to the region. It is normally considered that basic measurements are wind speed/direction, atmospheric pressure, air temperature and SST with a data logger to collect, process and store the data from sensors and to manage the communication protocols with remote servers (https://library.wmo.int/doc_num.php?explnum_id=318). In addition, for climate change studies, long-term sea level data using tide gauges installed on the coast along with satellite data sets are required. Aside from the aforementioned EOVs and EBVs, measurements related to ocean acidification could start with involvement in GOA-ON (http://www.goa-on.org/resources/manuals.php). In addition, sea level is paramount to measure for coastal nations as it is a key parameter for inundation severity (for early warning systems), and the understanding of local relative sea level (as opposed to global absolute sea level), is necessary for efficient coastal management and policy making.

- *How much of the critical data can be downloaded from satellite services, what kind of training is needed for downloading and using the data and to produce data products tailored to the local context, and who provides such training?*

Most data from satellites is not well resolved or validated near the coast, so even though it can be downloaded (e.g., via the Copernicus Marine Service portfolio), there needs to be a clear understanding of the potential errors. Countries with limited capacity to analyse raw data could be interested in co-designed science products based on several in-situ or remotely sensed datasets. There are

[10] https://www.frontiersin.org/research-topics/8224/oceanobs19-an-ocean-of-opportunity.

various global-scale programs that can assist with this, such as CoastPredict (https://www.coastpredict.org/). The GOOS Observation Coordination Group (https://www.goosocean.org/) and the observing networks discussed in this chapter also have various capacity development workshops to support observations and data access and analysis. There are various python/github packages to help with data analysis (e.g., https://pyoceans.github.io/sea-py/), which are a great place to start if necessary skills are available within the coastal nation. The IODE Ocean Teacher Global Academy (https://classroom.oceanteacher.org/) offers various courses, and POGO and SCOR offer various training opportunities, including visiting scholars, and summer schools in data analysis are often hosted by universities across the world. As part of the Ocean Decade, a program has been put in place to try and begin coordination of capacity development opportunities.

- *What is the use of the global datasets provided through GOOS, to coastal communities?*

Global data may not be immediately evident as useful to coastal nations; however, much of the data (e.g., Argo, drifters, etc.) is very useful in terms of weather and climate forecasting, especially as it is often near real-time. Local phenomena are nested in global patterns. Access to any data is useful but in the short term it often seems some data are more useful than others. However, it might not be possible for under-resourced nations to participate directly in global programs; what is important is that there are opportunities to support global networks with, for example, access to EEZs, support in deployment or maintenance of instrumentation, as well as local knowledge of regional systems and local data for enhanced validation and calibration.

- *What observations need to be conducted locally on a smaller scale for blue economy purposes?*

As discussed in this chapter, Essential Ocean Variables have been globally decided on as important observations to be collected, even at smaller scales. The OECD-GOOS-MEDIN survey gives some insight into variables that different parts of the marine sector use: (https://www.youtube.com/watch?v=36dRXGO7Nqs). It is essential to consider the resources (coral reefs, seagrasses and mangroves, coastal fisheries, groundwater inputs, tourism, offshore minerals) and environmental threats (ocean acidification, coastal pollution, harmful algae, climate change) covered in other chapters of the book and their relevance at the local scale. Ultimately, any measurements, following accepted best practices and that are of known accuracy will contribute to knowledge generation. Through CoastPredict a handbook for coastal observations is being developed.

The focus moving forward needs to be co-development of observing programs from the beginning, whether it is global programs wanting to make coastal observations in under-developed regions through to incorporating local ecological knowledge. In addition, the emphasis is no longer on translating science to policy but rather involving policy makers in the design of the science and observations from the beginning. This will help in the communication between policy makers and scientists.

References

Beal LM, Vialard J, Roxy MK et al (2020) A road map to IndOOS-2: better observations of the rapidly warming Indian Ocean. Bull Am Meteorol Soc 101(11):E1891–E1913

Bittig HC, Maurer TL, Plant JN et al (2019) A BGC-Argo Guide: planning, deployment, data handling and usage. Front Mar Sci 6:502. https://doi.org/10.3389/fmars.2019.00502

Bojinski S, Verstraete M, Peterson TC et al (2014) The concept of essential climate variables in support of climate research, applications, and policy. Bull Am Meteorol Soc 95(9):1431–1443. https://doi.org/10.1175/BAMS-D-13-00047.1

Bork K, Karstensen J, Visbeck M et al (2008) The legal regulation of floats and gliders—In quest of a new regime? Ocean Dev Int Law 39(3):298–328. https://doi.org/10.1080/00908320802235338

Carrasco De La Cruz PM (2021) The knowledge status of coastal and marine ecosystem services—Challenges, limitations and lessons learned from the application of the ecosystem services approach in management. Front Mar Sci 8:684770. https://doi.org/10.3389/fmars.2021.684770

Chaudhuri D, Sengupta D, D'Asaro E et al (2019) Response of the salinity-stratified Bay of Bengal to Cyclone Phailin. J Phys Oceanogr 49(5):1121–1140

de Ruijter WPM, Ridderinkhof H, Lutjeharms JRE et al (2002) Observations of the flow in the Mozambique Channel. Geophys Res Lett 29(10):1502–1504

Francis PA, Jithin AK, Effy JB et al (2020) High resolution operational ocean forecast and reanalysis system for the Indian Ocean. Bull Am Meteorol Soc 101(8):E1340–E1356. https://doi.org/10.1175/BAMS-D-19-0083.1

GOOS Biogeochemistry Panel (2013) First technical experts workshop of the GOOS Biogeochemistry Panel: defining Essential Ocean Variables for biogeochemistry http://www.ioccp.org/images/10FOO/Technical%20Experts%20Meeting%20Report_Draft_20140212.pdf

Halo I, Backeberg B, Penven P et al (2014) Eddy properties in the Mozambique Channel: a comparison between observations and two numerical ocean circulation models. Deep-Sea Res, Part II 100:38–53

Han W, Vialard J, McPhaden MJ et al (2014) Indian Ocean decadal variability: a review. Bull Amer Meteor Soc 95:1679–1703

Howe BM, Arbic BK, Aucan J et al (2019) SMART cables for observing the global ocean: science and implementation. Front Mar Sci 6:424. https://doi.org/10.3389/fmars.2019.00424

Intergovernmental Oceanographic Commission (IOC) (2019) The Global Ocean Observing System 2030 Strategy. IOC, Paris, IOC Brochure 2019–5 (IOC/BRO/2019/5 rev.2), GOOS Report No. 239. https://goosocean.org/index.php?option=com_oe&task=viewDocumentRecord&docID=24590

IOC/ABELOS (2005) The Advisory Body of Experts on the Law of the Sea (IOC/ABELOS), fifth session, Buenos Aires, Argentina, 11–15 April 2005. IOC. Reports of meetings of experts and equivalent bodies, 203, p 40, UNESCO

Izumo T, Vialard J, Lengaigne M et al (2010) Influence of the state of the Indian Ocean Dipole on the following year's El Niño. Nat Geosci 3(3):168–172. https://doi.org/10.1038/Ngeo760

Jaquemet S, le Corre M, Marsac et al (2005) Foraging habitats of the seabird community of Europa island (Mozambique Channel). Mar Biol 147:573–582

Jolly C, Jolliffe J, Postlethwaite C et al (2021) Value chains in public marine data: a UK case study, 2021/11. A joint OECD Working Paper in collaboration with the UK Marine Environmental Data and Information Network (MEDIN) and the Global Ocean Observing System (GOOS) in the Intergovernmental Oceanographic Commission of UNESCO. https://doi.org/10.1787/d8bbdcfa-en

Kite-Powell HL, Colgan CS, Weiher R (2003) Economics of an integrated ocean observing system. Mar Technol Soc J 37(3):55–66. https://doi.org/10.4031/002533203787537276

Lellouche J-M, Eric G, Romain B-B et al (2021) The Copernicus global 1/12° oceanic and sea ice GLORYS12 reanalysis. Front Earth Sci 9:698876. https://doi.org/10.3389/feart.2021.698876

Le Traon PY, Reppucci A, Fanjul EA et al (2019) From observation to information and users: the Copernicus Marine Service perspective. Front Mar Sci 6:234. https://doi.org/10.3389/fmars.2019.00234

Lindstrom E, Gunn J, Fischer A et al (2012) A framework for ocean observing: by the task team for an integrated framework for sustained ocean observing. UNESCO, Paris. https://doi.org/10.5270/OceanObs09-FOO

Luo JJ, Zhang RC, Behera SK et al (2010) Interaction between El Niño and extreme Indian Ocean Dipole. J Clim 23(3):726–742. https://doi.org/10.1175/2009jcli3104.1

Mackenzie B, Celliers L, Assad LPdF et al (2019) The role of stakeholders in creating societal value from coastal and ocean observations. Front Mar Sci 6:137. https://doi.org/10.3389/fmars.2019.0013

Malauene BS, Shillington FA, Roberts MJ et al (2014) Cool, elevated chlorophyll-a waters off northern Mozambique. Deep-Sea Res, Part II 100:68–78

Malauene BS, Moloney CL, Roberts MJ et al (2018) Impact of offshore eddies on shelf circulation and river plumes of the Sofala Bank, Mozambique Channel. J Mar Syst 185:1–12

Marcelli M, Piermattei V, Gerin R et al (2021) Toward the widespread application of low-cost technologies in coastal ocean observing (Internet of Things for the Ocean). Mediterr Mar Sci 22(2):255–269. https://doi.org/10.12681/mms.25060

Mathew S, Natesan U, Latha G et al (2018) Dynamics behind warming of the southeastern Arabian Sea and its interruption based on in situ measurements. Ocean Dyn 68:457–467. https://doi.org/10.1007/s10236-018-1130-3

McPhaden PM, Meyers G, Ando K et al (2009) RAMA—Research moored array for African-Asian-Australian monsoon analysis and prediction. Bull Am Meteorol Soc 90:459–480. https://doi.org/10.1175/2008BAMS2608.1

Miloslavich P, Bax NJ, Simmons SE et al (2018) Essential ocean variables for global sustained observations of biodiversity and ecosystem changes. Glob Change Biol 24(6):2416–2433. https://doi.org/10.1111/gcb.14108

Mohanty UC, Osuri KK, Tallapragada V et al (2015) A great escape from the Bay of Bengal “Super Sapphire–Phailin” Tropical Cyclone: a case of improved weather forecast and societal response for disaster mitigation. Earth Interact 19(17):1–11

Nammalwar P, Satheesh S, Ramesh R (2013) Applications of remote sensing in the validations of Potential Fishing Zones (PFZ) along the coast of North Tamil Nadu, India. Indian J Geo-Mar Sci 42(3):283–292

Navaneeth KN, Martin MV, Jossia Joseph K et al (2019) Contrasting the upper ocean response to two intense cyclones in the Bay of Bengal. Deep-Sea Res, Part I 147:65–78

Rayner R, Jolly C, Gouldman C (2019) Ocean observing and the blue economy. Front Mar Sci 6:330. https://doi.org/10.3389/fmars.2019.00330

Ridderinkhof H, de Ruijter WPM (2003) Moored current observations in the Mozambique Channel. Deep-Sea Res, Part II 50:1933–1955

Roberts MJ, Ternon JF, Morris T (2014) Interaction of dipole eddies with the western continental slope of the Mozambique Channel. Deep-Sea Res, Part II 100:54–67

Roxy MK, Modi A, Murtugudde R et al (2016) A reduction in marine primary productivity driven by rapid warming over the tropical Indian Ocean. Geophys Res Lett 43:826–833. https://doi.org/10.1002/2015GL066979

Saji N, Goswami B, Vinayachandran P et al (1999) (1999) A dipole mode in the tropical Indian Ocean. Nature 401:360–363. https://doi.org/10.1038/43854
Sætre R, da Silva AJ (1984) The circulation of the Mozambique Channel. Deep-Sea Res, Part I 31:485–508
Schouten MW, de Ruijter WPM, van Leeuwen PJ et al (2003) Eddies and variability in the Mozambique Channel. Deep-Sea Res, Part II 50:1987–2003
SCOR Working Group 154 (2020) Recommendations for plankton measurements on the GO-SHIP program with relevance to other sea-going expeditions. SCOR Working Group 154 GO-SHIP Report. Scientific Committee on Oceanic Research, p 70. https://doi.org/10.25607/OBP-718
Stefanoudis PV, Licuanan WY, Morrison TH et al (2021) Turning the tide of parachute science. Curr Biol 31:R161–R185. https://doi.org/10.1016/j.cub.2021.01.029
Tanhua T, McCurdy A, Fischer A et al (2019) What we have learned from the framework for ocean observing: evolution of the global ocean observing system. Front Mar Sci 6:471. https://doi.org/10.3389/fmars.2019.00471
Ternon JF, Roberts MJ, Morris T et al (2014) In situ measured current structures of the eddy field in the Mozambique Channel. Deep-Sea Res, Part II 100:10–26
Tew-Kai E, Marsac F (2009) Patterns of variability of sea surface chlorophyll in Mozambique Channel: a quantitative approach. J Mar Syst 77:77–88
Trenberth KE, Karl TR and Spence TW (2002) The need for a systems approach to climate observations. Bull Am Meteorol Soc 83(11):1593–1602. https://doi.org/I0.II75/BAMS-83-11-1593
Ullgren J, Aken H, Ridderinkhof H et al (2012) The hydrography of the Mozambique Channel from six years of continuous temperature, salinity and velocity observation. Deep-Sea Res, Part I 69:36–50
Ullgren JE, Andre E, Gammelsrød T et al (2016) Observations of strong ocean current events offshore Pemba, northern Mozambique. J Oper Oceanogr 9:55–66
Venkatesan R, Vedachalam N, Vengatesan G et al (2020) Fuel for cyclones: quantification of ocean-atmosphere energy exchange during tropical cyclones in the Bay of Bengal using Indian Ocean Moored Observatories. Mar Technol Soc J 54(4):81–92. https://doi.org/10.4031/MTSJ.54.4.4
Webster P, Moore A, Loschnigg J et al (1999) Coupled ocean–atmosphere dynamics in the Indian Ocean during 1997–98. Nature 401:356–360. https://doi.org/10.1038/43848
Weimerskirch H, Le Corre M, Jaquemet S et al (2004) Foraging strategy of a top predator in tropical water: great frigatebirds in the Mozambique Channel. Mar Ecol Prog Ser 275:297–308
Wilkinson M, Dumontier M, Aalbersberg I et al (2016) The FAIR Guiding Principles for scientific data management and stewardship. Sci Data 3:160018. https://doi.org/10.1038/sdata.2016.18

Chapter 15
Developing Capacity for Ocean Science and Technology

Patricia Miloslavich, Rebecca Zitoun, Edward R. Urban Jr., Frank Muller-Karger, Nicholas J. Bax, Brian K. Arbic, Ana Lara-López, Cláudia Delgado, Marc Metian, Sophie Seeyave, Peter W. Swarzenski, Jacqueline Uku, and Alexis Valauri-Orton

Abstract The ability of coastal nations to manage their coastal and marine environments is vital in the development and maintenance of national blue economies following the 2030 Agenda. Thus, capacity development (CD) is an important priority area to strengthen education and training for various stakeholders to help

P. Miloslavich (✉) · E. R. Urban Jr.
Scientific Committee On Oceanic Research (SCOR), University of Delaware, Newark, DE, USA
e-mail: patricia.miloslavich@scor-int.org

E. R. Urban Jr.
e-mail: ed.urban@scor-int.org

P. Miloslavich
Departamento de Estudios Ambientales, Universidad Simón Bolívar, Caracas, Venezuela

R. Zitoun
Department of Ocean Systems (OCS), Royal Netherlands Institute for Sea Research (NIOZ), 't Horntje, Netherlands
e-mail: rzitoun@geomar.de

F. Muller-Karger
College of Marine Science, University of South Florida, St. Petersburg, FL, USA
e-mail: carib@usf.edu

N. J. Bax
Oceans and Atmosphere, Commonwealth Science and Industry Research Organisation (CSIRO), Hobart, TAS, Australia
e-mail: Nic.Bax@csiro.au

B. K. Arbic
Department of Earth and Environmental Sciences, University of Michigan, Ann Arbor, MI, USA
e-mail: arbic@umich.edu

A. Lara-López
Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, TAS, Australia
e-mail: ana.lara@utas.edu.au

C. Delgado
International Oceanographic Data and Information Exchange of the Intergovernmental Oceanographic Commission of UNESCO, Ostend, Belgium
e-mail: c.delgado@unesco.org

E. R. Urban Jr. and V. Ittekkot (eds.), *Blue Economy*,
https://doi.org/10.1007/978-981-19-5065-0_15

create an appropriately trained workforce able to develop, implement, and expand blue economies, especially in developing countries. The chapter is separated into three parts. Part one provides a synthesis of existing global and regional initiatives that build the foundation of CD for ocean sciences. Some multilateral initiatives that are discussed are the Intergovernmental Oceanographic Commission (IOC) of UNESCO, the Scientific Committee on Oceanic Research (SCOR), and the Partnership for Observation of the Global Ocean (POGO). The Western Indian Ocean Marine Science Association (WIOMSA) is presented as a prime example for a regional CD organization. Part two showcases lessons learned from case studies and success stories from training programs such as summer schools that bring together students from various backgrounds for intensive theoretical and practical training on cross-cutting topics. Part three provides recommendations for scientists, policymakers, and the private industry to accelerate global CD efforts and responses to achieve SDG 14 in the current decade.

Keywords Capacity development · Ocean science · Ocean observations

15.1 Introduction

The ability of coastal nations to manage their coastal and marine environments is vital in the development and maintenance of national blue economies. To achieve a blue economy, there needs to be economic growth that improves livelihoods and creates more jobs, while sustainably using ocean resources and preserving ecosystem health. Capacity development (or "capacity building") is intended to highlight activities designed to provide education and training for the private sector, the public, scientists, technicians, and policymakers to develop and expand blue economies. Capacity development is a fundamental aspect of "capacity sharing" which refers to the joint efforts of working as a team to achieve capacity development as the common

M. Metian · P. W. Swarzenski
Marine Environment Laboratories, International Atomic Energy Agency (IAEA), Principality of Monaco, Monaco
e-mail: M.Metian@iaea.org

P. W. Swarzenski
e-mail: pswarzen@usgs.gov

S. Seeyave
Partnership for Observation of the Global Ocean (POGO), Plymouth, UK
e-mail: ssve@pml.ac.uk

J. Uku
Kenya Marine and Fisheries Research Institute (KMFRI), Mombasa, Kenya

A. Valauri-Orton
The Ocean Foundation, Washington, DC, USA
e-mail: avalauriorton@oceanfdn.org

objective. Capacity sharing also recognizes that there is valuable local and traditional knowledge that can inform approaches to advance the Sustainable Development Goals (SDGs). The responsibility for capacity development primarily lies with academic institutions, informal education entities like aquaria and museums, government and intergovernmental agencies, and industry (Fig. 15.1). All these sectors require appropriately trained people in all nations, as today the blue economy reaches beyond coastal states. Importantly capacity development also needs to target existing institutions to increase their engagement regionally and globally (Cicin-Sain et al. 2018). Coordination of capacity sharing efforts must therefore be a priority during the UN Decade of Ocean Science for Sustainable Development (hereafter referred to as the "Ocean Decade"), to ensure that coastal nations achieve their capacity development goals and best serve the needs of their own people and of societies everywhere.

