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Rajarshi Dasgupta
Shizuka Hashimoto
Osamu Saito *Editors*

Assessing, Mapping and Modelling of Mangrove Ecosystem Services in the Asia-Pacific Region

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Rajarshi Dasgupta • Shizuka Hashimoto •
Osamu Saito
Editors

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Editors
Rajarshi Dasgupta
Institute for Global Environmental Strategies
Hayama, Kanagawa, Japan

Shizuka Hashimoto
Department of Ecosystem Studies
University of Tokyo
Tokyo, Tokyo, Japan

Osamu Saito
Institute for Global Environmental Strategies
Hayama, Kanagawa, Japan

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Preface

Mangroves provide a plethora of indispensable ecosystem services that are vital to human well-being in low-lying coastal areas. They store a disproportionately high amount of carbon, regulate coastal water quality, protect from storms and waves, support livelihood, and thus play a pivotal role in both climate change mitigation and adaptation. Despite providing such immense benefits to humankind, nearly 3.6 million hectares of mangroves have already been lost due to a variety of anthropogenic factors, including coastal development, agricultural land conversion, aquaculture expansion and over-harvesting. The remaining mangroves also suffer from the threat of deforestation, and it is feared that the ecosystem services of mangroves may be functionally lost by the end of this century. To protect the remaining mangroves, it is important to integrate their ecosystem services in coastal land use planning by monitoring synergies and trade-offs in the coastal development process.

The current and future delivery of vital mangrove ecosystem services, such as the ability to store carbon, sediment retention, pollution control and coastal hazard mitigation, will depend on a series of external factors and uncertainties, including climate change and anthropogenic disturbances. In 2016, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) recommended the adoption of scenario exercises to assess biodiversity and ecosystem services through space and time. Scenarios are a useful tool and a structured process to determine the uncertain futures, and along with models, can provide important information on the current and future availability of ecosystem services. As a structured process, scenario planning involves steps such as identification of potential influential drivers, their ranking and narrative development, among others. Similarly, there are multiple types of models, namely, correlative models, process-based models and expert-based models, to explore ecosystem services.

This book consists of 16 chapters, which aim to assess, map and model the mangroves and their vital ecosystem services. Focusing on the Asia-Pacific region and different ecosystem services of mangroves, the book presents case studies and methodological overviews on mangrove scenario planning, including trend analysis, identification of influential drivers, geospatial mapping and modelling of ecosystem services. The book is divided into two parts. The first part covers five chapters on trend analysis and identification of influential drivers of change. The rest of the chapters narrate different tools and techniques of mapping mangrove ecosystem services.

The book is meant for students and researchers on mangroves; however, it should be also useful for foresters and field-level practitioners. We are hopeful that the shared knowledge from this book will promote scenario research in Asia-Pacific and promote evidence-led policy planning for foresting sustainable mangrove communities.

Hayama, Japan Rajarshi Dasgupta
Tokyo, Japan Shizuka Hashimoto
Hayama, Japan Osamu Saito

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Editors and Contributors

About the Editors

Rajarshi Dasgupta is a Senior Policy Researcher in the Institute for Global Environmental Strategies. He received his Ph.D. in Global Environmental Studies from Kyoto University, Japan. He has worked extensively with the mangrove communities in India, Bangladesh, Myanmar and the Philippines and authored several research articles in peer-reviewed journals and edited volumes. He served as a Lead Author (LA) for the Intergovernmental Science-Policy Platform for Biodiversity and Ecosystem Services (IPBES) Asia-Pacific Regional Assessment Report and currently serving as the Lead Author for the IPBES assessment on Sustainable Use of Wild Species. His current research interest includes assessment and management of mangrove ecosystem services and their effective utilization for climate change adaptation and disaster risk reduction through proactive landscape planning.

Shizuka Hashimoto is an Associate Professor at the Department of Ecosystem Studies, Graduate School of Agricultural and Life Sciences, the University of Tokyo. He has more than ten years of experience in ecosystem services evaluation and scenario analysis. He is a member of the Science Council of Japan. At the international level, he contributed to the Intergovernmental Science Policy Platform on Biodiversity and Ecosystem Services (IPBES) Global Assessment and the Asia-Pacific Regional Assessment as a Lead Author, and IPCC-IPBES Co-sponsored workshop report as a Scientific Steering Committee member. Since 2018, he has served as one of the Multidisciplinary Expert Panel members of IPBES and a co-chair of the Task Force on Scenarios and Models.

Osamu Saito is a principal policy researcher and an expert in the field of biodiversity and ecosystem services. He has been working on the interlinkages between ecological, human and social systems through sustainability science approaches. His research experiences include socio-ecological studies on the ecosystem services provided by traditional rural production landscapes (Satoyama) in both Japan and other Asian countries. He worked for the Advanced Study of Sustainability (UNU-IAS) as Academic Director from 2011 to 2020. He has been also actively promoting various activities for the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) as a lead author of both regional and global assessments.

Contributors

Anirban Akhand Coastal and Estuarine Environment Research Group, Port and Airport Research Institute, Yokosuka, Kanagawa, Japan
Department of Ocean Science, Hong Kong University of Science and Technology, Kowloon, Hong Kong, SAR, China

Ram Avtar Faculty of Environmental Earth Science, Hokkaido University, Hokkaido, Japan

Kanika Bimrah Laboratory of Regional Planning, Graduate School of Global Environmental Studies, Kyoto University, Kyoto, Japan

Abhra Chanda School of Oceanographic Studies, Jadavpur University, Kolkata, West Bengal, India

Abhiroop Chowdhury Tagore Society for Rural Development, Kolkata, West Bengal, India
Jindal School of Environment and Sustainability, O.P. Jindal Global University, Sonipat, Haryana, India

Ming-Kuang Chung Institute of Information Science, Academia Sinica, Taipei, Taiwan

Syarifah Aini Dalimunthe Research Center for Population, National Research and Innovation Agency (BRIN), Jakarta, Indonesia
Graduate School of Environmental Studies, Nagoya University, Nagoya, Aichi, Japan

Rajarshi Dasgupta Institute for Global Environmental Strategies, Hayama, Kanagawa, Japan

Kriselda Anna delos Santos Graduate School of Environmental Science, Hokkaido University, Hokkaido, Japan

Shalini Dhyani National Environmental Engineering Research Institute (CSIR-NEERI), Nagpur, Maharashtra, India

Masahiko Fujii Faculty of Environmental Earth Science, Hokkaido University, Hokkaido, Japan

Sonali Ghosh Ministry of Environment Forest and Climate Change, New Delhi, India

Shizuka Hashimoto Department of Ecosystem Studies, University of Tokyo, Tokyo, Japan

Wan-Hui Huang The Research Institute for Humanity and Nature, Kyoto, Japan

Muhammad Hussain Department of Geography, The Islamia University of Bahawalpur, Bahawalpur, Pakistan

Chitiz Joshi Wildlife Institute of India, Dehradun, India

Saniya Joshy Kerala University of Fisheries and Ocean Studies, Kochi, Kerala, India

Rakesh Kadaverugu CSIR-National Environmental Engineering Research Institute (NEERI), Nagpur, Maharashtra, India

Peter King Institute for Global Environmental Strategies (IGES), Hayama, Kanagawa, Japan

Pankaj Kumar Institute for Global Environmental Strategies (IGES), Hayama, Kanagawa, Japan

D. B. Magcale-Macandog Institute of Biological Sciences, College of Arts and Sciences, University of the Philippines Los Banos, Laguna, Philippines

Anukul Nath Wildlife Institute of India, Dehradun, India

Aliya Naz Tagore Society for Rural Development, Kolkata, West Bengal, India
Jindal School of Liberal Arts and Humanities, O.P. Jindal Global University, Sonipat, Haryana, India

Muktipada Panda Banki (Autonomous) College, Banki, Odisha, India

Md. Shah Paran The Unnayan Onneshan, Dhaka, Bangladesh

Li-Pei Peng Department of Bio-Industry Communication and Development, National Taiwan University, Taipei, Taiwan