The need for expanded and better coordination of capacity sharing efforts is a recurring topic of discussion of UN programs and in other discussion fora. This

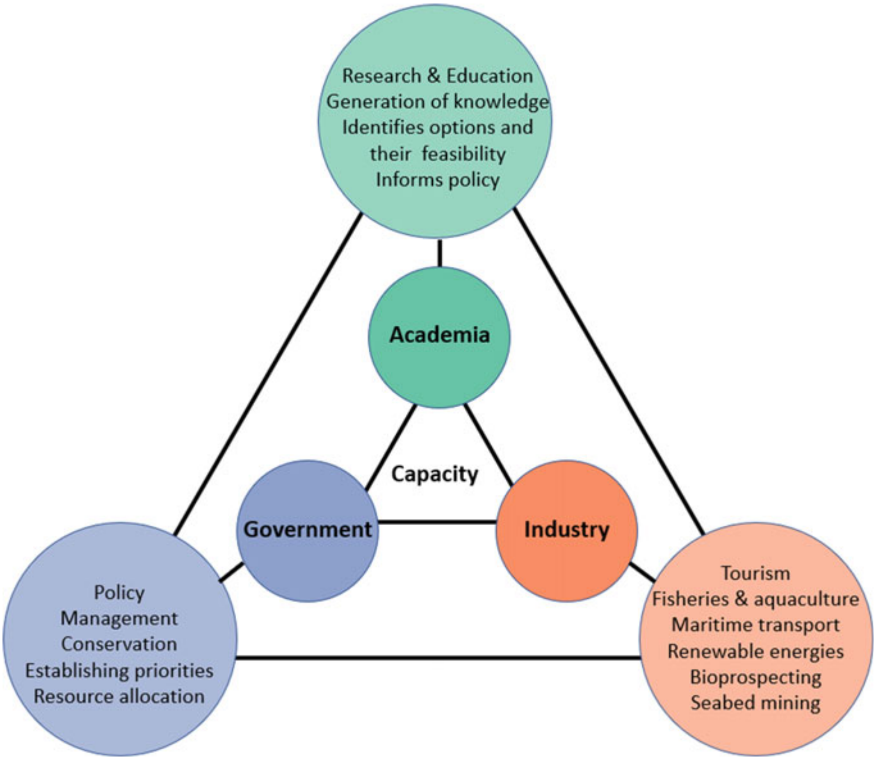


Fig. 15.1 The iron triangle of capacity sharing: Capacity development is generated and required by all sectors, that is academia, governments, and industry. These sectors are interlinked, supporting jobs, the generation of knowledge, and decision making. The stronger the linkages and support among the three vertices, the stronger the blue economy of a particular state

topic is also a key challenge identified for the Ocean Decade: “deliver data, knowledge and technology to all” (IOC 2020). The first World Ocean Assessment noted a gap in capacity for integrated assessment of the marine environment (Inniss et al. 2016). Over the last few decades, the global ocean science community has made great progress in exploring, describing, understanding, modeling, and enhancing current knowledge of the ocean and its processes (e.g., Urban et al. 2020 for understanding of the ocean iron cycle). Recognition by some sectors of society of the fundamental importance of the ocean led to investments in research and development to improve and create new technologies, methods, collaborations, projects, and scientific infrastructure to gain a better understanding of our ocean, adopt effective mitigation and management strategies, improve the ability to predict future ocean changes, and inform policy (Khan et al. 2016; IOC 2019; Urban et al. 2020; Zitoun et al. 2020). However, there are still major geographical disparities in the capacities that exist around the world to achieve SDG 14 (“Conserve and sustainably use the hot oceans, seas and marine resources for sustainable development”) (UNESCO 2017; IOC-UNESCO 2021). Global ocean science capacities are unevenly distributed, and developing countries, including Small Island Developing States (SIDS) and the Least Developed Countries (LDC), are largely disadvantaged as they have inherently weaker institutional capacities, and fewer human and financial resources (Kullenberg 1998; UNESCO 2017; IOC 2019; Zitoun et al. 2020).

Generally, developing countries tend to have a lower capacity to conduct marine research and thus lack in-depth scientific data on which to base policies and develop necessary adaptation and mitigation strategies. As highlighted by the 2020 Global Ocean Science Report (IOC-UNESCO 2021), despite the recognition of the importance of marine science, funding for ocean science, especially in less-developed countries, is largely inadequate (typically <1% of national research budgets). For instance, research and development expenditure (% of GDP) in SIDS UN Member States does not exceed 0.4% of their GDP, a value well below the expenditures of the global scientific powerhouses, such as the United States (2.8%), China (2.2%), United Kingdom (1.7%), and Germany (3.0%) (Zitoun et al. 2020). Since the absolute GDP value is considerably lower in developing countries relative to developed countries, the financial capacity in developing countries is dire. Likewise, the technical capacity, the number of ocean science personnel (researchers and technical staff), and the scientific output remains unequally distributed among countries and regions (IOC-UNESCO 2021) with developing countries largely lagging behind developed countries. For instance, there is a strong correlation between the number of ocean scientists and science productivity (as measured by peer-reviewed publications), since countries with the fewest ocean science personnel commonly also have fewer scientific publications (IOC-UNESCO 2021). The number of published articles in developing countries has to be viewed with care though, owing to the wide practice of ‘parachute science’ in marine research. For instance, according to Stefanoudis et al. (2021) 40% of publications with fieldwork conducted in Indonesia or Philippines exclude host nation scientists from their authorships.

Access to technical infrastructure required for ocean science also remains unequally distributed among developed and developing countries, with countries in the Southern Hemisphere commonly having limited access to ocean science technologies and infrastructure. Only a few science institutions located in developing countries can report information regarding their capacities, highlighting that reporting mechanisms on marine science capacities are also generally lacking (Zitoun et al. 2020). Further, the IOC-UNESCO (2021) report highlights that developing countries are inadequately equipped to manage their ocean data and information in a 'FAIR' way (findable, accessible, interoperable, and reusable), thereby hampering open access, data sharing, the ability to submit data related to SDG 14 indicators, and the capacity of these countries to measure progress towards the achievement of SDG 14 targets, in particular to have indicators for and advance on SDG 14 target 14.a ("Increase scientific knowledge, develop research capacity and transfer marine technology").

The need for intensifying capacity development efforts, especially in SIDS and LDCs, was also highlighted in a 2017 review of the Large Marine Ecosystem (LME) program (Vousden and Scott 2017). Consequently, developing countries need sustained cooperation, international partnership, capacity development efforts, and resource sharing to develop their own innovative solutions, scientific research, and new technologies to produce the data they need for the ocean they want, in line with their nationally identified ocean-related priorities (UNFCCC 2005; UN-OHRLLS 2015; IOC-UNESCO 2021; Zitoun et al. 2020). Hence, capacity development is a key element in current negotiations under the United Nations Convention on the Law of the Sea (UNCLOS) to develop a legally binding implementing agreement to conserve and sustainably use marine biodiversity in Areas Beyond National Jurisdiction (Cicin-Sain et al. 2018). Capacity development is also vital for robust management and regulation of emerging and potentially impactful ocean activities such as deep-sea mining and geoengineering (Bradley and Swaddling 2016; Bourrel et al. 2017). The gaps in academic and research infrastructure required for capacity sharing and capacity development among nations is highlighted in detail in the 2020 Global Ocean Science Report (IOC-UNESCO 2021).

In this chapter, we provide a synthesis of the existing global initiatives that build the foundation for capacity development for ocean sciences (Information), showcase lessons learned from case studies and successful stories from training programs (Integration), and provide examples of pathways to improve capacity in ocean science and technology in the current decade (Innovation).

15.1.1 Making the Case for the Need of Capacity Development to Achieve Blue Economies

The current state of ocean science capacity, where the most vulnerable regions have the greatest gaps in capacity, limits the growth and benefits of sustainable blue economies.

Within an international framework, the United Nations Sustainable Development Goal 14 (SDG 14: Life Below Water) is underpinned by ten targets that address the conservation and sustainable use of the ocean, seas, and marine resources (United Nations 2015; Sturesson et al. 2018). Seven of the targets are ‘outcome targets’ and include reducing marine pollution; protecting and restoring ecosystems; reducing ocean acidification; achieving sustainable fishing; conserving coastal and marine areas; ending subsidies contributing to overfishing; and increasing economic benefits from sustainable use of marine resources (United Nations 2015). The other three targets are means of achieving the seven outcome targets, and include increasing scientific knowledge, research, and technology for ocean health; supporting small-scale fisheries; and implementing and enforcing international sea law. SDG 14 is closely intertwined with most other SDGs, including Ending Poverty (SDG 1), Ending Hunger (SDG 2), Good Health and Well-Being (SDG 3), Climate Action (SDG 13), and Creating Decent Work and Economic Growth (SDG 8) (Claudet et al. 2019). Addressing sustainable uses and conservation of ocean spaces, resources, and marine life is thus critical for an integrated approach to achieve the SDGs by 2030 (Schmidt et al. 2017; Ntona and Morgera 2018; Sturesson et al. 2018; Singh et al. 2018).

To address these targets and tackle the challenges of a changing ocean and a dynamic global society, we collect ocean information at local to global scales in several ways (see Chap. 14 on Observations). Perhaps the most advanced sharing of information and capacity is demonstrated by the weather agencies of every nation. The paradigm established in the mid-1900s of standardizing, curating, and openly sharing weather information around the world led to a revolution in basic and applied research that has yielded significant benefits to the academic community (publications, grants, students), and has benefited merchant and navy mariners, diverse industry sectors, non-governmental institutions, local and indigenous groups, and the public through improved weather and climate prediction. The identification of a limited set of important atmospheric variables to observe led to the concept of Essential Climate Variables (Bojinski et al. 2014).

All sectors seek to derive some form of information to test concepts and to develop forecasts and solutions based on their own scientific processes. A goal is therefore to learn from the process that led to the formation of a global weather monitoring system through individual national and local contributions, and implement for the ocean a similar human, observing, and forecasting capacity for integrated biological, biogeochemical, physics, and socio-economic variables and processes. The Ocean Decade (2021–2030) provides this framework. The Ocean Decade facilitates international cooperation, helping to further connect ocean science with societal needs, which are changing more rapidly than our traditional, rather siloed disciplinary approaches have been able to accommodate. Addressing these needs is possible today because there are common information requirements of societies around the world that may be solved by co-designing, co-developing, and strategic pairing of ocean research and technology capacity (Canonico et al. 2019). This new multi-disciplinary framework offers an opportunity to co-design strategies from their conceptualization to their implementation and thus move toward more equitable access to ocean knowledge, with benefits for all.

Much emphasis is now devoted to the participation of groups that have traditionally been disadvantaged or excluded from ocean research, that is, developing countries, indigenous people, and early career researchers, to understand problems and co-develop solutions. In 2021, the Ocean Decade endorsed an Early Career Ocean Professionals (ECOP) Programme as an informal Working Group intended to incorporate new ways of thinking into global ocean sustainability and stewardship challenges through engagement of diverse participants, in terms of gender, culture, age, career stage, and other dimensions of social diversity. The ECOP Programme helps many early career programs initiated by different organizations to collaborate. The vision of the ECOP Programme is to elevate and strengthen the diverse perspectives of new generations of ocean professionals to achieve a collective voice, ensuring that knowledge is transferred between experienced and early-career ocean professionals, to promote ocean sustainability for "The Ocean We Want" and help create the ocean leaders of tomorrow.

15.1.2 The Special Case of Small Island Developing States (SIDS) (See also Chap. 13)

The importance of capacity development in developing countries, especially SIDS, is recognized by the 2030 Agenda for Sustainable Development via mean 14.a (IOC-UNESCO 2021), the Ocean Decade (2021–2030) (IOC 2019), and other international frameworks such as the SIDS Accelerated Modalities of Action (SAMOA) Pathway (SAMOA Pathway 2015; Zitoun et al. 2020). The Ocean Decade, for instance, highlights the necessity to build the scientific and institutional capacity to generate scientific knowledge for best science-based management of our ocean and its resources, and thus increase the ability to better inform policy (IOC 2019). All frameworks highlight that SIDS remain a special case for sustainable development, recognizing that SDG 14 is one of the most critical goals for SIDS whose societies, cultures, livelihoods, and economies are inherently linked with a healthy, productive, and resilient ocean (SAMOA Pathway 2015; IOC 2019).

SIDS are a distinct group of maritime countries, territories, and island nations that tend to share some similar sustainable development challenges, such as small size, geographical remoteness, narrow resource base, low-lying coastal territories, concentration of population along coastal zones, growing coastal populations, high volatility of economic growth, dependency on external markets and international assistance, susceptibility to natural disasters (i.e., cyclones and tsunamis) and high vulnerability to the impacts of climate and external shocks (UN-OHRLLS 2015). The SIDS group comprises 38 UN Members and 20 Non-UN Members or Associate Members of Regional Commissions situated in the tropics and low-latitude subtropics across three geographical regions: the Caribbean; the Pacific; and the Atlantic and Indian oceans, and South China Sea (AIS) (UN-OHRLLS 2015).

Although SIDS are geographically dispersed and have diverse social and economic structures, they face similar social, economic, and environmental challenges (World Health Organization 2017). Of particular concern to SIDS are the marine risks associated with climate change and anthropogenic impacts. SIDS are highly dependent on marine resources and associated coastal and marine ecosystem services, and thus are particularly vulnerable to the effects of human and climate change impacts on marine life and human health, including pollution, intensified natural disasters, water resource scarcity, rising sea levels, and the impacts of overuse and depletion of non-living, non-renewable resources (World Health Organization 2017; see other chapters of this book). These vulnerabilities must be recognized, understood, and addressed for sustainable development to be realized in SIDS. However, despite their similar challenges, SIDS do not easily fit into standard solution models since each SIDS has its own social, cultural, economic, and environmental priorities, different adaptive capacities and capabilities, and vulnerabilities (Nurse and McLean 2014; Sjöstedt and Povitkina 2017; Zitoun et al. 2020). Therefore, effective capacity development and adaptive strategies for marine challenges in SIDS must be custom tailored for each SIDS, addressing each country's specific goals and needs.

Current information shows that more capacity is urgently needed in SIDS to enhance their education (SDG 4—Quality Education), human, research, and infrastructure capacities to help them achieve their SDGs, especially regarding SDG 14. Both UNESCO (2016) and the SAMOA Pathway highlight that quality education, and human and institutional capacities are indispensable elements for achieving sustainable development in SIDS and thus these features should be part of any strategy to achieve socially, culturally, politically, economically, and environmentally sustainable development, the hallmarks of blue economies. All SDGs are interdependent and can only be achieved if tackled and implemented together, reinforcing each other (UNESCO 2016). The importance of research capacity and infrastructure in SIDS has been recognized globally, and national and international organizations, including the United Nations, have accorded priority to this need, as reflected by SDG 4 and several other initiatives, such as UNESCO's Sandwatch Project and the IAEA's Technical Cooperation Programme (TCP). Taken together, capacity development in SIDS is necessary if a sustainable global blue economy is to be achieved by 2030, with developing countries becoming equal partners in addressing global ocean challenges.

15.2 Part I: Building the Foundation of Capacity Development for Ocean Sciences

Information is a driver for improvement. Managers and policy makers require good data that can only be acquired by properly trained people collecting reliable measurements, following the mantra "you can't manage what you can't measure". Linking capacity development to sustained monitoring activities through existing observing networks will allow for recently trained individuals to consolidate and expand their knowledge (Miloslavich et al. 2018b; Bax et al. 2018). Some examples of this approach include multilateral organizations such as the Intergovernmental Oceanographic Commission (IOC) of UNESCO, the Scientific Committee on Oceanic Research (SCOR), the Partnership for Observation of the Global Ocean (POGO), the International Atomic Energy Agency (IAEA), and the Convention on Biological Diversity (CBD), as well as international initiatives such as the Global Ocean Acidification-Observation Network (GOA-ON), the Large Marine Ecosystems (LME) program, the Regional Seas program of the United Nations Environmental Program (UNEP) and the Ecologically and Biologically Significant Areas (EBSAs) initiative. These organizations and programs are involved in global capacity development activities for ocean science and can help countries build the necessary capacity via resources, guidance, scientific mentorship, training, workshops, summer schools, scholarships, and financial support. Regional capacity development responses are provided by groups such as the Western Indian Ocean Marine Science Association (WIOMSA), the Secretariat of the Pacific Regional Environment Programme (SPREP), and the Caribbean Community Climate Change Centre (5Cs). Capacity development activities are also offered by universities, NGOs, and various community initiatives. However, despite the importance of coordinating among these efforts nationally and internationally, these initiatives are out of the scope of this chapter.

15.2.1 Global Capacity Development Initiatives

15.2.1.1 The Intergovernmental Oceanographic Commission (IOC) of UNESCO

The Intergovernmental Oceanographic Commission (IOC) of UNESCO has a unique role in the United Nations (UN) system in relation to ocean science and the science base for ocean and coastal management. It is recognized through the UN Convention on the Law of the Sea (UNCLOS) as the competent international organization in the fields of Marine Scientific Research (Part XIII) and Transfer of Marine Technology (Part XIV). Capacity development is an essential tenet of IOC's mission: it enables all Member States to participate in and benefit from ocean research and services that are vital to sustainable development and human welfare on the planet. The IOC's Capacity Development Strategy (https://www.ioc-cd.org/) identifies capacity development as the primary catalyst through which IOC will achieve its high-level objectives related to ocean health and sustainability, effective warning systems, resilience to climate change and enhanced knowledge of ocean issues. To meet these objectives, IOC undertakes—through international collaboration—relevant actions to assist Member States with developing and sustaining the necessary capacity to conduct activities necessary to achieve the IOC vision at national and international levels.

The IOC's Capacity Development strategic framework provides six outputs and several activities. These outputs call for investing in people and the institutions of which they are a part, enhancing access to scientific tools and methodologies, reinforcing IOC's capabilities to provide services to Member States, enhancing the communication between scientific and policy maker communities, expanding ocean literacy in civil society and mobilizing resources to accomplish these goals. These outputs include, among others (1) Human Resources developed (including promoting higher education and continuous professional development in ocean sciences as well as promoting and assisting with the establishment of training and research centers and promoting the coordinated sharing of training resources), (2) Access to physical infrastructure established or improved, and (3) Development of ocean research policies in support of sustainable development. IOC's Capacity Development Strategy is further elaborated and implemented through its Global Ocean Observing System (GOOS), International Oceanographic Data and Information Exchange (IODE) including the Ocean Biodiversity Information System (OBIS), Tsunami Warning and Mitigation, Harmful Algal Blooms (HAB), Coastal Zone Management and Marine Policy, etc., and regional programs (IOC Africa, IOC Caribe and WestPac). The IOC Group of Experts on Capacity Development conducts global baseline surveys of capacity needs and is working to develop a clearing-house mechanism to link needs to available resources (IOC-UNESCO 2021). The 2020 Global Ocean Science Report (GOSR, IOC-UNESCO 2021) is an important IOC activity that documents the current state of national ocean science capabilities in the Global Ocean Science Report series. Investment in ocean research currently ranges from a low of 0.03% to a high of 11.8% of individual countries' research budgets (average 1.7%). It is anticipated that the many and diverse programs and other actions announced by the Ocean Decade, all of which include and contribute to global capacity sharing and capacity development needs, will help prioritize investment in ocean research (https://www.oceandecade.org/resource/166/Announcement-of-the-results-of-the-first-endorsed-Decade-Actions-following-Call-for-Decade-Actions-No-012020). The capacity development initiatives carried out by the IOC are summarized below.

OceanTeacher Global Academy (OTGA)

IODE started organizing ad hoc training courses for the National Oceanographic Data Centres (NODCs) in the early 1990s to fill a gap in formal training on ocean data and information management. Soon after, the IODE started developing a ResourceKit distributed on a compact disk compiling training resources, software and other resources. With the rapid development of information communications technology, IODE launched the OceanTeacher website in 2001. In 2009, the OceanTeacher Academy project started with support from the Government of Flanders (Belgium), and a regular portfolio of courses related to ocean data and information management was organized at the IODE offices in Oostende, Belgium. In 2013, a review of the OceanTeacher Academy resulted in a number of recommendations: (1) need to train more students from each country, (2) need to reduce travel of students and lecturers, (3) need to provide training in local languages, (4) need to focus more on local issues and case studies, and (5) need to make the (e-learning) platform available to other IOC programs. A new phase for OceanTeacher Global Academy (OTGA) started in 2014, based on two main pillars: (1) a single e-learning platform promoting the sharing and co-designing of training courses in several languages, and (2) a network of Training Centres enabling training in locally relevant languages and bringing in local expertise to work on relevant case studies. Building on its experience, OTGA now aims to further develop the collaborative network of training centers that share education and training materials, staff and technical expertise, and provide cost-effective education and training services for the needs of IOC Member States and other stakeholders.

OTGA currently includes new initiatives and challenges, for example, the 2030 Agenda and its SDGs and the Ocean Decade. Besides being a fundamental tool for the implementation of the IOC Capacity Development Strategy, OTGA supports several international processes. The network of Training Centres includes Regional (region-focused) and Specialized (topic-focused) Training Centres. Training topics also include tools that can help Member States achieve the SDGs as well as emerging topics such as Ocean Acidification and Blue Carbon. Some of the IOC programs that have training activities supported by the OTGA are the Global Ocean Observing System (GOOS) and the Ocean Biodiversity Information System (OBIS). Within OTGA, new, ready-to-deliver courses are being made available online. The e-Learning Platform is an essential component of OTGA. As a fully-fledged Learning Management System (LMS), it facilitates face-to-face classroom learning, blended learning, and online learning. All training course contents are hosted on the Ocean Teacher e-Learning Platform. It also allows the use of different languages for training; currently, OTGA has courses in four different languages (English, Spanish, French, Portuguese). Content is freely available during and after courses (Creative Commons Attribution 4.0 license), although registration on the OceanTeacher platform is mandatory. OTGA fosters collaborations beyond UNESCO/IOC-IODE to position itself to become the 'training hub' for ocean sciences, including topics related to the management of the impact and interactions with human activities.

Ocean Best Practices System (OBPS)

The OBPS is a global, sustained system comprising technological solutions and community approaches to enhance management of methods as well as support the development of ocean best practices. Coordinated methodologies, including guidelines, policies, standard specifications, and methods enable comparability among regions and scales, and increase the user base to other stakeholder groups. Equally important is developing these methodologies following the 'findability, accessibility, interoperability, and reusability' (FAIR) principles (Wilkinson et al. 2016). These principles improve discoverability and sharing of knowledge, enable harmonization of data, and promote the evolution of "Best Practices" (Pearlman et al. 2019; Horstmann et al. 2020). However, methods, best practices, and information, by themselves, do not increase our ability to use and adopt them. Capacity development efforts are needed for the global community to understand the importance of best practices and learn to apply the appropriate methods. Additionally, capacity development needs to incorporate decision-makers to ensure that the information is used in a wise manner.

The Ocean Practices for the Decade was endorsed by the Ocean Decade to support all ocean stakeholders in securing, equitably sharing, and collectively advancing this methodological heritage. This program builds on the Ocean Best Practices System (OBPS). OBPS is a facility at the service of the ocean observing community that makes methods visible, discoverable, and available for all. It ensures that methods are kept in a persistent repository. It also supports the development of best practices by the community (Pearlman et al. 2019). The OBPS is underpinned by technology that allows content discovery and management through fine-scale indexing via text-mining and ontology-based semantic search tools (Buttigieg et al. 2019). In addition to the repository, the OBPS includes peer-reviewed journal research topics. It provides training programs that use many online tools and it leverages a collaboration with the OTGA (Pearlman et al. 2019). The IOC-OBPS initiative is ready and available to support capacity development. It embraces online training for and by the community. Important priorities now include developing strategies tailored to address local needs (see Simpson et al. 2021). Where possible, training would use open resources to enable trainers to adapt to their local needs or for self-learning.

There are many challenges concerning the development, availability and use of best practices. Among them is the small value and incentive given to publishing of complete methods for advancing professional advancement in scientific research (Pearlman et al. 2021). Other important challenges include traceability of the methods, language barriers, fragmentation of methodological archives and management systems.

Capacity development can help address some of these challenges. Through capacity development we can highlight the value of documenting methodological know-how and incentivize the production of documentation that is archived and served by sustained and secure open-access repositories. These processes support reproducibility, build trust, and enable knowledge transfer.

Global Ocean Observing System (GOOS)

GOOS is a sustained collaborative system of observations of Essential Ocean Variables (EOVs), encompassing in situ networks and satellite systems, implemented by national governments, UN agencies and individual scientists operating under the Framework for Ocean Observations (FOO) developed by the global ocean observing community in 2009 (Tanhua et al. 2019). GOOS works by fostering and facilitating international collaboration in ocean observations, building expert teams, developing ocean observing capacity, and providing guidance and incentives for researchers to systematize and share their measurements. GOOS covers the areas of physics, biogeochemistry, and biology and ecosystems.

GOOS supports end-to-end best practices in ocean observation and has an endorsement mechanism for best practices available within the OBP repository. GOOS is also facilitating training courses through the OTGA. GOOS is a major contributor to the Ocean Decade through several transformative programs that integrate efforts from other Ocean Decade programs and activities, and that seeks to unite the community to address issues of societal relevance. Additional Ocean Decade programs that have roots in GOOS include the Observing Air-Sea Interactions Strategy (OASIS), the Deep Ocean Observing Strategy (DOOS), and the Ocean Practices for the Decade. Marine Life 2030 (ML2030) and the Ocean Biomolecular Observing Network (OBON) are also Ocean Decade programs that are fully integrated with GOOS, and which together seek to transform ocean biology and ecosystem observations. The ForeSea program will turn observations into actionable information by extending ocean prediction capacity of the future. Ultimately, the aim is to build the process, infrastructure, and tools for co-design, creating an international capacity to evolve a truly integrated ocean observing system, matching agile observing and modelling capability with requirements. These action points will provide the largest possible impact from investments. The EOV framework provides a focus for the collection of standardized measurements and interoperability of information to address specific societal problems. Close collaboration between GOOS and other ML2030 partners, including the Marine Biodiversity Observation Network (MBON) of the Group on Earth Observations BON (GEO BON) seeks to develop higher level time series of maps of biodiversity metrics called Essential Biodiversity Variables (EBVs) based on collections of biological EOVs (Miloslavich et al. 2018a; Muller-Karger et al. 2018). GOOS is working with OBIS to ensure that all relevant information on the biological EOVs is available through OBIS.

15.2.1.2 Scientific Committee on Oceanic Research (SCOR)

The approach of the Scientific Committee on Oceanic Research (SCOR) to capacity development has been focused primarily on training individual ocean scientists and graduate students from developing countries to improve their scientific skills and on creating networking opportunities between scientists from developed and developing countries (Urban and Boscolo, 2013). SCOR's focus does not extend to building institutions, addressing national conservation or broader goals, although training scientists and facilitating networks should make it easier to achieve such goals. Since 1984, SCOR has promoted networking by supporting scientists from developing countries to attend scientific conferences to present their research results. SCOR also promotes networking by involving developing country scientists in every SCOR activity, such as working groups and large-scale research projects. Some global SCOR-supported research projects (GEOTRACES, IMBeR, and SOLAS) conduct summer schools on a regular basis to teach ECOPs from both developing and developed countries techniques needed to achieve the scientific goals of the respective projects (see Box 15.1 in next section). Finally, SCOR's more regional support of Research Discovery Camps at the University of Namibia brings together students and scientists from Namibia, other African countries, and beyond to study aspects of the Namibian sector of the Benguela Current System to learn research techniques. These intensive efforts often develop scientific collaborations that extend through an ECOP's career. SCOR supports in-country training in developing countries to reach a greater number of trainees in their home areas on topics relevant to local research questions, through the SCOR Visiting Scholar program (Urban and Seeyave 2021). SCOR also partners with the Partnership for Observation of the Global Ocean (POGO) consortium to support a training program to develop skills in ocean observations for developing country students and scientists.

Box 15.1 Scientific Committee on Oceanic Research (SCOR) project summer schools

Three SCOR-sponsored research projects regularly convene summer schools:

GEOTRACES: The GEOTRACES project, which focuses on documenting the distributions of trace elements in the ocean and understanding the processes controlling these distributions, has held two summer schools so far, in Plouzané, France (2017) and Cadiz, Spain (2019). The third summer school was held in 2022. The first two summer schools involved 99 trainees from 23 countries. The schools have lasted 6–7 days. GEOTRACES summer schools aim at teaching the skills and knowledge necessary for a good understanding of the biogeochemical cycles of trace metals and include shipboard work. Participants are trained in sampling marine trace elements on ships, sample processing, data validation, visualization, and a perspective on modelling with such data.

SOLAS: The Surface Ocean-Lower Atmosphere Study (SOLAS) is a global and multidisciplinary research project that aims to understand the key biogeochemical-physical interactions and feedbacks between the ocean and atmosphere, which in academic departments and journals are often separated. SOLAS has held 7 summer schools since 2003, involving 491 trainees from 46 countries. Most of these events have been held in Corsica, France, although they have also been held in Xiamen, China. In 2022, SOLAS will organize a virtual-mini school and in 2023 the school will be held in Cape Verde. SOLAS summer schools have always included shipboard experience. Several of the students from early summer schools have gone on to become leaders in the SOLAS project later in their careers. SOLAS is unique among the projects in having produced a textbook for its course (Le Quéré and Saltzman 2009).

IMBeR: The Integrated Marine Biosphere Research (IMBeR) project brings together researchers who study processes from the base of marine food webs to human interactions with the ocean environment, as well as marine law and policy and human well-being. IMBeR has held 6 ClimEco summer schools since 2008, involving more than 355 trainees from 63 countries. The focus of IMBeR summer schools has always been interdisciplinary. In the early years, the focus of the schools was on how biogeochemical cycles and ecosystems influenced each other, and how to model such interactions. As IMBeR evolved, the summer schools also evolved to focus on interactions between natural and social sciences in the ocean and also the science-policy interface. IMBeR summer schools have been held in several different locations, depending on offers from local hosts, including Ankara, Turkey (2008, 2012); Brest, France (2010); Shanghai, China (2014); Natal, Brazil (2016); and Yogyakarta, Indonesia (2018). The 2020 summer school that was due to be held in Vancouver, Canada was postponed to 2021 and was held virtually. IMBeR summer schools have lasted 5–8 days each. They usually involve about 10 lecturers who attend the entire summer school. Since 2012, the number of participants (MSC and PhD students and postdocs) has been between 60 and 70 for each event, as it has been found to be a good ratio of lecturers: participants to ensure good interactions and discussions. Usually more than 250 applications are received for each event.

15.2.1.3 Partnership for Observation of the Global Ocean (POGO)

Over the last 20 years, the Partnership for Observation of the Global Ocean (POGO) has developed an extensive array of training programs targeted primarily at ECOPs from developing countries. In 2001, POGO established a Visiting Fellowship program, initially in partnership with IOC and SCOR, and which continues currently in partnership with SCOR. The Nippon Foundation has been a major sponsor of POGO capacity development since 2004, particularly through the establishment of the NF-POGO Centre of Excellence in Observational Oceanography (https://pogo-ocean.org/capacity-development/centre-of-excellence/), now hosted by the Alfred-Wegener-Institute (AWI) Helmholtz Centre for Polar and Marine Research (http://www.awi.de/). Of equal importance is the continued support POGO provides to its alumni, particularly through the NF-POGO Alumni Network for Oceans (NANO) (https://nf-pogo-alumni.org/) and its collaborative ocean observation projects (https://nf-pogo-alumni.org/projects/). POGO maintains a database of all its alumni and evaluates the impacts of the training provided through surveys sent to the alumni five years after the training, to gather feedback on how the knowledge and skills gained have supported their career development and how they have passed these on to their peers and/or students. POGO also recognizes that new technologies, and the emergence of low-cost technologies for ocean observing, can provide solutions to enhance ocean observations in developing countries and fill current gaps in data coverage. To this end, POGO is funding two projects on developing low-cost sensors for coastal monitoring: the Open Access Marine Observation Devices (OpenMODs, https://pogo-ocean.org/innovation-in-ocean-observing/activities/openmods-open-access-marine-observation-devices/) and the citizen science project Social AGITation for Temperature Analysis (SAGITTA).

15.2.1.4 International Atomic Energy Agency (IAEA)

The International Atomic Energy Agency's (IAEA) Monaco-based Environment Laboratories were established in 1961 as part of the IAEA's Department of Research and Isotopes and are the only marine laboratories within the UN system. The core mandate of the IAEA laboratories is to develop and transfer modern nuclear science, technology, and knowledge to help countries address the effects of climate and anthropogenic change on the ocean, its ecosystems, and its adjacent communities. A key goal of the IAEA laboratories is to support IAEA's Member States in fulfilling their obligations in the framework of global conventions, including relevant nationally identified targets under SDG 14 (Life Below Water) and the SAMOA Pathway. Accordingly, the Agency assists its Member States in better understanding, monitoring, and protecting the marine environment to address key marine challenges, such as microplastics, ocean acidification, pollution (e.g., persistent organic pollutants, hazardous trace elements, and marine biotoxins), sustainable aquaculture, and sea level rise (Betti 2008). The IAEA laboratories develop capacities for Member States through various mechanisms, including the IAEA's Technical Cooperation Programme (TCP), Coordinated Research Projects (CRPs), and Peaceful Uses Initiative (PUI) projects such as the Ocean Acidification International Coordination Centre (OA-ICC). The OA-ICC and its global partners have been involved in more than 850 capacity development opportunities with 750 scientists from more than 100 Member States since the project's inception in 2012. These efforts support IAEA Member States to build, strengthen, and maintain human expertise and institutional capacities to help (1) define national needs; (2) make informed decisions on action plans and measures to protect the ocean; (3) assure the sustainable delivery of ecosystem services; and (4) ensure sustainable social and economic development. Currently, there are close to 50 TCP projects and CRPs that the IAEA Monaco-based laboratories implement which also involve many SIDS Member States.

15.2.1.5 Convention on Biological Diversity (CBD)

Sustainable Ocean Initiative (SOI) of the CBD

The Sustainable Ocean Initiative (SOI) is coordinated by the CBD Secretariat to provide training and capacity development to developing countries in support of their progress towards the Aichi Biodiversity Targets. It has raised awareness of the different tools and opportunities available to implement effective marine conservation actions in national waters, encouraged inter-ministry dialogue, and motivated local stakeholders and community groups to engage in such efforts.

The SOI Global Dialogues (2016 and 2018) have brought together experts from the CBD, Regional Seas Organizations, Regional Fisheries Bodies, relevant United Nations/international organizations/initiatives as well as experts from national governments and agencies, and non-governmental organizations to work on increased collaborations, creating the enabling conditions for sectors that often seem opposed.

Participants at these meetings have acknowledged the diversity of experiences, challenges, priorities and capacities among countries and regional organizations, and emphasized the need for capacity development activities in support of cooperation at the regional level (Tittensor et al. 2014). The critical importance of national-level coordination in facilitating regional-level cross-sectoral cooperation and coordination was also underlined (Seoul Outcome: www.cbd.int/soi).

Ecologically or Biologically Significant Areas (EBSAs) Initiative of the CBD

An EBSA is an area of the ocean from the coastline to deep ocean trenches that has special importance in terms of its ecological and/or biological characteristics (Dunstan et al. 2016). More than 300 of these special marine areas have been described around the world in the last decade, through highly collaborative regional meetings that brought together over 500 scientists, and key data holders from a range of stakeholder organizations, including governments, intergovernmental and non-governmental organizations, research institutions, and indigenous peoples and local communities (SCBD 2021). The EBSA process has drawn attention to these special areas in 75% of the ocean to date and identifies measures that may be needed to safeguard biodiversity assets, either through further scientific research, awareness raising among local communities, and/or better management of human activities. The process has been a global catalyst for regional collaboration, drawing together experts from different fields, organizations, and communities to strengthen national capacity, regional cooperation, and scientific understanding. Information from the regional workshops has stimulated national and regional conservation and management efforts as well as progress towards the Aichi Biodiversity Targets.

EBSAs have also helped to strengthen the ocean science base by focusing research efforts, building scientific capacities, and raising awareness. The EBSA process has exposed knowledge and data gaps, highlighted skills shortages in different scientific disciplines, such as taxonomy, and has helped focus new scientific research into areas of the ocean about which we know far too little. More than 100 global datasets built to support the EBSA process have been made available to country participants in easily accessible formats to help build their scientific capacity.

15.2.1.6 Global Ocean Acidification Observing Network (GOA-ON)

The Global Ocean Acidification Observing Network (GOA-ON) is a collaborative international network of 800 members representing 105 nations. GOA-ON assisted the IOC Sub-Commission for the West Pacific (WESTPAC), supported by the U.S. National Oceanic and Atmospheric Administration, to develop capacity through establishing an interdisciplinary observing network to monitor the ecological impacts of ocean acidification on coral reefs. WESTPAC works closely with countries of Southeast Asia and the Coral Triangle. Developing local capacity was supported by engaging with GOA-ON to provide consistent, comparable, and cost-effective standard operating procedures, documented as EOVs, that built on existing regional capacity and programs. These were introduced and tested in the laboratory and at pilot sites through a series of regional and national training and scientific workshops, including the transfer of knowledge and technology among experts and institutions within and outside the region. Workshops continue to review the lessons learned from implementing the agreed approach while identifying partnership building opportunities to further expand the program and associated research opportunities. GOA-ON has continued its capacity development activities, providing sensor kits to scientists in Fiji, Mauritius, Mozambique, Seychelles, South Africa, and in several Caribbean nations and through creating international networking opportunities for early-career and experienced scientists through the GOA-ON Pier2Peer program (http://goa-on.org/GOA-ON_Pier2Peer.html) that reported 128 matches in early 2021 (https://oceanconference.un.org/commitments/?id=16542). In September 2020, GOA-ON organized the Ocean Acidification Week, an online multi-day forum on ocean acidification research and initiatives and has instituted a webinar series to continue to expand collaboration during the global pandemic.