Nehru Prabakaran Wildlife Institute of India, Dehradun, India

Ari Purwanto Sarwo Prasojo Research Center for Population, National Research and Innovation Agency (BRIN), Jakarta, Indonesia
Department of Economics, Faculty of Economics and Business, Universitas Indonesia, Depok, Indonesia

Paras Pujari CSIR-National Environmental Engineering Research Institute (NEERI), Nagpur, Maharashtra, India

Intan Adhi Perdana Putri Research Center for Population, National Research and Innovation Agency (BRIN), Jakarta, Indonesia

A. F. M. Raganas Department of Biological Sciences and Environmental Studies, College of Science and Mathematics, University of the Philippines Mindanao, Mintal, Davao City, Philippines
WISER BioCon Lab, College of Science and Mathematics, University of the Philippines Mindanao, Mintal, Davao City, Philippines

Atta-ur Rahman Department of Geography, University of Peshawar, Peshawar, Pakistan

Osamu Saito Institute for Global Environmental Strategies, Hayama, Kanagawa, Japan

Izuru Saizen Laboratory of Regional Planning, Graduate School of Global Environmental Studies, Kyoto University, Kyoto, Japan

Severino Salmo III College of Science, Institute of Biology, University of the Philippines Diliman, Quezon City, Philippines

Nagisa Shiiba Institute for Global Environmental Strategies (IGES), Hayama, Kanagawa, Japan

Binaya Raj Shivakoti Institute for Global Environmental Strategies (IGES), Hayama, Kanagawa, Japan

Jayshree Shukla National Environmental Engineering Research Institute (CSIR-NEERI), Nagpur, Maharashtra, India
CSIR-National Environmental Engineering Research Institute (NEERI), Nagpur, Maharashtra, India

Sunidhi Singh CSIR-National Environmental Engineering Research Institute (NEERI), Nagpur, Maharashtra, India

Yasuo Takahashi Institute for Global Environmental Strategies (IGES), Hayama, Kanagawa, Japan

Gautam Talukdar Wildlife Institute of India, Dehradun, India

Rashed Al Mahmud Titumir Department of Development Studies, University of Dhaka, Dhaka, Bangladesh
The Unnayan Onneshan, Dhaka, Bangladesh

Huang Wanhui The Research Institute for Humanity and Nature, Kyoto, Japan

Chapter 1
Envisioning the Future of Mangroves Through Mapping and Modeling of Mangrove Ecosystem Services

Rajarshi Dasgupta, Shizuka Hashimoto, and Osamu Saito

Abstract Mangrove forests are among the most diverse tropical forests, and they provide critical ecosystem services indispensable for human well-being. These ecosystem services play a critical role in climate change mitigation and adaptation, sustainable development, and disaster risk reduction in vulnerable tropical coastal areas. Mangroves are particularly important for Asia, given the high population density in coastal areas, the rising threat of natural hazards, and climate-induced sea-level rise. Despite the growing importance of mangroves in international policy documents, mangrove cover continues to decline across the world, particularly in Asia, due to a variety of natural and anthropogenic drivers. Against this backdrop, this introductory chapter outlines the current state of mangroves in Asia, together with the influential drivers behind their degradation as well as efforts for restoration in recent years. Given the high uncertainty surrounding the future existence of mangroves in Asia and the delivery of the vital ecosystem services, the chapter highlights the need for assessing, mapping, and modeling mangrove ecosystem services and scenario-based quantification of such services across space and time. In particular, the chapter calls for assessing the future of mangroves funder plausible alternative development pathways and identifies their importance in evidence-led policy planning. This chapter further outlines the book's subsequent chapters and expectations.

Keywords Mangrove · Scenarios · Ecosystem services · Decision-making · Asia-Pacific

R. Dasgupta (✉) · O. Saito
Institute for Global Environmental Strategies, Hayama, Kanagawa, Japan
e-mail: dasgupta@iges.or.jp

S. Hashimoto
Department of Ecosystem Studies, The University of Tokyo, Tokyo, Japan

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1.1 Introduction

Mangroves are among the most diverse tropical forests that occupy the tropical coastline and provide a plethora of ecosystem services indispensable to human well-being (Donato et al. 2011). Despite occupying only 0.7% of the tropical forested areas, mangroves have become central to numerous recent policy advocacy reports, owing to their exceptional ecosystem services and contribution to the contemporary sustainability agenda, including climate change, disaster risk reduction, and sustainable development (Alongi and Mukhopadhyay 2015). In particular, mangroves have become central to Ecosystem-based Adaptation (EbA) strategies, which advocate the use of natural ecosystem services, as a part of the overall adaptation strategy to climate change.