15.2.1.7 Large Marine Ecosystem (LME) Program

The Large Marine Ecosystem (LME) approach focuses on five areas of changing LME status: productivity, fish and fisheries, pollution and ecosystem health, socioeconomics, and governance (Sherman 1993, 2014). It pulls together multiple layers of governance from all jurisdictions within the LME through a Transboundary Diagnostic Analysis (TDA) followed by a Strategic Action Plan (SAP) to identify priorities for action through integrated marine spatial planning considerations with 5-year approvals (and an optional second 5 years), typically signed off at ministerial level (GEF LME:LEARN 2017).

Noting that 37% of the world population lives around LMEs, sustainable use of resources has a role in contributing to several SDGs, especially those relating to reducing hunger (SDG 2), reducing poverty (SDG 1) and improving the ocean (SDG 14). Yet, LME assessments are constrained by limitations in the availability and quality of data and recommended appropriate research, monitoring, and observing programs, including assessments at sub-LME scales where necessary to address pressures (and/or their causes) at appropriate scale.

More formal regional coordination mechanisms and improved translation of scientific results into policy, including through adaptive management, is recognized as part of a critical need for capacity for developing countries in relation to ocean and coastal management and ecosystem-based management (EBM) (UNDP 2017).

15.2.1.8 United Nations Environmental Program (UNEP) Regional Seas Program (RSP)

Launched in 1974, UNEP's Regional Seas Program (RSP) consists of 18 Regional Seas Conventions and Action Plans (RSCAPs) covering 146 countries; seven RSCAPs are hosted by the UN Environment Programme (UNEP). The RSP is UNEP's most important regional mechanism for conservation of the marine and coastal environment that brings together stakeholders including governments, scientific communities, and civil societies. A review of the RSP (UNEP 2020) highlights the "unique position" of Regional Seas Conventions and Action Plans to provide regional-scale coordination for reducing threats, considering the trans-boundary commitments of EBM. In-place governance mechanisms, including legal arrangements, regional convening power, and extensive expert networks were seen as important contributions of the RSP to improved EBM.

While most RSCAPs carry out regular assessments of the state of the marine environment, priorities and activities vary in relation to a region's environmental challenges and its socioeconomic and political situation (UNEP 2014), although the ecosystem approach is clearly promoted. Regional alliances could be improved through increased collaboration with the LME program and regional fisheries bodies. Around half of the RSCAPs have signed Memoranda of Understandings with regional fisheries bodies, including as a response to the Sustainable Ocean Initiative of the Convention on Biological Diversity (UNEP 2020). The RSP and RSCAPs are key elements of UNEP's Global Programme of Action for the Protection of the Marine Environment from Land-Based Activities. Communication/education, training, monitoring, and assessment are some of the priority issues covered by RSCAPs.

15.2.2 Regional Capacity Development Initiatives

15.2.2.1 Western Indian Ocean Marine Science Association (WIOMSA)

The Western Indian Ocean Marine Science Association (WIOMSA) is one of the largest associations of marine scientists in Africa. Members are drawn from the ocean scientific communities of 10 countries: Comoros, Kenya, Madagascar, Mauritius, Mozambique, Reunion (France), Seychelles, Somalia, South Africa,, and Tanzania.

Since its inception, WIOMSA has been largely funded through the Swedish International Development Cooperation Agency (SIDA). This funding has been channeled into competitive grants designed to build capacity of ocean scientists from the WIOMSA member states. The grants include Marine Research Grants (MARG) (960,000 USD from 2018 to 2021) that are awarded to young scientists to larger multi-disciplinary Marine Science for Management (MASMA) grants (6,160,000 USD from 2013 to 2021). These grants have been used to support MSc and PhD projects and to incorporate mentoring through collaborations between older and younger scientists within the funded projects. The outputs from these grants have included technical reports, publicity materials and policy interventions that have been adopted by countries of the region.

15.2.2.2 Caribbean Community Climate Change Centre

The Caribbean Community Climate Change Centre, operated by the Caribbean Community (CARICOM) and functional since 2004, is the only regional institution established to address the impacts of climate change. As a Centre of Excellence, the Centre aims to address the impact of climate variability and change on all aspects of economic development by providing timely forecasts and analyses of potentially hazardous impacts of both natural and human-induced climatic changes on the environment. The Centre also develops and supports education programs at all levels (e.g., school children, university students, policy makers, citizens) including training courses for different organizations and levels of management on climate change-related issues. These include technical areas like the use of climate models, capacity development in the assessment and monitoring of climate impacts and use of tools developed by the Centre.

15.2.2.3 Secretariat of the Pacific Regional Environment Programme (SPREP)

The mission of the Secretariat of the Pacific Regional Environment Programme (SPREP) is to promote cooperation in the South Pacific Region and to aid in protecting and improving the environment, ensuring sustainable development for present and future generations. It began its activities in the late 1970s as a component of the UNEP's Regional Seas Programme but became independent as an intergovernmental organization in 1993. The Secretariat acts as a clearinghouse of information and knowledge to ensure that essential technical and scientific information, and traditional knowledge is available to the members. The SPREP works around five organizational goals, of which continuous capacity development is a key activity. In addition to a variety of online resources (e.g., the Virtual Library), the SPREP also offers online courses through its Inform E-Learning platform (e.g., Environment Data Management and Reporting).

15.3 Part II: Lessons Learned from Case Studies—Success Stories

Capacity development and capacity sharing can take many forms. Face-to-face courses, summer schools, ship-based courses, and day- or week-long sessions can introduce methods, hands-on experience and ocean knowledge. However, they may be limited in their geographic outreach and number of trainees (Pearlman et al. 2021). Recorded and written materials, Massive Open Online Courses (MOOCs), mentoring and peer-to-peer training, internships in laboratories, and field work can all become part of a mix of capacity development activities that the ocean science community can undertake to improve our know-how knowledge base (Simpson et al. 2021). We focus on scientific training here while recognizing the equal importance of institutional capacity development.

MOOCs and online training represent an opportunity for global reach and wider access. Progress in communication technology and the increased use of mobile technologies allow large-scale online training. It offers opportunities to develop new approaches for capacity development almost anywhere and anytime. Universities and industry have revolutionized online educational and communications practices to increase their impact and align with more dynamic and diverse business models (Lara-Lopez et al. 2019). The COVID-19 pandemic forced a paradigm shift, ramping up such online work (Mishra et al. 2020).

15.3.1 Integration of Capacity Development Efforts—Scientific Training

Integration of the existing initiatives is key to strengthen the quality of the global efforts that already exist to develop capacity and also to ensure that any new program learns from former experiences from formulation to implementation. In the following section we will focus on lessons learned from different case studies to showcase some steps taken towards the use of science (observations, research, modelling, etc.) that can help advance blue economies.

15.3.1.1 Case Study 1—Training Opportunities for Observers on Research Cruises

Many nations require observers on research vessels permitted to conduct research within their exclusive economic zones (EEZs). The UNCLOS, particularly Part XIII (Articles 238–265) on Marine Scientific Research, deals with research within a nation's EEZ. Articles 245–246 of UNCLOS states that research in a nation's territorial sea, EEZ, and continental shelf can only be carried out with express permission of the nation. The coastal nation should generally grant access but may withhold permission in limited cases (Article 246). Consent is approved if the coastal nation does not respond to the access request. Article 249 permits hosting nations to place an observer on visiting research vessels and allows host nations to request sharing of samples and data with the coastal nation hosting the research cruise. Other sections of UNCLOS encourage technology transfer. The UN issued a guide to marine scientific research in 2010 (United Nations 2010).

Research cruises are expensive and often seek to maximize opportunities for researchers from their country to fill berths on the ship to conduct research on specific topics. At the same time, when research is conducted in another nation's EEZ, they must offer a berth for at least one observer, if requested by the host nation. Planning can bring about the best outcomes from cruise experiences for observers. Various procedures are used to select observers for research cruises. The observer may be a naval officer tasked only with ensuring that the foreign ship follows all local laws or may be a scientist who has some expertise on the topic of the cruise. In either case, full advantage is not always taken in terms of the opportunities for training provided by the cruise. At a minimum, the cruise principal investigator (PI) prefers that the observer do their job without hindering planned research observations. At best, PIs would like to help train the observer in ocean science. Indeed, many nations proactively seek to invite participants from the nations in which EEZs they plan to work, regardless of access requirements.

The Ocean Training Partnership (http://www.oceantrainingpartnership.org/) is a clearinghouse of opportunities for early-career scientists from developing countries to gain shipboard experience. It is led by POGO, with funding from the Nippon Foundation, in collaboration with the Strategic Marine Alliance for Research and Training (SMART) and the Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research (AWI). Training opportunities are provided by matching scientific cruises with spare berths to early-career scientists in developing countries who need training in a specific field. AWI, POGO and NF also partner to provide dedicated cruises for multi-disciplinary training on-board the German ice-breaker R/V *Polarstern* during a one-month expedition between Europe and the South Atlantic. Examples of using project activities are available from several different research projects (Morrison et al. 2013). The GEOTRACES project of the Scientific Committee on Oceanic Research (SCOR) is sampling trace elements and isotopes in all ocean basins worldwide. Some of the most interesting and important processes occur close to coastlines, requiring research vessels to sample in the EEZs of many nations. Some GEOTRACES cruises have required observers and have involved young scientists from developing nations, identified in advance and sometimes with travel costs paid by SCOR or the nation conducting the cruise, to join the cruise for training in chemical oceanography.

How can host nations and nations sending research vessels to their waters work together to proactively use research cruises to build ocean science capacity in their countries? What actions could be taken to improve the situation?

1. Build from UNCLOS requirements. The UN has a standard form that can be used to request access, including the name of a scientist from the host nation. The identified scientists should be consulted extensively about potential training and outreach opportunities.

2. The cruise PI can be proactive in training, not merely meeting the minimum requirements. Ideally, the PI could train the developing country scientist in advance regarding their planned duties on the cruise, involve them in data collection, and involve them in data analysis after the samples are collected.
3. Build on past experience and relationships. Many national cruises have made attempts to use cruises for capacity development when their ships travel into developing country waters, yet observers do not want to participate in the research of the cruise. It would be helpful to gather information about experiences with past cruises to develop a "how to" guide to make best use of the opportunities available and to avoid the pitfalls that can occur.
4. Establish an international program that could be adopted by interested nations, funded by national development agencies and foundations. Such a program might have the following elements:
5. Countries seeking access to a developing country's EEZ submit the permission request required by the developing country and, at the same time, contact national universities and/or research institutes to inform them about the purpose of the cruise.
6. The host country identifies a qualified student, technician, or scientist who would benefit from the activity in terms of learning new skills and networking. The involvement might take place onboard the research vessel and/or at the local institution.
7. Take advantage of transit legs between the end of one cruise and the beginning of the next cruise to provide training for scientists from nations in whose EEZs the cruise will be held. German cruises have used this approach.
8. The country from which the ship is coming provides training for the observer, either before or during the cruise and have them do work on the cruise to contribute to the research.
9. The cruise PI and/or other scientists on the cruise involve the observer as a co-author of a publication of the research, if they made meaningful contributions, or at least acknowledge the observer. This would reduce the chance of research cruises becoming another example of 'parachute science'.
10. The observer serves as the liaison in terms of arrangements for data and sample sharing, if sharing is required by the host nation.

15.3.1.2 Case Study 2—Summer Schools

Several research projects supported by SCOR and other organizations organize "summer schools" (which may take place in any season) to bring together graduate students from around the world for intensive classroom, laboratory, and shipboard study on the topics on which the projects focus. These events have several important features: (1) they focus on topics that cross-cut traditional research fields, (2) they promote networking of students and trainers from many different countries with different expertise, and (3) they allow trainees to focus for one to two weeks on their course topics and also learn "soft skills". Organizers attempt to keep per-student costs as low as possible, through support from host institutions, and national and international funding agencies. In some cases, students must pay some or all of their own expenses, but some support is usually provided for students from developing countries. See Box 15.1 for SCOR project summer schools. Examples of other successful summer schools are provided below.

Coastal Ocean Environment Summer School in Ghana

The Coastal Ocean Environment Summer School in Ghana (COESSING; https://coessing.org) has been run for one week in August every year since 2015. The school alternates between the Regional Maritime University, which trains students for careers in the maritime industry, and the Department of Marine and Fisheries Sciences at the University of Ghana. The 2015 school was relatively small, with about 40 Ghanaian participants. The school has had about 100 African participants per year since 2016, mostly from Ghana, but with an increasing number in recent years from other West African countries, especially Nigeria. African participants include undergraduate and graduate students, faculty members, and some private and government employees. Due to the COVID-19 pandemic, the 2020 and 2021 schools were held online. Since 2016, 15 or more U.S. and European participants, including undergraduates, graduate students, postdocs, faculty, and research scientists, have enrolled in the school every year. The school covers physical oceanography, chemical oceanography, resources, and environmental science, and employs lectures, lab exercises, panels, field trips (see Fig. 15.2), software and data analysis training, and independent research projects. The positive impacts of the school on participants are documented in the school testimonials page (https://coessing.org/testimonials) and two recent articles (Moskel et al. 2021; Nyadjro et al. 2021). Many school participants have enrolled in graduate schools around the world, enabling African research. For instance, participants have included satellite observations, or improved software, in their research because of the school (Nyadjro et al. 2021). The school is featured in at least four funded/in-review U.S. National Science Foundation proposals, including an effort led by Howard University, a Historically Black College and University (HBCU), to improve weather prediction in West Africa, and an effort led by the University of Michigan to introduce sediment coring and geochemical isotope analysis research to West Africa.

Inspired by the success of COESSING and by the United States Peace Corps concept, a complementary initiative known as "Ocean Corps for Ocean Science" (https://globaloceancorps.org) is being developed. The idea of Ocean Corps is that progress in ocean science will be greatly enabled by the development of interpersonal relationships between scientists around the world. Many ocean scientists in well-resourced countries are eager to help but do not know scientists in under-resourced countries. Just as the Peace Corps inspired many Americans to engage the rest of the world, a funded Ocean Corps would provide a platform for scientists in higher-resourced countries to engage their counterparts in under-resourced countries, through summer schools such as the Ghana summer school, MSc programs

Fig. 15.2 2018 field trip of the Coastal Ocean Environment Summer School in Ghana (Photo credit: Paige Martin, Columbia University/Australian National University)

such as the long-standing French program run in Benin, or other exchange programs. The potential of an Ocean Corps can be seen in the makeup of the U.S. scientists engaged in the Ghana summer school. Many of these scientists had never been to Africa prior to their participation in the school. They are now regular participants and passionate advocates for capacity development. Scientists in several under-resourced nations have indicated an interest in hosting summer schools like the one in Ghana, and numerous U.S. and European scientists, especially early-career scientists, have expressed interest in participating in global capacity development projects. Accordingly, the co-leads of Ocean Corps include early-career scientists from the U.S. and scientists from under-resourced countries such as Ghana and Jamaica. Ocean Corps could benefit from the successful model provided by the Visiting Scholar program of the Scientific Committee on Oceanic Research (SCOR) operating since 2009 (Urban and Seeyave 2021).

15.3.1.3 Case Study 3—Impact of Policy Intervention on Women, Youth, and Early Career Participation in Ocean Science

There is clear evidence of the effect of recent policy interventions on the inclusion of women and youth in ocean science. In 2017, WIOMSA launched the Women in

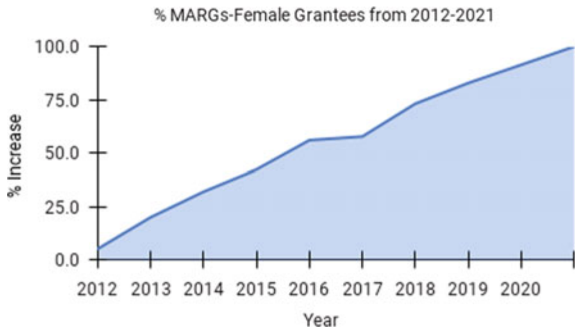


Fig. 15.3 Increase in the number of female grantees of the Marine Research Grants (MARG) from 2012 to 2020. The Marine Science for Management (MASMA) grants are aimed to raise capacity in the Western Indian Ocean region. Arthur Tuda, Julius Francis, and Mathias Igulu from the Western Indian Ocean Marine Science Association (WIOMSA) provided data to generate this figure

Marine Science Network (WIMS) and the Early Career Scientists Network (WIO-ECSN). These networks were initiated after recommendations from an external evaluation of the association conducted in 2016. To ensure gender equality, the WIOMSA Board also endorsed a gender policy in 2017. As part of awareness creation and communication, WIOMSA published two magazines focusing on documenting the career journeys of a wide range of women from the region's countries and the production of a documentary on women in science. Four years later, there has been a spike in the MARG I grants for research awarded to women scientists and young scientists (Fig. 15.3). Statistics of awarded grants show a 40% increase in grants to women (total number of female grantees from 2012 to 2021 is 107). This demonstrates the increased empowerment of women to participate in this competitive process.

The Global Ocean Science Report 2020 highlights that to achieve SDG 5, which provides for gender equality and empowerment of all women and girls, there is a need to move beyond the measurement of the number of grantees to documentation of the fate of these women along scientific career paths and into the realm of policy (Roberts et al. 2020), where they can serve as leaders in key transformations in the WIO region. This is a much-needed next step in the evaluation of the fate of the capacity built through WIOMSA grants.

15.3.1.4 Case Study 4—Training Linked to Sustained Monitoring

Fisheries Monitoring in the South Pacific

Pacific Island countries have recognized the importance of sustained marine scientific capacity development programs and technology transfer programs (Veitayaki and South 2001; Veitayaki and Manoa 2014). The Pacific Islands Forum Fisheries Agency and the Secretariat of the Pacific Community have a long history of implementing and supporting data collection and reporting programs that enable SIDS members to monitor fishing effort and impacts within their extensive waters under national jurisdiction, and in adjacent areas beyond national jurisdiction (Harden-Davies 2016). These data are analyzed by these regional institutions, from capacity development programs that mentor government officials and provide critical support for governments as they manage and monitor fishing activities and impacts (Hanich and Tsamenyi 2009). Technology transfer facilitates these activities, including sophisticated maritime domain open-source access to satellite databases, such as the automatic identification system for fishing vessels (Hanich et al. 2008; Goodman 2017). These efforts are mandated and owned by the SIDS themselves and align closely with SIDS development priorities, which collectively empower SIDS to voluntarily commit institutional and national resources in deciding where, how, and what to monitor. The approach is long term and programmatic in nature, with a regional institutional focus on development and strengthening sovereign rights, and a flexible approach that works within diverse national contexts and regionally agreed reporting frameworks (McNulty 2013). Given the high dependence of this region on coral reefs and trans-boundary fisheries (FFA/SPC 2015), and the inherently limited capacity of Pacific SIDS (Hanich and Tsamenyi 2009), these collective approaches that link monitoring and capacity development are fundamental to the ocean observing needed to inform management decisions.

Marine Biodiversity Observation Network (MBON) Pole to Pole of the Americas

In conjunction with the Ocean Teacher Global Academy (OTGA), the MBON Pole to Pole regional project has organized workshops to train Venezuelan and South American early career scientists in biological EOV monitoring in collaboration with U.S. professionals. The first workshop consisted of lectures, field and lab activities, and data QA/QC to learn standard and innovative methods to (1) assess cover and biomass of seagrasses, (2) assess abundance and species diversity of fish associated to seagrasses, (3) assess fish predation rates, (4) extract satellite data on sea surface temperature and chlorophyll, and (5) quality assess and control data and register in OBIS. A second workshop was held a year later and was an essential means of consolidating the knowledge gained at the workshop, including addressing any issues arising as participants put the training into practice. The second workshop focused on methods to conduct research and monitoring in rocky shores (focusing on the macroalgal EOV), and training on climate change communication (http://www.goosocean.org/index.php?option=com_oe&task=viewEventRecord&eventID=2593). During the COVID-19 pandemic, the network continued its capacity sharing activities through virtual means.

Nippon Foundation, POGO and SCOR Training in Observational Oceanography

Since 2001, POGO and SCOR have provided short-term visiting fellowships for scientists from developing countries to spend up to three months receiving one-to-one training and supervision in ocean observations at a major oceanographic institution (usually, but not necessarily in a developed country). By 2021, 177 young scientists from 36 countries have been trained in this program. This program is aimed specifically at strengthening the sustained, long-term capacity of institutions in developing countries to conduct routine monitoring in their coastal waters as well as interpret and manage data. In partnership with the Nippon Foundation, POGO has also run since 2008 a Centre of Excellence in Observational Oceanography, which is a 10-month multi-disciplinary program, focused on developing practical skills for ocean observing, as well as data processing, visualization, management, and modelling. For both of these programs, priority is given to candidates with a position to return to and demonstrated plans to implement and pass on the knowledge gained from their training to their peers and students.

Surveys of former trainees conducted 5 years or more after the training have shown that the training enabled participants to participate in new research projects, implement new techniques, use new equipment and/or use new software/models that were previously unavailable at their institute, as well as to forge new relationships and collaborations with international scientists. A large proportion of respondents replied that they had given seminars or lectures based on the training received, had supervised students and/or mentored colleagues, and the vast majority said they had passed on the knowledge gained during the training. The training also resulted in an average of 3 oral and 2 poster presentations and 2 peer-reviewed publications per trainee. Another survey directed at the institutions who benefited from the training indicated that the training enabled the institutes' staff and students to benefit from the new knowledge and skills gained by the POGO trainees, supporting the conclusion that these training programs are "training the trainers" and fulfilling their objective of leading to *sustained* capacity development. The training has also broadened the scope of oceanographic research conducted by the institutes. This is also evidence of "sustained capacity development", whereby a new area of research is implemented and maintained because of the training (with the institute providing the infrastructure/staff to sustain the new area of research). The results also showed that the training enabled host or parent institutes to set up new monitoring or observation programs (e.g., time-series stations, repeat cruises, tide gauges, moored buoys, etc.).

Alumni from past NF-POGO programs are integrated into the NF-POGO Alumni Network for the Ocean (NANO), which supports them to work together to establish a global network of long-term monitoring stations. Participants from 13 countries (being expanded in 2021 to 18–20) receive modest funding from NF-POGO to support bimonthly sampling trips to measure a minimum set of EOVs (temperature, salinity, chlorophyll-a, dissolved oxygen, pH).

15.4 Part III: Looking to the Next Decade

15.4.1 Innovative Capacity Development to Overcome UN Ocean Decade Challenges

Innovations are key to address today's challenges and prepare for the future. 2020 brought an unexpected challenge: a global pandemic put the world on hold. Society was affected at all levels, and ocean sciences were no exception: fewer research cruises took place, training was cancelled, and the world became dependent on virtual communication and training. The global COVID-19 pandemic has been tragic and presented many challenges for teaching and capacity development because of the inability to meet face to face. However, the pandemic also made us realize that governments, scientists, and the private industry can and have to work together to achieve common goals. Further, the pandemic can be used as a prime example of societies overcoming challenges together by "thinking outside the box", which was the key to innovative solutions within the pharmaceutical and logistics industry that were desperately needed during these trying times. Taken together, the pandemic has proven that stakeholders can put their differences aside to work innovatively, coherently, and in coordination to meet societal needs and hopefully this momentum can be transferred to ocean sciences to achieve SDG 14 during the Ocean Decade. In the current Ocean Decade, structural changes and new approaches in capacity development are necessary if sustainable blue economies are to be achieved by 2030 and if ECOPs and developing countries are to become equal partners in addressing global ocean sustainable development and management challenges. Required structural changes that will lay the foundation of globally concerted and effective capacity development efforts include the elimination of parachute science, the establishment of transparency, and the implementation of truly collaborative partnerships based on trust, respect, and accountability (Zitoun et al. 2020). Effective long-term capacity development will also only be achieved if new technological approaches are implemented and made available in a cost-effective manner, especially to developing countries (Zitoun et al. 2020).

Below is a summary of recommendations to accelerate global capacity development efforts and responses to achieve SDG 14 by 2030 and to create the ocean we want and need together. These recommendations distinguish between efforts that can and indeed should be implemented by different stakeholders, with a primary focus on the scientific community, policymakers, and private industry.

15.4.1.1 Blue Economy Outlook for Scientists

For institutional, research, and human capacity development activities to be most effective during the Ocean Decade, scientists of all ocean disciplines need to work together to address the following challenges to achieve blue economy goals (Zitoun et al. 2020). Many of these challenges relate to ocean science and thus approaching these challenges are best led by transdisciplinary ocean scientists, but success will require broad participation of multiple stakeholders in the co-design, co-development, and co-implementation of activities and solutions from the start. Scientists should help define priorities for ocean science capacity development over the next decade based on science, industry, government, and civil society needs.

Advance Scientific Understanding—Conduct national/regional vulnerability assessments to identify the potential impact of climate change and anthropogenic activity on key ecological, cultural and economic marine resources and species, as well as the communities that depend on them.

Define Indicators—Identify a manageable set of measurements that are globally relevant and applicable to evaluate ecosystem health in various regions to reduce cost and time, engage diverse stakeholders, and allow the interoperability of research data.

Establish Baseline Measurements of EOVs—Establish monitoring programs or engage with existing programs to evaluate baselines and detect changes in the water chemistry and ecology to evaluate ecosystem health. These data are needed to inform policymakers and thus support better decision making on mitigation and management strategies (See Chap. 14).

Establish Protocols and Standards—Standards and protocols for various measurements including sample collection, handling, analysis, and data products, are necessary to obtain high-quality data, meet global standards, and allow the interoperability of data.

Improve Local Modelling Projections—Advance the resolution of existing models to improve the identification and evaluation of local issues.

Strengthen/Create Data Reporting Networks—Strengthen (or create if needed) data products, reporting networks, and mechanisms to facilitate the sharing of scientific data, findings, and lessons.

Take Meaningful Actions—Reduce the causes of climate change by implementing effective and long-term mitigation, resilience, and adaptation strategies, tailored to local and regional needs, priorities, and means. The success of such management strategies, both existing and emerging, must be validated and quantified with scientific means.

Implement Solution-based Strategies—Mitigate problems using human interventions. For example, the British lobster industry cultures larvae to help them through their most sensitive life stages before they release them into the natural environment.

Minimize Research Costs/Optimize Research—Enhance the capacity to address sustainable development challenges by developing low-cost instrumentation and secondary standards to reduce costs. There is also a need to make pre-existing low-cost technologies more widely available in developing countries to obtain relevant data for effective adaptation, mitigation, and resilience strategies.

Raise Public Awareness—Promote ocean literacy by informing and educating the wider public on current and emerging local marine challenges and its impacts on social, cultural, environmental, and economic security. Such efforts will help to develop local awareness, expertise, and knowledge, and thereby strengthen ownership and the drive for action. It is also important to encourage diverse stakeholders, including indigenous communities, to assess and manage local marine environments together while respecting local priorities.

15.4.1.2 Blue Economy Outlook for Policymakers

Effective and long-term capacity development in ocean science and technology will only be achieved if policymakers contextualize the priorities of ocean science capacity development within global frameworks and processes, as well as implement science-based frameworks and management strategies. To be effective, such policy activities must be based on the principles of empowering national ownership, local leadership, and self-determination (Crossley and Holmes 2001; Zitoun et al. 2020; Stefanoudis et al. 2021).

Build Coordinated Capacity—Strengthen the ability of countries to generate information and knowledge on which to base policy by facilitating robust scientific capacity development through access to tertiary education in environmentally relevant fields, enhanced funding, improved infrastructure, and logistics.

Enhance Collaboration and Coordination—Facilitate international collaborations to build capacity, transfer technology, link initiatives, share networks, and mobilize resources and funding.

Targeted Policies—Develop frameworks and mitigation, adaptation, and management strategies targeted to local priorities.

Increase Sustained Financial Support—Develop a coordinated funding strategy to identify existing or new funding sources as an essential component to building sustainable capacity. Long-term funding is vital to support countries with steadily increasing costs of analyses, training, staffing, and facilities maintenance.

15.4.1.3 Blue Economy Outlook for Private Industry

The Economist Group's World Ocean Initiative (WOI) describes as blue economy "a sustainable ocean economy that harnesses ocean resources for long-term economic development and social prosperity while protecting the environment in perpetuity". Therefore, for the private sector this translates into creating jobs, improving income and growth, but also restoring ocean health by implementing environmentally friendly technologies and sustainable practices, with transparency to avoid duplication and fragmentation.

Develop a Scientifically Trained Workforce—It is in the best interest of companies that need scientists and technicians to support the development of the required employees by investing in national universities and technical institutes. The investments can be through endowed chairs in universities, contributions of equipment for laboratories and shops, provision of internships in the company to provide practical experience, and bursaries at institutions that produce staff for their company. There are many advantages to hiring staff from within a country rather than needing to recruit more broadly.

Develop New Approaches and Technology—Private industry can be a source of new technology and new approaches to complement hands-on interactions. Such new methods, including telepresence and robotics, can be used for training in using new technology, laboratory techniques, and other activities that require manual handling. Virtual reality provides an option to overcome the need for face-to-face training. Virtual reality and telepresence are now common in many fields, such as medicine (Basdogan et al. 2001; Gonzalez Izard et al. 2018), engineering and construction (Wang et al. 2018; Goedert and Rokooei 2016), and where training is required on equipment that is fragile, unavailable, costly, or dangerous (Mollet and Arnaldi 2006). The miniaturization of computers, and the improvement of their processing capacity, allows Virtual Reality to become a viable technology in our society (Joo-Nagata et al. 2017). The time is ripe to advance such interdisciplinary methods to make it a reality.

15.4.2 Co-Designing Recommendations for Improved Capacity Development for Global Oceanography

To define priorities for ocean science capacity development over the next decade, and to contextualize these priorities within global frameworks and processes, more than 200 scientists and resource managers have attended focused capacity development sessions at Ocean Obs'19, Ocean Sciences 2020, and sixteen virtual regional stakeholder dialogues held in 2020. Their recommendations have created a community-developed concept note that identifies the programs, resources, and activities needed to enable equitable distribution of ocean science capacity, and the costs of such activities. The concept note developed into EquiSea: The Ocean Science Fund for All, a new initiative to coordinate and finance effective ocean science capacity development. EquiSea (https://equisea.org) is hosted by The Ocean Foundation and co-led by representatives from seven institutions spanning six countries: Ecuador, Ghana, Jamaica, Malaysia, Mauritius and the United States.

Based on this consultation process, the key recommendations to achieve effective coordination and support of capacity development in ocean science include:

1. **Sustained Ocean Science Capacity Requires Multi-Sector Collaboration and Investment**

   At present, many regions lack basic infrastructure required for ocean science; therefore, government investment is necessary for maintenance of such infrastructure and sustained scientific programs.

   This includes the creation of new jobs in ocean science, as such lack of jobs limits capacity even where academic infrastructure is robust. Finally, technology should be co-developed/designed with end users as technology is currently developed by/for highly resourced countries, excluding potential buyers and users and limiting data collection.
2. **A Robust Sustainable Blue Economy Requires Equitably Distributed Ocean Science Capacity**

Many of the regions expected to have the largest blue economic growth are resource-limited and have limited ocean science capacity. Such lack of ocean science capacity has tangible economic effects and limits growth of the sustainable blue economies (e.g., port safety issues due to lack of bathymetric data). Currently, multi-national companies prefer U.S.- and European-based consulting firms, and this perpetuates the cycle of insufficient local ocean science capacity. A new blue economic sector development will be key to economic recovery in coastal regions with a high dependence on tourism or trade impacted by COVID-19.

3. **A Significant Increase in Funding is Required to Enable Equitable Distribution of Ocean Science Capacity**

   Currently and historically, funding has been sparse and entirely insufficient, therefore, dedicated sources of funding for ocean science capacity development are needed. The EquiSea authors estimate a minimum required investment of $13m USD/year.

15.5 Concluding Words

In this chapter, we have identified examples of a range of capacity development programs for science that range over several orders of magnitude in investment and the scale of their aspirations. Which approaches and programs most effectively use financial and human resources? We do not know. If we are serious in our desire to expand global scientific capacity, to reverse the trend of increasing inequality in the capacity to engage in an increasingly technological world, and to empower all nations to participate actively in increasingly complex global negotiations, it is incumbent on the scientific community engaged in capacity development to start to measure and evaluate the effectiveness of our institutions and programs. This effort will require development of a recognized evaluation approach and above all the willing participation of established programs and institutions. We already have many capacity development initiatives, but few are funded sufficiently (Cicin-Sain et al. 2018) and there has been a growing realization that effective capacity development needs to be appropriate to the social and political context in which it is to be delivered (i.e., the individual country or community) and is not a purely technical transfer of information and knowledge (OECD 2006).

It must be recognized that there is no "silver bullet" or "one size fits all" solution to solve the Ocean Decade challenges since research priorities and related capacities are highly heterogeneous among nations. Some countries and regions will need more help and funding then others to reach international standards and to engage productively with international agendas to achieve sustainable blue economies. Long-term success can only be ensured if ocean science capacity is regionally focused and equitably distributed. For example, including and supporting the attendance of more scientists from under-resourced nations on the steering committees of large UN Decade global ocean observation/monitoring projects will maximize the likelihood that the results of these programs will be appropriate and disseminated to government officials and citizens of such nations. Achieving this goal requires capacity development programs such as those described in this chapter appropriately targeted through direct engagement with recipient countries and regularly assessed for their effectiveness, to ensure that development activities are appropriate to the political and social context in which they will operate.

Capacity development is everyone's responsibility and requires collective actions, but its sustainability depends on political will and engagement of all stakeholders, with scientists, government, and industry each doing what they do best. The efforts to develop capacity described in this chapter have been significant and far reaching, but global capacity development cannot be maintained by just a few, mostly underfunded, organizations. To achieve a successful blue economy, we need all coastal nations to engage and all sectors to contribute resources. Only through collective action can we develop the capacity to expand the skilled workforce required to generate knowledge for informed decision-making in the blue economy.

Acknowledgements Arthur Tuda, Julius Francis, and Mathias Igulu from the Western Indian Ocean Marine Science Association (WIOMSA) provided data to generate Fig. 16.2. PM and EU acknowledge the United States National Science Foundation (NSF) for its support to international capacity development through grant OCE-2027831 to the Scientific Committee on Oceanic Research (SCOR). PWS and MM recognize the generous support provided by the UN's International Atomic Energy Agency (IAEA) Environment Program. The IAEA is grateful for the support provided to its Environment Laboratories by the Government of the Principality of Monaco. BKA acknowledges NSF grants OCE-1381837 and OCE-1851164, the International Centre for Theoretical Physics (ICTP), and various sources within Ghana and the University of Michigan, for support of the Ghana oceanography summer school. Contributions by FMK were supported by the Marine Biodiversity Observation Network (MBON) and the OceanObs Research Coordination Network (OceanObs RCN) through NASA (awards 80NSSC20K0017 and NNX14AP62A), NOAA (award NA19NOS0120199), and NSF (grants 1762493 and 1728913). POGO wishes to acknowledge the generous support of the Nippon Foundation and the Alfred Wegener Institute for Polar and Marine Research (AWI), and their dedication to capacity development in ocean science, as well as the financial contributions of POGO member institutions that support other POGO training programs.

References

Basdogan C, Ho CH, Srinivasan MA (2001) Virtual environments for medical training: graphical and haptic simulation of laparoscopic common bile duct exploration. IEEE/ASME Trans Mechatron 6:269–285

Bax NJ, Appeltans W, Brainard R et al (2018) Linking capacity development to GOOS monitoring networks to achieve sustained ocean observation. Front Mar Sci 5:346. https://doi.org/10.3389/fmars.2018.00346

Betti M (2008) ASLO 2009: The Marine Environment Laboratories of the International Atomic Energy Agency, Monaco (IAEL-MEL). Limnol Oceanogr Bull 17:88–89. https://doi.org/10.1002/lob.200817388

Bojinski S, Verstraete M, Peterson TC et al (2014) The concept of essential climate variables in support of climate research, applications, and policy. Bull Am Meteorol Soc 95:1431–1443. https://doi.org/10.1175/BAMS-D-13-00047.1

Bourrel M, Swaddling A, Atalifo V et al (2017) Building in-country capacity and expertise to ensure good governance of the deep sea minerals industry within the Pacific region. Mar Policy 95:372–379. https://doi.org/10.1016/j.marpol.2017.03.022

Bradley M, Swaddling A (2016) Addressing environmental impact assessment challenges in Pacific island countries for effective management of deep sea minerals activities. Mar Policy 95:356–362. https://doi.org/10.1016/j.marpol.2016.06.017

Buttigieg PL, Caltagirone S, Simpson P et al (2019) The ocean best practices system - supporting a transparent and accessible ocean. In: OCEANS 2019 MTS/IEEE Seattle, IEEE, Seattle, WA, pp 1–5. https://doi.org/10.23919/OCEANS40490.2019.8962680

Canonico G, Buttigieg PL, Montes E et al (2019) Global observational needs and resources for marine biodiversity. Front Mar Sci 6:367. https://doi.org/10.3389/fmars.2019.00367

Cicin-Sain B, Vierros M, Balgos M et al (2018) Policy brief on capacity development as a key aspect of a New International Agreement on marine biodiversity beyond national jurisdiction (BBNJ). FAO, GEF, GOF, Common Oceans, University of Delaware. http://www.fao.org/fileadmin/user_upload/common_oceans/docs/policy-brief-on-bbnj-capacity-development-aug-2018.pdf

Claudet J, Bopp L, Cheung WWL et al (2019) A roadmap for using the UN Decade of Ocean Science for Sustainable Development in support of science, policy, and action. One Earth 2(1):34–42. https://doi.org/10.1016/j.oneear.2019.10.012

Crossley M, Holmes K (2001) Challenges for educational research: international development, partnerships and capacity building in small states. Oxford Rev Educ 27:395–409. https://doi.org/10.1080/03054980120067429

Dunstan PK, Bax NJ, Dambacher JM et al (2016) Using ecologically or biologically significant marine areas (EBSAs) to implement marine spatial planning. Ocean Coast Manage 121:116–127. https://doi.org/10.1016/j.ocecoaman.2015.11.021

FFA/SPC (2015) Future of fisheries: a regional roadmap for sustainable Pacific fisheries. Pacific Islands Forum Fisheries Agency, Honiara

GEF LME:LEARN (2017) The large marine ecosystem approach: an engine for achieving SDG 14. Paris

Goedert JD, Rokooei S (2016) Project-based construction education with simulations in a gaming environment. Int J Constr Educ Res 12:208–223

Gonzalez Izard S, Juanes JA, García Peñalvo FJ et al (2018) Virtual reality as an educational and training tool for medicine. J Med Syst 42: Article No. 50. https://doi.org/10.1007/s10916-018-0900-2

Goodman C (2017) The cooperative use of coastal state jurisdiction with respect to highly migratory stocks: insights from the western and central Pacific region. In: Martin L, Salonidis C, Hioureas C (eds) Natural resources and the law of the sea: exploration, allocation, exploitation of natural resources in areas under national jurisdiction and beyond. Juris, New York, p 474

Hanich Q, Teo F, Tsamenyi M (2008) Closing the gaps: building capacity in Pacific fisheries governance and institutions. Pacific Islands Forum Fisheries Agency, Honiara

Hanich Q, Tsamenyi M (2009) Developments in cooperative approaches to fisheries management in the Pacific islands region In: Bourne R, Collins NM (eds) From Hook to plate: the state of marine fisheries. A commonwealth perspective. Commonwealth Foundation, London, pp 69–86.