Historically, mangroves used to extend over 200,000 km^2 but have suffered severe deforestation and degradation over the last three decades (Worthington et al. 2020). The United Nation's Food and Agricultural Association (FAO) statistics, which are often used for official reporting and target setting, estimated that mangroves cover some 148,000 km^2 globally, with nearly 40% located in just four countries, namely, Indonesia, Brazil, Nigeria, and Mexico. Despite the large-scale annihilation of mangroves over the past three decades, mangroves continue to provide extraordinary ecosystem services, including all the four designated categories, namely, provisioning, regulating, supporting, and cultural.

Mangroves are the most carbon-rich forests in the tropics and store an average of 1023 Mg carbon per hectare (Alongi and Mukhopadhyay 2015; Donato et al. 2011). They store a significantly high amount of carbon compared to any other terrestrial ecosystem, thus playing a pivotal role in both climate mitigation and ecosystem-based adaptation (EbA) measures (Adame et al. 2021; Sannigrahi et al. 2020). It is estimated that mangrove deforestation alone generates emissions of 0.02–0.12 Pg carbon per year, which is roughly 10% of emissions from global deforestation (Alongi and Mukhopadhyay 2015; Donato et al. 2011). They further act as the first line of defense against coastal hazards. Evidence from past mega-disasters such as the Indian Ocean Tsunami in 2004 and Super Typhoon Haiyan 2013 suggested their exceptional wave attenuation ability, resulting in a call for better conservation and management of mangroves across vulnerable tropical coastlines (DasGupta and Shaw 2013a; Kamil et al. 2021). Mangroves act as nurseries and breeding sites for fish, birds, mammals, and crustaceans. They support water purification, trap sediment, recycle nutrients, and remove contaminants from coastal waters (Barbier 2016; Schwenke and Helfer 2021). Globally, some 120 million people depend on mangroves for their livelihoods (Mukherjee et al. 2014), although the exact number is possibly much higher considering both direct and indirect dependence on mangroves. Furthermore, there are some 3945 mangrove "attractions" in 93 countries and territories boosting the cultural and emotional well-being of local communities (Spalding and Parrett 2019). In terms of economic value, all these ecosystem services together can reach values of between USD 2772 per hectare per year to

USD 80,334 per hectare per year depending on the diverse estimation method and the local socioeconomic context (Salem and Mercer 2012).

Despite providing such immense benefits to humankind, the state of mangroves globally remains in a perilous condition. Over 20%, or nearly 3.6 million hectares of mangroves, have already been lost due to a variety of anthropogenic factors, including coastal development, agricultural land conversion, aquaculture expansion, and overharvesting (DasGupta and Shaw 2013a). Mangrove cover is still decreasing, albeit at a marginally slower pace than originally measured. Initially, it was estimated that between 2000 and 2010, the global losses of mangrove cover reached approximately 1%–2% every year (Goldberg et al. 2020; Hamilton and Casey 2016; Pendleton et al. 2013). Recent estimates reveal that the annual loss of mangroves probably ranged from 0.16% to 0.39% per year between 2000 and 2012. While many continents, including South and North America, reported an increase in mangrove forests over the last decade, Asia continues to suffer from a net loss of mangroves despite some serious restoration and rehabilitation efforts (FAO 2020). Such an accelerated loss of mangroves led to global concerns that the mangrove ecosystem services might be functionally extinct by the end of this century (Andradi-Brown et al. 2013; Duke 2007). Such concerns might seem far-fetched, but mangroves may well vanish from the coast of many countries in Asia, if the current trend prevails.