Harden-Davies H (2016) Marine science and technology transfer: can the intergovernmental oceanographic commission advance governance of biodiversity beyond national jurisdiction? Mar Policy 74:260–267. https://doi.org/10.1016/j.marpol.2016.10.003

Horstmann C, Buttigieg PL, Simpson P et al (2020) Towards a best practice for developing best practices in ocean observation (BP4BP): supporting methodological evolution through actionable documentation. UNESCO, Paris, 26 pp. (English). (Intergovernmental Oceanographic Commission Manuals and Guides No. 84). (IOC/2020/MG/84). UNESCO. https://doi.org/10.25607/OBP-781

Inniss L, Simcock A, Ajawin AY et al (2016) The first global integrated marine assessment: World Ocean Assessment I. United Nations. Cambridge University Press, Cambridge. https://www.un.org/regularprocess/content/first-world-ocean-assessment

IOC (2019) The science we need for the ocean we want: the United Nations Decade of Ocean Science for Sustainable Development (2021–2030). IOC Brochure 2018–7 (IOC/BRO/2018/7 Rev). IOC, Paris, p 24

IOC (2020) The science we need for the ocean we want: the United Nations Decade of Ocean Science for Sustainable Development (2021–2030). https://oceandecade.org/assets/The_Science_We_Need_For_The_Ocean_We_Want.pdf

IOC-UNESCO (2021) IOC Group of Experts on Capacity Development (GE-CD), second meeting of the GE-CD Task Team related to the revision of the IOC Capacity Development Strategy. https://www.ioc-cd.org/components/com_oe/oe.php?task=download&id=46196&version=1.0&lang=1&format=1

Joo-Nagata J, Abad FM, Giner JGB et al (2017) Augmented reality and pedestrian navigation through its implementation in m-learning and e-learning: evaluation of an educational program in Chile. Comput Educ 111:1–17

Khan M, Sagar H, Huq S et al (2016) Capacity building under the Paris Agreement; European capacity building initiative. https://oxfordclimatepolicy.org/sites/default/files/Capacity_Building_under_Paris_Agreement_2016.pdf

Kullenberg G (1998) Capacity building in marine research and ocean observations: a perspective on why and how. Mar Policy 22:185–195. https://doi.org/10.1016/S0308-597X(98)00005-0

Lara-López A, Klein E, Strutton P et al (2019) Using an Australian Massive Open Online Course to upskill marine science in the use of openly available marine data. Mar Technol Soc J 14(2):9–16. https://www.thejot.net/archive-issues/?id=63

Le Quéré C, Saltzman ES (eds) (2009) Surface ocean-lower atmosphere processes. American Geophysical Union, Washington

McNulty J (2013) Western and central Pacific Ocean fisheries and the opportunities for transnational organised crime: monitoring, control and surveillance (MCS) Operation Kurukuru. Aust J Marit Ocean Aff 5:145–152. https://doi.org/10.1080/18366503.2013.10815747

Miloslavich P, Bax NJ, Simmons SE et al (2018a) Essential Ocean Variables for global sustained observations of biodiversity and ecosystem changes. Glob Change Biol 24:2416–2433. https://doi.org/10.1111/gcb.14108

Miloslavich P, Seeyave S, Muller-Karger F et al (2018b) Challenges for global ocean observation: the need for increased human capacity. J Oper Oceanogr 12:S137–S156. https://doi.org/10.1080/1755876X.2018.1526463

Mishra L, Gupta T, Shree A (2020) Online teaching-learning in higher education during lockdown period of COVID-19 pandemic. Int J Educ Res Open 1: 100012. https://doi.org/10.1016/j.ijedro.2020.100012

Mollet N, Arnaldi B (2006). Storytelling in virtual reality for training. In: Pan Z, Aylett R, Diener H, Jin X, Göbel S, Li L (eds) Technologies for e-learning and digital entertainment lecture notes in computer science. Springer Berlin Heidelberg, Berlin, pp 334–347. https://doi.org/10.1007/11736639_45

Morrison RJ, Zhang J, Urban ER et al (2013) Developing human capital for successful implementation of international marine scientific research projects. Mar Pollut Bull 77:11–22. https://doi.org/10.1016/j.marpolbul.2013.09.001

Moskel JM, Shroyer EL, Rowe S et al (2021) The Coastal Ocean Environment Summer School in Ghana: exploring the research capacity building potential of a higher education informal science learning program. J High Educ Outreach Engagem 25(2):187–207

Muller-Karger FE, Miloslavich P, Bax NJ et al (2018) Advancing marine biological observations and data requirements of the complementary Essential Ocean Variables (EOVs) and Essential Biodiversity Variables (EBVs) frameworks. Front Mar Sci 5:211. https://doi.org/10.3389/fmars.2018.00211

Ntona M, Morgera E (2018) Connecting SDG 14 with the other Sustainable Development Goals through marine spatial planning. Mar Policy 93:214–222. https://doi.org/10.1016/j.marpol.2017.06.020

Nurse LA, McLean RF (2014) Small islands. Chapter 29 of IPCC AR5. https://www.academia.edu/21810282/Small_islands_IPCC_AR5_Chapter_29_
Nyadjro ES, Arbic BK, Buckingham CE et al (2021) Enhancing satellite oceanography-driven research in West Africa: A case study of capacity development in an underserved region. Remote Sens Earth Syst Sci. https://doi.org/10.1007/s41976-021-00051-4
OECD, D (2006). The challenge of capacity development: working towards good practice. Network on governance. DCD/DAC/GOVNET (2005) 5REV1. OECD, Paris. https://www.oecd.org/dac/evaluation/dcdndep/40945568.pdf
Pearlman J, Bushnell M, Coppola L et al (2019) Evolving and sustaining ocean best practices and standards for the next decade. Front Mar Sci 6:277. https://doi.org/10.3389/fmars.2019.00277
Pearlman J, Buttigieg PL, Bushnell M et al (2021) Evolving and sustaining ocean best practices to enable interoperability in the UN Decade of Ocean Science for Sustainable Development. Front Mar Sci 8:619685. https://doi.org/10.3389/fmars.2021.619685
Roberts S, Uku J, Isensee K et al (2020) Ocean science for sustainable development. In: Isensee K (ed) IOC-UNESCO. 2020. Global ocean science report 2020–charting capacity for ocean sustainability. UNESCO Publishing, Paris, pp 175–195. http://hdl.handle.net/20.500.11810/5542
SAMOA Pathway (2015) SIDS accelerated modalities of action outcome statement. https://www.un.org/ga/search/view_doc.asp?symbol=A/RES/69/15&Lang=E
Schmidt S, Neumann B, Waweru Y et al (2017) SDG14 conserve and sustainably use the oceans, seas and marine resources for sustainable development. In: A guide to SDG interactions: from science to implementation. International Council for Science, Paris, pp 174–218. http://oceanrep.geomar.de/id/eprint/40022
Sherman, K (1993) Large marine ecosystems as global units for marine resources management–an ecological perspective. In: Sherman K, Alexander DG, Gold BD (eds) Large marine ecosystems. Stress, mitigation, and sustainability. Wiley, pp 3–14
Sherman K (2014) Adaptive management institutions at the regional level: the case of large marine ecosystems. Ocean Coast Manage 90:38–49. https://doi.org/10.1016/j.ocecoaman.2013.06.008
Simpson P, Pearlman F, Pearlman J et al (2021) Evolving and sustaining ocean best practices workshop IV, 18; 21–25 & 30 Sep 2020 [Online]: Proceedings, Vols 1 & 2. UNESCO, Paris, 66 pp & 115 pp (IOC Workshop Report No. 294, Vols 1 & 2). https://doi.org/10.25607/OBP-1036
Singh GG, Cisneros-Montemayor AM, Swartz W et al (2018) A rapid assessment of co-benefits and trade-offs among sustainable development goals. Mar Policy 93:223–231. https://doi.org/10.1016/j.marpol.2017.05.030
Sjösted M, Povitkina M (2017) Vulnerability of small island developing states to natural disasters: how much difference can effective governments make? The J Environ Dev 26:82–105. https://doi.org/10.1177/1070496516682339
Stefanoudis PV, Licuanan WY, Morrison TH et al (2021) Turning the tide of parachute science. Curr Biol 31:R184–R185. https://doi.org/10.1016/j.cub.2021.01.029
Sturesson A, Weitz N, Persson A (2018) SDG 14: Life below water. A review of research needs. Technical annex to the Formas report Forskning för Agenda 2030. Översikt av forskningsbehov och vägar framåt. Stockholm Environment Institute, Stockholm. https://www.sei.org/wp-content/uploads/2018/11/sdg-14-life-below-water-review-of-research-needs-1.pdf
Tanhua T, McCurdy A, Fischer A et al (2019) What we have learned from the Framework for Ocean Observing: evolution of the Global Ocean Observing System. Front Mar Sci 6:471. https://doi.org/10.3389/fmars.2019.00471
Tittensor DP, Walpole M, Hill SLL et al (2014) A mid-term analysis of progress toward international biodiversity targets. Science 346:241–244. https://doi.org/10.1126/science.1257484
UNDP (2017) Large marine ecosystems and sustainable development: a review of strategic management processes and goals. United Nations Development Programme. https://www.undp.org/content/undp/en/home/librarypage/poverty-reduction/global-environmental-finance/large-marine-ecosystems-and-sustainable-development--a-review-of.html

UNEP (2020) Regional seas biodiversity under the post-2020 global biodiversity framework. Report to UNEP authored by DE Johnson, MA Ferreira and CB Froján. https://www.cbd.int/doc/c/0c09/8814/cc8c0cd04f77b9a61240a33c/sbstta-24-inf-24-en.pdf
UNESCO (2016) Unpacking SDG 4–education 2030 commitments. https://en.unesco.org/sites/default/files/briefing_note_2_-_unpacking_sdg_4.pdf
UNESCO (2017) Global ocean science report—the current status of ocean science around the world. UNESCO Publishing, Paris
UNFCC (2005) Climate change, small island developing states. https://unfccc.int/resource/docs/publications/cc_sids.pdf
United Nations (2010) The Law of the Sea: marine scientific research—a revised guide to the implementation of the relevant provisions of the United Nations Convention on the Law of the Sea. New York
United Nations (2015) Draft outcome document of the United Nations Summit for the adoption of the post-2015 development agenda. https://www.un.org/en/development/desa/population/migration/generalassembly/docs/globalcompact/A_RES_70_1_E.pdf
UN-OHRLLS (2015) Small island developing states in numbers. Climate change edition 2015. United Nations, New York. https://sustainabledevelopment.un.org/content/documents/2189SIDS-IN-NUMBERS-CLIMATE-CHANGE-EDITION_2015.pdf
Urban E, Boscolo R (2013) Using scientific meetings to enhance the development of early career scientists. Oceanography 26(2):164–170. https://doi.org/10.5670/oceanog.2013.16
Urban E, Bowie A, Boyd P et al (2020) The importance of bottom-up approaches to international cooperation in ocean science: the iron story. Oceanography 33:11–15. https://doi.org/10.5670/oceanog.2020.109
Urban E, Seeyave S (2021) Visiting scientists provide capacity development: Lessons learned by POGO and SCOR. Oceanography 34(3):44–52. https://doi.org/10.5670/oceanog.2021.306
Veitayaki J, Manoa PE (2014) Building capacity in the marine sector in the Pacific Islands and the role of The University of the South Pacific. In: Dakuidreketi MR, Lingam GI (eds) Higher education and community engagement in the Pacific. Development and policy issues. University of the South Pacific Press, Suva, pp 71–91.
Veitayaki J, South GR (2001) Capacity building in the marine sector in the Pacific islands: the role of the University of the South Pacific's Marine Studies Programme. Mar Policy 25:437–444. https://doi.org/10.1016/S0308-597X(01)00028-8
Vousden DH, Scott L (2017) Large marine ecosystems and sustainable development: a review of strategic management processes and goals. United Nations Development Program, New York.
Wang P, Wu P, Wang J et al (2018) A critical review of the use of virtual reality in construction engineering education and training. IJERPH 15:1204. https://doi.org/10.3390/ijerph15061204
Wilkinson MD, Dumontier M, Aalbersberg IJ et al (2016) The FAIR guiding principles for scientific data management and stewardship. Sci Data 3:160018. https://doi.org/10.1038/sdata.2016.18
World Health Organization (2017) Small island developing states: health and WHO: country presence profile. World Health Organization. https://apps.who.int/iris/handle/10665/255804
Zitoun R, Sander SG, Masque P et al (2020) Review of the scientific and institutional capacity of small island developing states in support of a bottom-up approach to achieve Sustainable Development Goal 14 targets. Oceans 1(3):109–132. https://doi.org/10.3390/oceans1030009

Chapter 16
Summary Reflections on Advancing Ocean Science for Blue Economy

Edward R. Urban Jr. and Venugopalan Ittekkot

Abstract This chapter summarizes the need for science and technology to sustainably use products and services from the ocean, as well as responding to and mitigating environmental threats that have negative impacts on blue economies that are beginning to develop. The chapter summarizes case studies of successful use of science and technology for blue economies, as well as documenting the results of disregard of science. Finally, the chapter makes recommendations about steps that nations should consider when contemplating the implementation of national blue economies.

Keywords Blue economy resources · Threats to blue economies

16.1 Introduction

The High-level Panel for a Sustainable Ocean Economy ("Ocean Panel") estimates that the benefits of investments in four ocean economy approaches outweigh the costs of implementing these approaches by at least five-fold over the period 2020–2050 (Konar and Ding no date). These approaches include "conserving and restoring mangrove habitats, scaling up offshore wind production, decarbonising the international shipping sector and increasing the production of sustainably sourced ocean-based proteins". Science and technology are a necessary foundation for establishing such approaches for sustainable blue economies, regardless of the definition of blue economy. No resource can be used sustainably without understanding the ecology of the marine system where the resource use takes place, and the effects of use on the local and national economies and environments, and related social systems. Nevertheless, little of the literature surveyed emphasizes the importance of ocean science and technology for blue economies. Very often, countries focus on the economic

E. R. Urban Jr. (✉)
Scientific Committee on Oceanic Research (SCOR) (Retired), Newark, DE, USA
e-mail: ed.urban@scor-int.org

V. Ittekkot
Leibniz Centre for Tropical Marine Research, University of Bremen (Retired), Bremen, Germany

E. R. Urban Jr. and V. Ittekkot (eds.), *Blue Economy*,
https://doi.org/10.1007/978-981-19-5065-0_16

benefits of one marine economic sector at the expense of others, at the expense of the environment, and/or at the expense of local communities, which negates the basic principles of the World Bank definition of sustainable blue economies given in Chap. 1:

> "the sustainable use of ocean resources for economic growth, improved livelihoods and jobs while preserving the health of ocean ecosystems" to achieve "triple bottom line objectives" that balance economic, environmental, and social outcomes. (World Bank and United Nations Department of Economic and Social Affairs 2017)

Coastal nations wishing to embrace the full blue economy concept will need to decide how to transition to a balance of economic, environmental, and social sustainability and equity (Österblom et al. 2020).

While the blue economy literature does not appear to adequately emphasize the need for scientific and technical foundations, until recently not much attention was given to the topic by the ocean science community either. Most contributors to this book welcomed the opportunity to consider for the first time how their areas of science intersect with the concept of blue economy.

The premise of this book is that establishing sustainable economic activities based on use of coastal zones and adjacent ocean areas depends on establishing a solid foundation of knowledge and a community of ocean scientists, engineers, technicians, and policymakers committed to applying science and technology to achieve blue economy goals. This is more urgent than ever before. Global climate change and its effects—particularly sea-level rise, ocean acidification, oxygen depletion, and ocean warming—affect every aspect of developing and maintaining blue economies that depend on coastal ecosystem products and services. Global changes pose additional challenges to blue economies that will require an even better foundation of ocean research and observations.

The book does not include chapters on every possible blue economy resource and sector or threat to these resources. For example, marine transportation and ports that form an important part of blue economy (e.g., trade, supply lines for energy and raw materials) are not covered in separate chapters. There is evidence that port facilities may be overcapitalized, and port areas can pose substantial threats to environmental and social sustainability, and even endanger the financial stability of developing countries when financed from abroad (Bond 2019). National planners should carefully consider the existing and predicted supply and demand for port facilities, and the multiple costs of excess supply.

16.1.1 Blue Degrowth and Trade-Offs Between Blue Economy Sectors

"Blue degrowth" has been discussed as a reaction against unlimited focus on economic growth at the expense of other important blue economy goals (Ertör and Hadjimichael 2020). The objections to blue economy concepts from degrowth advocates seem to be that blue economy, as stated in many policy documents, emphasizes the economic benefits of marine resource use and minimizes potential negative environmental and social effects. Many adherents of the blue economy philosophy see it as a means to grow their economies indefinitely. Critics of blue economy assert that these approaches assume continued growth, which will propel additional global climate change and other undesirable environmental impacts. In the European Union, non-governmental organizations (NGOs) have urged the EU to use the EU Good Environmental Status and precautionary management approaches to temper blue economy strategies. In addition, Bond (2019) points out the trade-offs of blue economies' claims versus the reality of implementation. When forming their blue economy plans, countries should consider the concerns that are the basis of degrowth discussions, while not ignoring the desires of many developing countries to better use and benefit from their natural resources. The Global South appears to be less favorable to the degrowth concept because it limits growth advantages that northern countries have already utilized (e.g., using coal as an energy source).

A common theme that emerges from the chapters of this book is that blue economy decisions must consider tradeoffs between one sector and another. Examples include the following:

- Offshore mining and fishing in Namibia (Chap. 8). Extensive offshore phosphate deposits could be a substantial blue economy resource for Namibia and help provide needed phosphate for the coming global shortage of phosphate from terrestrial sources, yet the fishing industry and environmental groups in Namibia are concerned that phosphate mining will harm populations of marine fish and other organisms, as well as harming the fishing industry and communities that rely on this industry.
- Public health and environmental agencies in South Africa are in conflict over pesticide spraying to control mosquitoes carrying malaria and tsetse flies carrying trypanosomiasis (Chap. 9). Flow of land-based pesticides into coastal ecosystems in the Maputaland coastline and the iSimangaliso Marine Protected Area accumulates in marine species and damages coral reefs.
- Balancing the benefits from mangroves and seagrasses as draws for ecotourism, fisheries, and aquaculture versus harvesting for food, natural products, and biofuel sources, or coastal development (Chap. 3). Although mangroves and seagrasses provide many benefits for blue economies if left in place, there is pressure in many areas to replace these blue carbon ecosystems with tourist and aquaculture sites, or other commercial development, or to harvest mangroves and seagrasses for their product values.
- Energy-efficient technologies such as wind turbines and electric motors for cars require increased mining of rare earth elements, which has environmental consequences (Chap. 8). Renewable energy could decrease CO_2 emissions and, thus, decrease global warming and ocean acidification, yet there are environmental costs from mining.
- Research has indicated that sharks are far more valuable kept alive for tourism than killed as fishery products in the Pacific Islands (Chap. 6)

Balancing among different blue economy sectors is not easily accomplished because the economic and social "winners" and "losers" of any changes are different people and the potential losers will oppose any changes they expect to harm them and their communities. Mechanisms for sharing gains must be developed. Ocean spaces used by blue economic sectors are either the same or they overlap, and very often there is competition for space among sectors. This has an impact on the quality of marine ecosystems and resources on which the sectors depend. In addition to sectoral ecosystem-based management practices, a tool that can be used to address the allocation of coastal areas (land and sea) among different uses is Marine Spatial

Planning (MSP) (Box 16.1). MSP does not solve all balance issues, but at least can be used to make informed decisions about how to separate uses that can impact each other.

Box 16.1 Marine spatial planning

It is increasingly recognized that Marine Spatial Planning (MSP) could be an important tool for implementing national blue economy activities. MSP is a "public process of analyzing and allocating the spatial and temporal distribution of human activities in marine areas to achieve ecological, economic and social objectives" (IOC-UNESCO 2018). The term "Integrated Coastal Zone Management" (ICZM) is sometimes used interchangeably with MSP. The MSP process may result in a map of uses and activities. Most countries already have ocean areas where certain activities are prohibited or allowed, such as marine protected areas, offshore oil and gas leases, mineral leases, wind farms, waste disposal, etc., but the areas are not necessarily located and managed with regard to their potential interactions.

Instructions and recommendations for creation of MSPs have been published by various groups (e.g., Ehler and Douvere 2009; Jay 2017; UNESCO-IOC/European Commission 2021). Jay (2017) summarized the state of the art for MSP for the Organization for Economic Co-operation and Development (OECD) for its Green Growth and Sustainable Development Forum.

Gopnik et al. (2012) studied the issue of public involvement in MSP development and (based on interviews and analysis) recommended that "government planners need to engage outsiders earlier, more often, more meaningfully, and through an open and transparent process". It is essential that MSP not only apply to environmental protection, but that it embraces all three blue economy objectives.

The MSP for each country will look different, depending on products and services currently available and their condition (sustainably managed to depleted), the locations of existing and planned blue economy activities, activities in the EEZs of neighboring nations, and other factors. As noted by Ehler and Douvere (2009), MSP is not a one-time process, but MSPs must be adapted over time based on experience with specific MSPs.

Lee et al. (2020) note that the relations of the UN Sustainable Development Goals (SDG) to blue economy concepts is vague. Their bibliometric study found that the top three SDGs mentioned in relation to blue economy are SDG 14 on "Life Below Water", SDG 16 on "Peace, Justice, and Strong Institutions" and SDG 17 on "Partnership for the Goals". When examined from the view of which stakeholders are interested in the SDG-blue economy intersection, Lee et al. (2020) ranked the following as the top five stakeholder groups: (1) government agencies and policymakers, (2) NGOs, (3) scientists and researchers, (4) businesses and industries, and (5) local communities and society. This is clearly an indication of some priorities for aligning SDGs with blue economic goals at local levels.

16.2 Progress in Using Science and Technology: Blue Economy Resources and Sectors

16.2.1 Coral Reefs (Chap. 2)

Coral reefs are a major blue economy resource for many coastal nations in the tropics and subtropics, especially for island nations. Reefs support tourism, fisheries, and bioprospecting, as well as protecting coastal shorelines against wave energy. Coral reefs face major stress from increasing ocean temperatures (causing bleaching and ecosystem shifts from corals to algae) and ocean acidification (reducing the ability of corals to maintain their structures). Increasing impacts of coral diseases and outbreaks of crown-of-thorn sea stars on reefs also is being observed. Threats of mechanical damage to corals come from tourism and fisheries affect coral cover. The Global Ocean Observing System (GOOS) has established an Essential Ocean Variable (EOV) for Hard Coral Cover and Composition, which will help track the areas of live reef and changes over time. Microbial ecology represents a useful tool to understand large-scale ecological status of coral reefs. Remote sensing and modeling have been useful in the development of alert systems, for example, for bleaching events.

16.2.2 Seagrasses and Mangroves (Chap. 3)

Research to understand the role of seagrasses and mangroves in marine ecosystems has helped identify the value to ecosystem function of maintaining these ecosystems intact and healthy, as well as their value for storage of “blue carbon”, protection of adjacent land areas from storms, treatment of land-derived wastes, and provision of other services. Seagrass and mangrove systems can be threatened when other blue economy activities are pursued, such as coastal development for tourism and marine aquaculture, and damage from fishing and from anchors of tourist boats.

Healthy seagrass and mangrove ecosystems, linked with coral reef ecosystems in many areas, are essential foundations for other blue economy resources such as fisheries and ecotourism. Advances have been made in recent years to estimate the carbon sequestration potential of seagrasses, mangroves, and tidal marshes in different areas (Macreadie et al. 2019), as well as estimation of the areal extent of these ecosystems using remote sensing from satellites and aircraft. These methods, combined with modeling, have made possible the creation of global datasets of mangrove and seagrass abundance and distribution (e.g., see Simard et al. 2019 for mangroves). More intensive monitoring of seagrass and mangrove ecosystems is being implemented through GOOS by establishment of EOVs for Mangrove Cover and Composition, and Seagrass Cover and Composition, and an Essential Biodiversity Variable (EBV) for the Marine Biodiversity Observation Network (MBON) (Duffy et al. 2019). Future observations of these EOVs and EBV will likely require an integration of remote sensing and in situ “ground truthing” of remote observations. Establishment of EOVs and EBVs will make it possible to standardize global observations to create comparable datasets and will help establish a coordinated global network of researchers working on this topic.

16.2.3 Coastal Fisheries (Chap. 4)

Coastal fisheries is a well-established blue economy resource in many coastal and island nations (e.g., McKinley et al. 2019), often the primary blue economy resource. Seafood represents the major source of protein for communities in coastal states and small island nations, and is a major export product for many developing countries. The fisheries and aquaculture sectors are major sources of employment globally, with Asia accounting for more than 85% of the world total. Marine fisheries can take many forms, from small-scale artisanal activities to large-scale commercial fisheries carried out by companies wholly owned by national governments or companies, or joint ventures with foreign companies. The United Nations recognized the importance of marine fisheries in sustainable development when it approved Sustainable Development Goal 14 on “Life Below Water”. SDG 14 has more sub-goals directly related to fishing than to any other topic: SDG 14.4 (Sustainable fishing), SDG 14.6 (Remove subsidies contributing to overfishing), SDG 14.7 (Increase the economic benefits from sustainable use of marine resources), and SDG 14-B (Support small-scale fishers). We can add the fishery aspects of SDG 14-A (Increase scientific knowledge, research and technology for ocean health), related to the focus of this book.

Overfishing can reduce the ability of fish populations to replenish themselves and certain types of fishing (e.g., bottom trawling) can result in significant damage to the physical environment at the seafloor and result in high levels of bycatch of unwanted species, which are usually discarded to the sea dead. Fishing can have negative impacts on the blue economy resources of tourism and can damage coral reefs if done with destructive methods. Discarded fishing gear can continue to catch fish and other organisms (ghost fishing) and can add to plastic pollution in the ocean.

Offshore mining can negatively affect fisheries if areas used by commercial fish populations are directly disturbed or sediments suspended from mining activities negatively affect fish and invertebrates outside the mined areas (see also Chaps. 8 and 9). Establishment of Marine Protected Areas (MPAs) and other area-based conservation measures (Estradivari et al. 2022), though primarily a tool for biodiversity conservation, can play an important role for fisheries management in some settings, and science and technology are critical for the delineation and maintenance of MPAs (Edgar et al. 2014; Gill et al. 2014). Fishery management policies need to consider updated information on the local effects of climate change periodically, to design possible adaptive and mitigating measures.

Fisheries stock assessment and management based on scientific principles is well established, but fisheries worldwide are increasingly overfished (United Nations

2021). Many developed countries conduct regular fish stock assessments and set catch quotas based on these assessments, although stock assessment advice may be overruled by political considerations. Often, funding for fish stock assessments is more limited in many developing countries, so they must manage their fisheries based on more limited information.

A major need for effective fisheries management is estimation of fish catch, fishing effort, and bycatch. For commercial fisheries, a new technology that could help better estimate bycatch of unwanted fish species are remote electronic monitoring (REM) cameras (Course et al. 2020). Use of remote sensing to identify highly productive sea areas as potential fishery zones can make fishing more efficient, but this increased efficiency could lead to more serious overfishing. Genetic analysis of seafood samples with recently developed methods can discover seafood fraud, where one species is sold as a usually higher priced species.

16.2.4 Freshwater (Chap. 5)

Variability and changes in regional hydrologic cycles due to natural climate variations and human-induced global warming are major factors affecting the supply of freshwater to coastal systems. Human use of freshwater is constrained by rain falling on land; global change is expected to change the amounts and locations of terrestrial precipitation.

A large share of the world's people inhabit coastal regions, which are hotspots of blue economic development dependent on a reliable freshwater supply. Freshwater flow also influences coastal circulation patterns and controls the flux of sediments and nutrients to estuaries and coastal seas, and thus the biogeochemical processes sustaining blue economy resources, such as fish populations. Freshwater flow management can affect coastal ocean salinity and nutrient levels and ratios, which can lead to HABs and other threats. The chapter discusses issues related to the role and availability of freshwater resources in blue economic development, and the need for science- and technology-based management of freshwater resources.

The exploitation of major freshwater resources—groundwater and river water—and the modification of their flow regimes can create several environmental problems. Construction and operation of dams altering surface and subsurface freshwater flow affect estuaries, deltas, and adjacent seas and their associated blue economy resources. Groundwater (and hydrocarbon) extraction leads to subsidence and exacerbates the threat of enhanced coastal erosion and flooding from climate change and sea level rise.

Wise management of freshwater resources in coastal areas is critical to sustain coastal and marine resources, requiring science-based and ecosystem-inclusive management plans. Needed are assessments of freshwater requirements of the other blue economic resources such as mangroves and seagrass beds and of blue economic sectors such as tourism, aquaculture and fisheries. There is also the need to assess the quantity and quality of freshwater carried in surface and subsurface flows, and their direction. Tailored multidisciplinary scientific observations to match these needs and their primary locations need to be established. The use of natural geochemical tracers (e.g., radium isotopes) is considered a promising scientific approach to study freshwater flows, and will allow assessments of hydrodynamics in surface and subterranean estuaries, and quantification of associated terrestrial material fluxes from land to sea. Wavelet analysis is a relatively new technique to correlate precipitation and groundwater supplies, which can provide a useful predictive tool. Engineering solutions to protect freshwater aquifers, such as underground "dams", are being tested.

16.2.5 Tourism (Chap. 6)

Marine tourism is an important revenue source in many countries and it represents the largest component of the blue economy in many island states. It is sustained primarily by healthy coastal marine ecosystems and their biodiversity, which can be affected by climate and other global changes, as well as local human activities. Global change impacts to tourism are exacerbated by rapid, uncontrolled tourism development and aquatic touristic activities (e.g., habitat and biodiversity destruction), as well as the development of other blue economy sectors such as fisheries, oil and gas, and mining. Ecosystem-based management and marine spatial planning can be important methods to put tourism into the context of other coastal blue economy activities.

Science-based management of coastal tourism requires a change in perception on the nature of marine tourism—that it should be managed as another human-caused stressor—and a better awareness and acceptance of the benefits of scientific research to implement sustainable solutions. Tourism revenues should be used to support more research and monitoring focusing on the direct impacts of marine tourism activities on other blue economy sectors under both natural and perturbed conditions (e.g., climate change).

Limiting or banning some detrimental aquatic touristic activities will reduce their lethal and sublethal impacts on major tourism resources such as coral reefs and other coastal ecosystems. Further useful measures include reef enhancement and restoration projects (e.g., coral planting and giant clam restocking).

Education and awareness creation among stakeholders, especially tourists and tour operators, are especially important to minimize the impacts of tourism. Scientific data and information are needed related to potential tradeoffs between fisheries and tourism, to guide future scientific research and assessments by providing baselines for future assessments, Such data have come from activities within Marine Conservation Agreements (MCAs) between tourism operators and indigenous, resource-owning communities (e.g., shark fisheries and tourism).

16.2.6 Oil and Gas (Chap. 7)

Offshore oil and gas production plays a major role in the blue economies of some developing coastal and island nations (e.g., Angola, Brazil, Indonesia, Nigeria, and Venezuela). This is expected to continue in the short to medium term, even in the transition to lower carbon economies and a net-zero carbon society, until the available renewable energy options become feasible and alternative energy sources can ensure adequate energy supplies to meet demand.

Currently available and emerging science and technology options can address some of the environmental challenges related to oil and gas exploration and production. The chapter authors argue that a realistic and important pathway is the combination of CO_2- Enhanced Oil Recovery and CO_2 Capture and Storage, which have been applied in both developed and developing countries. They conclude that the development of science and technology supported by the necessary regulatory framework can help match economic outcomes and environmental requirements related to the impact of oil and gas production in the ocean and coastal areas. To be effective globally, this requires broad global interdisciplinary partnerships.

16.2.7 Minerals (Chap. 8)

The chapter discusses the relevance of mining to national blue economies, especially in sectors such as food and energy, which will require increased exploitation of minerals from coastal areas. Countries will continue to conduct coastal mining because of the relevance of mineral extraction for major blue economic sectors and their current or predicted scarcity/absence from terrestrial sources. Offshore mining of phosphates will be needed to maintain global agriculture, rare earth elements are required for modern electronics and production of some forms of renewable energy, and sand deposits are needed for new construction in coastal areas. Furthermore, offshore mining of diamonds is a major source of national income in Namibia, as the terrestrial supply of diamonds dwindles.

The impact of coastal and offshore mining can be enormous, especially in the form of environmental degradation and the destruction of habitats that support fisheries, tourism, and general marine biodiversity. This, in turn, affects the livelihoods of the dependent coastal populations. Environmental and social sustainability of coastal mining can only be achieved by putting in place measures to mitigate or reduce these impacts. Such measures include implementation of research and observations to monitor short- and long-term impacts, and cooperation among the affected blue economic sectors to develop and implement them.

16.3 Progress in Mitigating Environmental Threats to Establishing and Maintaining Blue Economies

16.3.1 Coastal Pollution (Chap. 9)

The impact of the wide variety of pollutants (nutrients, metals and organic pollutants and radionuclides) on ecosystems and the potential exacerbation of pollution by climate change pose challenges to the development of several blue economic sectors (e.g., fisheries and tourism). The blue economic sectors such as tourism, energy, and aquaculture also are sources of some pollutants and there may be the need to evaluate the trade-off among sectors. The use of DDT in Africa to control insect-borne diseases is an example of the trade-off between disease control and related adverse effects on human and ecosystem health.

The implementation of effective legislative and regulatory measures to remove pollutants (e.g., wastewater treatment), and to limit, ban or better manage polluting activities require scientific data from research and monitoring to identify the sources and distribution of pollutants and their short- and long-term impacts on blue economic resources. Among scientific research themes are (a) the impact of the ingestion of pollutants on different levels of the food chain and their ecotoxicity, (b) the nature of pollutant mobilization from blue economic activities such as fisheries (bottom trawling) and mining, and (c) impacts on aquaculture from polluted water and sediments. Coastal ocean observations are also of interest in the development of early warning systems using modelling and satellite remote sensing to forecast the areal extent of the impacts of pollution and to respond with appropriate adaptive mitigation measures.

For many developing countries, there is need for infrastructure and capacity development (laboratory and field facilities, and trained personnel) to improve monitoring and management of marine pollution. Responses to the challenges of marine pollution will benefit from cooperation among research, industry, and government agencies. Some of these measures could form part of countries' commitment to fulfilling the aims of SDG 14.

16.3.2 Harmful Algal Blooms (HABs) (Chap. 10)

The chapter discusses the adverse impacts of harmful algal blooms (HABs) on blue economies and the available science and technology to adapt to or mitigate HABs. The complex biotic and abiotic factors controlling HABs, the unpredictable nature of their occurrences, as well as the immense diversity of the algal species and toxic mechanisms, present challenges for the practice of blue economic sectors. The problems associated with HABs are severe in many developing countries in tropical and subtropical areas, where they affect the practice of sustainable fisheries, aquaculture, and tourism. HABs are expected to continue to expand in at least some of these regions due to climate and other global changes. Though it may not be possible to completely prevent HABs, there are several science and technology measures and options that will help alleviate their impacts on blue economies. Case studies from around the world suggest that such measures need to include more reliable early detection of HAB occurrences and identification of involved species, as well as additional research efforts to understand HABs dynamics and the associated risks from algal toxins.

Tailored monitoring programs involving observing systems consisting of remote satellite detection as well as automated instruments that can be deployed on moored, ship-based, or autonomous mobile platforms can provide data for the development of predictive models for short-term early warning (days to months) to predict toxic blooms. In combination with eco-physiological studies, implementing these capabilities has the potential to increase forecast capacity for risk assessment and avoid economic losses from unnecessary banning of trade or fisheries, and aquaculture facility closures. Closures are currently being used as adaptive measures, for example, in shellfish and mussel farming in some countries.

There is a need to develop affordable and sustainable technologies for efficient monitoring of HABs. Some tools of basic research, though useful, are rarely used in monitoring programs due to high equipment cost, significant professional expertise required, and lack of toxin analytical standards. International coordination for the establishment of standard analytical procedures and regulations is urgent.

A large gap exists between developing and developed countries in the availability and implementation of S&T tools and measures, There is inadequate capacity and instrumentation needed for ocean observations and to develop forecast models based on these observations. Furthermore, in many developing countries, species identification is still a major challenge because of scarcity of trained personnel to carry out reliable molecular analyses; most HAB identifications in developing countries are still conducted using light microscopy. Ongoing basic research on HABs is focused on issues that are of immediate economic interest, such as maintaining the safety of exported seafood products. These limitations prevent modelling for early warning needed to implement management actions to alleviate the impacts of HABs.

In the meantime, developing countries can take advantage of the vast amount of already available scientific research to better understand HAB dynamics, improved taxonomy, toxin detection, monitoring, and forecasting. Recently developed functional and structural assays that would also be low-cost, user-friendly, and provide high-throughput analyses—despite their limitations—represent promising alternatives for the sustainable monitoring of HAB toxins. The Intergovernmental Oceanographic Commission and International Atomic Energy Agency provide training programs for HAB identification and HAB toxin monitoring, respectively.[1]

[1] See https://prod.hab.ioc-unesco.org/training-courses/ and https://www.iaea.org/services/technical-cooperation-programme.

16.3.3 Ocean Acidification (Chap. 11)

Ocean acidification is a global problem resulting from the increasing CO_2 in the atmosphere entering the ocean and decreasing the surface ocean's pH, which impacts each nation's blue economic activities. Fisheries and tourism are the two primary blue economic activities potentially affected by ocean acidification, through effects at the base of marine food webs, but also on coral reefs.

Because reduction of ocean acidification will require significant reductions in how human commerce and transportation are fueled, and cooperation among the largest CO_2 emitters, hopes are dim for a quick global solution to the ocean acidification problem. This means that the effects of ocean acidification on blue economies must be mitigated at national levels, although there is still a role for international cooperation in research and observations related to ocean acidification.

National responses to ocean acidification should start with comprehensive (in time and space) observations of pH levels in a nation's coastal waters (SDG 14.3), particularly in areas that are most susceptible to the impacts of low pH, such as coral reef and aquaculture zones. Nations can mitigate the impacts of ocean acidification on affected areas by reducing other environmental stressors, such as pollution and fishing. Blue economy resources such as coral reefs, and mangrove and seagrass systems, should be protected from damage from other human activities. It may be helpful to establish MPAs with no-take zones as "refuges" for coral, seagrass, and mangrove systems. Both "passive" and "active" approaches have been proposed as local responses to ocean acidification (Albright and Cooley 2019). Passive measures include efforts to improve the resilience of reef areas, including more conservative management of fisheries and coral reef areas to make them more resilient, establishment of coral nurseries, use of marine spatial planning to move damaging activities away from sensitive reef areas, establishment of marine protected areas to protect reef areas, including reef health and sustainability in national and regional blue economy plans, and improved wastewater treatment to decrease eutrophication. "Active" intervention approaches that can be used to mitigate or adapt to changes in ecosystem services that may be caused by ocean acidification and to increase the resilience of reefs include using aquatic plants to remove CO_2 from seawater, chemical remediation, reef restoration, and "assisted evolution" (Albright and Cooley 2019).

16.3.4 Climate Change (Chap. 12)

Climate change is a threat to blue economies worldwide, with multiple manifestations. Increases in CO_2 and global warming, and the risks associated with their attendant impacts on the planet's geophysical and ecological systems, affect all blue economic sectors. Sea level rise, changes in the frequency of extreme events and the changing pattern of dry and wet seasons affect coastal ecosystems and habitats through flooding, erosion and salinization. Acidification and deoxygenation additionally affect blue economic resources such as coral reefs and fisheries. Changes in global hydrologic cycles are predicted, with changes in the frequency, intensity, and location of rainfall events possibly already changing. Changes in the amount of rainfall and snow will change the amount and timing of the flow of freshwater—laden with nutrients, sediment, and pollutants—to the coastal ocean. Management and mitigation measures to protect blue economies need to be based on improved scientific assessments developed from observations and monitoring of potential ecosystem changes, and the development of model-based forecasting systems. There are also opportunities for scientific innovation in the form of development of both ecosystem-based and hard-engineering solutions. Regionally and locally, however, there is a need to monitor and weigh the costs and benefits of innovative measures for sustainable blue economies.

16.3.5 Small Islands (Chap. 13)

Small island states are rich in resources that can contribute to blue economic development, and tend to be more reliant on blue economy activities than other coastal nations. As in other developing coastal states, the resources in SIDS are under threat from climate change and other human interventions, leading to overfishing, loss of biodiversity and pollution. SIDS have, however, challenges and opportunities that set them apart from other developing countries, so a chapter is included in the book to highlight these issues. Although there is some overlap with other chapters, this chapter presents information in a small island-centric way. The SIDS' unique challenges are in some ways existential as, for example, the impacts of sea level rise and extreme natural events. There are also potential non-climate risks from new and emerging initiatives in resource exploitation (minerals and renewable energy). Optimum use of resources for sustainable blue economies requires an integrated strategy that is based on the application of science and technology to plan blue economic development and prioritize sectors, where traditional knowledge can enrich the strategy. Of particular interest are sectors such as fisheries, tourism, and renewables.

Inadequate scientific support systems, problems of logistics associated with the vastness of the ocean space, and transport and communication problems associated with the remoteness of individual islands, such as in the Pacific Ocean, are all issues that need to be addressed. International funding and cooperation, and transfer of technologies, are key elements for successful implementation of science and technology-supported blue economies.

16.4 Steps in Using Science and Technology Better to Establish Successful Blue Economies

Based on the information presented in the preceding chapters, the following steps are necessary to establish successful blue economies:

1. Commitment of national policymakers and administrators to the three-fold goals of sustainable blue economies. This commitment should be demonstrated by the establishment of new laws and regulations needed to create and maintain a national blue economy (Sect. 1.2.5).
2. Adoption of methods to properly quantify the costs and benefits of the extraction of renewable and non-renewable marine resources. This step should include periodic measurement and assessment of the performance of blue economy sectors, and the overall contribution of blue economy to national GDPs, as well as environmental and social objectives (Sect. 1.2.5).
3. Investment in ocean science (natural and social science) in areas needed to fill information gaps related to understanding marine systems well enough to quantify costs and benefits (Sect. 16.4.1).
4. Investment in technologies needed to observe ocean systems and effects of resource use, and to mitigate the negative impacts of resource use (Sect. 16.4.2).
5. Commitment to developing capacity for ocean science and technology to carry out the previous steps (Sect. 16.4.3).

Failure to achieve any of these steps poses a major barrier to establishing blue economies. Steps 1 and 2 were discussed briefly in Chap. 1 and will not be covered in detail in this chapter.

SDGs provide a global context for the implementation of blue economic approaches at national levels and the UN Decade of Ocean Science for Sustainable Development ("Ocean Decade") should help provide some of the information needed to meet SDG goals. Countries seeking to develop blue economies have a range of international frameworks to help jumpstart their efforts, including UNCLOS. However, UNCLOS was developed before the concepts of blue economy and marine spatial planning were developed, so some adaptations of UNCLOS may be necessary. Mechanisms that could be helpful for achieving SDG goals are being developed by the Ocean Decade and the Ocean Panel (see Sect. 16.4.4).

16.4.1 Investment in Ocean Research

Since blue economies are built on a foundation of ocean observations and research, national governments should identify science and observation needs and information that is already available to build their blue economies. (In many places, enough information is available to take positive steps, but the call for more science can be a tactic to delay needed, but controversial, policies.) Where information is truly lacking, governments need to identify necessary observations and research, and then support these. Sustainable blue economies are impossible without investment in ocean science (Stuchtey et al. 2020; Vierros 2021). Valuing resources (Step #2), tangible and intangible, requires a minimum level of scientific understanding about marine organisms in a nation's EEZ, how they interact in ecosystems, and how environmental variations affect ocean resources. This scientific understanding can be developed and synthesized by national science and environmental agencies. In the absence of adequate scientific understanding, the most prudent approach is to make precautionary decisions that are reversible. For example, in fisheries management, it could mean changing harvest quotas for individual species during the El Nino-Southern Oscillation (ENSO) cycle, depending on the effect of ENSO on the species (Feng et al. 2022), or deceasing harvest quotas if mining operations are planned and the effects are unknown.

It is important for national governments to identify fields of study that are key for developing and maintaining national blue economies and support academia and government laboratories to conduct research related to these fields. In other words, not every country needs to support research in all areas of ocean science; they can prioritize topics most important for the country. Each of the chapters identifies specific research topics that would be helpful to make blue economy resources more sustainable or to avoid or mitigate threats to blue economies. Some general research topics include the following:

- How do blue economy activities affect each other? Information from this kind of research will help managers balance among activities.
- What are effective actions to avoid or mitigate the threats of HABs, ocean acidification, pollution, climate change, and others?
- What areas could be particularly important to protect as "climate refuges" for corals (Sully et al. 2021) and other ecosystems to improve the likelihood of long-term sustainability of these ecosystems?

16.4.2 Investment in Ocean Observations

Fortunately, nations can take advantage of international facilities and assistance from other nations for some ocean observations and do not necessarily need to implement all their own observing capabilities. For example, satellite observations are available for sea surface temperature, sea surface salinity, and surface chlorophyll from the satellite services of many nations (see example of Ghana in Chap. 14). National investments to use such products involves funding to download and interpret data products, and to produce derived projects useful on a smaller national scale. This requires the development of technical and scientific expertise needed to handle satellite data and to handle models to put satellite data into the context of national fisheries, tourism, reef health, and other blue economy resources. Another asset is GOOS, which currently produces data products related to many parameters of interest to national policymakers (see Chap. 14). GOOS has developed the concept of EOVs, which include an expanded suite of parameters that will be useful for national managers responsible for blue economies. Coastal and island nations should commit to contributing data to help measure EOVs related to coral reef, seagrass, and mangrove systems, and to measure pH to monitor ocean acidification. Every coastal nation should regularly collect observations in situ. Such observations include measurements of oxygen, temperature, and pH levels in coastal waters; marine biology and biodiversity parameters (Estes et al. 2021), and monitoring of harmful algal blooms (if this is a problem in the nation's EEZ). Some priorities for expanding ocean observations include the following:

- Development and wide dissemination of low-cost instruments for important measures of HABs, ocean acidification, etc.
- Technology transfer and training for making observations
- Implementation of national observations related to GOOS EOVs.

It is important that data from observing systems and research are available openly, after appropriate periods of time for quality control (observations) and publication (for research data). Open data access will provide more justification for national decisions related to blue economy.

16.4.3 Promoting Ocean Science Capacity for Blue Economy in Developing Countries

As highlighted in Chap. 15 and mentioned throughout the other chapters, development of improved capacities to use science and technology as tools to achieve blue economy objectives is key.

This book has highlighted examples of how science and technology can contribute to sustainable use of ocean resources and mitigate coastal environmental problems. Generation of scientific knowledge on which to base blue economies depends on national ocean research and observation activities, which require the development and maintenance of an adequate base of scientific and technical expertise within a country. National governments need to enable the creation of the necessary scientific infrastructure and cooperation among government, academia, and industry. Developing a sufficient system of ocean observations and research is a long-term process, not a "quick fix". This process can be especially challenging for developing countries, which have limited resources to support necessary infrastructure and social support programs, and may view investments in ocean science as unfeasible, given other national budget priorities. In the short term, the relevant expertise can be "imported" from other countries until in-country expertise can be developed. Many sources of capacity development assistance are available from national aid agencies and international science organizations (see Chap. 15) to help boost national ocean science communities. At the national level, capacity development will require public and private sector investments by all stakeholders including academia, industry and non-governmental organizations. SDG commitments by UN Member States and the necessary reporting provide another incentive to build the needed capacity to strengthen communication at the science-policy interface.

International organizations, both intergovernmental and non-governmental, have important roles to play in fostering global ocean science and technology partnerships. These partnerships can help share knowledge and best practices and should be fostered at all levels, including individual scientists, institutions, national governments, and companies working together. Most international organizations mentioned in this book already have partnership efforts ongoing that could serve as foundations for expanded activities. The Ocean Decade has identified capacity development as a key component for the 2021–2030 period (UNESCO-IOC 2021).

16.4.4 Current Global Actions for Developing Sustainable Blue Economies

Several international activities currently being developed could have a major positive impact on the development of blue economies worldwide, including (1) the Ocean Panel; www.oceanpanel.org), (2) the Ocean Decade, and (3) the development of EOVs. The value of ocean knowledge is emphasized by all three of these activities, including the importance of understanding ocean processes, and the impact of stressors on them, to account for the full value of ocean assets and the ocean economy, as well as their role in guiding the sustainable development of the related ocean industries.

The Ocean Panel's focus is on the ocean economy and the panel has commissioned a variety of Blue Papers on practical aspects related to the ocean economy. As mentioned in Chap. 1, the Ocean Panel has provided advice on the importance of developing national ocean accounts to track both income and assets related to ocean resources.

The Ocean Decade is emphasizing the importance of science and technology in developing blue economy-related policies. This program will also provide foundational information to create sustainable blue economies and mitigate threats to blue economies.

Achievement of blue economy goals will be elusive without increased transfer of knowledge and technology from developed to developing nations, and in communicating and transferring results of science and technology application locally at the national level. Ocean Decade Challenge 4—Develop a sustainable and equitable ocean economy—is particularly relevant. IOC-UNESCO (2021) highlights how the intersection between activities of the Ocean Decade and the work of the Ocean Panel can reinforce each other.

Advances in EOVs by the Global Ocean Observing System is another promising activity that should be helpful in addressing the opportunities and challenges presented in preceding chapters because the EOVs will provide standard measurement approaches to help make measurements collected in different locations by different people comparable. Ideally, EOV-related data will be seamlessly available from different sources to enable global assessments of the status and trends of ocean parameters, such as through the World Ocean Assessments.

16.5 Concluding Remarks

The ambiguity of blue economy concepts means that actions to develop and maintain blue economies will differ among nations: developed versus developing, least developed versus countries further along the development pathway, SIDS versus continental nations, etc. The balancing required in blue economies must generally be accomplished by national governments, which are in a position to analyze the benefits and costs of using different resources, that balance between exploitation and environmental protection, and maintain social equity in the face of both resource exploitation and environmental protection. At the same time, ocean areas between adjacent coastal nations are linked by ocean currents and migrating organisms, so national actions must be considered in regional contexts.[2] Many international treaties recognize the interconnectedness of national policies and actions, and can serve as a basis for regional actions.

References

Albright R, Cooley S (2019) A review of interventions proposed to abate impacts of ocean acidification on coral reefs. Reg Stud Mar Sci 29:100612. https://doi.org/10.1016/j.rsma.2019.100612

Bond P (2019) Blue economy threats, contradictions and resistances seen from South Africa. Journal of Political Ecology 26:341–362. https://doi.org/10.2458/v26i1.23504

Course GP, Pierre J, Howell BK (2020) What's in the net? Using camera technology to monitor, and support mitigation of, wildlife bycatch in fisheries. WWF. https://wwfwhales.org/resources/2020-whats-in-the-net-remote-electronic-monitoring

Duffy JE, Rebelo LM, Miloslavich P (2019) Integrating global seagrass and mangrove ecosystem observations. Eos 100 https://doi.org/10.1029/2019EO136791

Edgar GJ, Stuart-Smith RD, Willis TJ et al (2014) Global conservation outcomes depend on marine protected areas with five key features. Nature 506:216–220

Ehler C, Douvere F (2009) Marine spatial planning: a step-by-step approach toward ecosystem-based management. Intergovernmental Oceanographic Commission and Man and the Biosphere

[2] For large nations with strong sub-national governments (e.g., states, provinces) having good ocean scientific infrastructures and well-established management traditions, it might be reasonable to establish sub-national blue economy plans in the context of national plans. Examples include the coastal states of the United States and Australia, and the eastern and western coastal provinces of Canada.

Programme. IOC Manual and Guides No. 53, ICAM Dossier No. 6. UNESCO (English), Paris. https://unesdoc.unesco.org/ark:/48223/pf0000186559
Ertör I, Hadjimichael M (2020) Editorial: Blue degrowth and the politics of the sea: rethinking the blue economy. Sustain Sci 15:1–10. https://doi.org/10.1007/s11625-019-00772-y
Estes M, Anderson C, Appeltans W et al (2021) Enhanced monitoring of life in the sea is a critical component of conservation management and sustainable economic growth. Mar Policy 132:104699. https://doi.org/10.1016/j.marpol.2021.104699
Estradivari MFA, Adhuri DS, Ferse SCA et al (2022) Marine conservation beyond MPAs: towards the recognition of other effective area-based conservation measures (OECMs) in Indonesia. Mar Policy 137:104939. https://doi.org/10.1016/j.marpol.2021.104939
Feng Z, Yu W, Chen X (2022) Concurrent habitat fluctuations of two economically important marine species in the Southeast Pacific Ocean off Chile in relation to ENSO perturbation. Fish Oceanogr 31:123–134. https://doi.org/10.1111/fog.12566
Gill DA, Mascia MB, Ahmadia GN et al (2014) Capacity shortfalls hinder the performance of marine protected areas globally. Nature 543:665–669
Gopnik M, Fieseler C, Cantral L et al (2012) Coming to the table: early stakeholder engagement in marine spatial planning. Mar Policy 36:1139–1149. https://doi.org/10.1016/j.marpol.2012.02.012
IOC-UNESCO (2018) Balancing sustainable use and conservation through marine spatial planning. Paris. http://msp.ioc-unesco.org/
IOC-UNESCO (2021) Ocean knowledge for a sustainable ocean economy: Synergies between the Ocean Decade and the outcomes of the Ocean Panel (The Ocean Decade Series, 17). UNESCO, Paris
Jay S (2017) Marine spatial planning: assessing net benefits and improving effectiveness. Issue note was prepared for the 2017 Green Growth and Sustainable Development Forum. https://www.oecd.org/greengrowth/GGSD_2017_Issue%20Paper_Marine%20Spatial%20Planning.pdf
Konar M, Ding H (no date) A sustainable ocean economy for 2050. High-level Panel for a Sustainable Ocean Economy and World Resources Institute. https://oceanpanel.org/sites/default/files/2020-07/Ocean%20Panel_Economic%20Analysis_FINAL.pdf
Lee KH, Noh J, Khim JS (2020) The blue economy and the United Nations' Sustainable Development Goals: challenges and opportunities. Environ Int 137(January):105528. https://doi.org/10.1016/j.envint.2020.105528
Macreadie PI, Anton A, Raven JA et al (2019) The future of blue carbon science. Nat Commun 10:3998. https://doi.org/10.1038/s41467-019-11693-w
McKinley E, Aller-Rojas O, Hattam C et al (2019) Charting the course for a blue economy in Peru: a research agenda. Environ Dev Sustain 21:2253–2275. https://doi.org/10.1007/s10668-018-0133-z
Österblom H, Wabnitz CCC, Tladi D et al (2020) Towards ocean equity. World Resources Institute, Washington, DC. www.oceanpanel.org/how-distribute-benefits-ocean-equitably
Simard M, Fatoyinbo L, Smetanka C et al (2019) Mangrove canopy height globally related to precipitation, temperature and cyclone frequency. Nat Geosci 12:40–45. https://doi.org/10.1038/s41561-018-0279-1
Stuchtey M, Vincent A, Merkl A et al (2020) Ocean solutions that benefit people, nature and the economy. World Resources Institute. Washington, DC, www.oceanpanel.org/ocean-solutions
Sully S, Hodgson G, van Woesik R (2021) Present and future bright and dark spots for coral reefs through climate change. Glob Change Biol 2022:1–14. https://doi.org/10.1111/gcb.16083
UNESCO-IOC (2021) The United Nations Decade of Ocean Science for Sustainable Development (2021–2030) implementation plan (IOC Ocean Decade Series, 20). UNESCO, Paris
UNESCO-IOC/European Commission (2021) MSP global international guide on marine/maritime spatial planning (IOC Manuals and Guides No. 89). UNESCO, Paris
United Nations (2021) The Sustainable Development Goals Report 2020. United Nations, New York. https://unstats.un.org/sdgs/report/2020/The-Sustainable-Development-Goals-Report-2020.pdf

Vierros MK (2021) Promotion and strengthening of sustainable ocean-based economies. United Nations. https://sdgs.un.org/sites/default/files/2022-01/2014248-DESA-Oceans_Sustainable_final-WEB.pdf

World Bank and United Nations Department of Economic and Social Affairs (2017) The potential of the blue economy: increasing long-term benefits of the sustainable use of marine resources for small island developing states and coastal least developed countries. World Bank, Washington DC

Index

E. R. Urban Jr. and V. Ittekkot (eds.), *Blue Economy*,
https://doi.org/10.1007/978-981-19-5065-0

D

E

F

V

W

Z