1.2 Drivers of Mangrove Loss in Asia and Pacific

According to the latest scientific estimate based on satellite observations, global mangrove cover is approximately 137,760 km^2 spreading over 118 countries (Giri et al. 2011). However, depending on the definition and assessment methods, this figure varies extensively. For instance, one study distinguished mangrove forests from their associated biome and reported a global mangrove forest cover of 83,495.24 km^2 over the same period (Hamilton and Casey 2016). Despite such disparity of definition and estimation methods, researchers across the world agree that the fate of mangroves, including the vital ecosystem services they provide, remains under great uncertainty (Andradi-Brown et al. 2013). While there are ongoing global efforts to strengthen mangrove conservation and restoration (DasGupta and Shaw 2013a; Worthington et al. 2020), mangrove loss still outweighs the gain from plantation and restoration activities (FAO 2020).

In Asia, mangroves mainly occupy the tropical coastline, predominantly in South and Southeast Asia, and extend over some 6.13 million ha, which is roughly 40.4% of the global extent of mangroves (DasGupta and Shaw 2013a). Additionally, Southeast Asia is a regional hotspot of mangrove deforestation (Hamilton and Casey 2016; Richards and Friess 2016), accounting for the loss of nearly 100,000 ha of mangroves between 2000 and 2012 (Richards and Friess 2016). In South Asia too, despite significant conservation and restoration efforts in recent years, mangroves suffered a net loss of 11,673 ha during the same time (Giri et al. 2015).

There are unique, region-specific drivers that continue to spur the conversion of mangroves to non-forest purposes. A good number of recent studies have provided a thematic overview of the responsible factors for mangrove degradation at the country, regional and continental scale in Asia (DasGupta et al. 2019b; Estoque et al. 2018; Giri et al. 2008, 2011, 2015; Richards and Friess 2016; Webb et al. 2014). On a continental scale, the most dominant factor of mangrove loss is land-use conversion, particularly for agricultural expansion including rice, coconut, and oil palm cultivation, as well as shrimp farming, especially in the low-lying Asian megadeltas. In fact, the history of human habitation in large deltas across Asia resonates with the history of mangrove deforestation. Giri et al. (2008) reported that agricultural activities are responsible for the bulk of the mangrove deforestation in major Asian countries, particularly in Myanmar and Thailand (Giri et al. 2008). A recent study further mentioned that Myanmar suffered from a net mangrove loss of 191,122 ha from 2000 to 2014, at a staggering rate of 2.2%, costing Myanmar a net loss of 2397 million USD/year in its mangrove ecosystem service value (Estoque et al. 2018). While conversion to agriculture dominated the loss of mangroves in Myanmar (Estoque et al. 2018; Webb et al. 2014), in other parts of Southeast Asia, particularly in Malaysia and Indonesia, oil palm plantation in recent years and diversion of aquaculture are the major factors behind the loss of mangroves (Richards and Friess 2016).

Apart from agriculture, diversion to aquaculture is a significant regional driver of mangrove deforestation (Giri et al. 2015; Ilman et al. 2016). Giri et al. (2008) mentioned that Thailand and Indonesia are the top two countries that lost close to 38,000 ha of mangroves to aquaculture (Giri et al. 2008). Notably, aquaculture is not new to the region; rather it is a traditional practice that has been practiced historically (Akber et al. 2020; Ilman et al. 2016). However, in recent years, growing international demand has industrialized shrimp cultivation in Asia, which has driven transformational changes in the way people practiced it previously (Akber et al. 2020). Today, Asia caters to more than 70% of all commercially produced shrimps, and the deforestation of mangroves often fuels the establishment of shrimp farming complexes in vulnerable coastal areas. Besides unplanned coastal development, industrialization, port construction, urbanization, tourism, and resorts also contributed to significant loss of mangroves (DasGupta and Shaw 2013a; Giri et al. 2008). In addition, large-scale disasters, such as the Indian Ocean Tsunami, and Cyclone Nargis have also destroyed a significant amount of Asian mangroves (DasGupta and Shaw 2013b; Estoque et al. 2018). However, mangroves still offer a great degree of ecological stability despite being subjected to various natural disturbances (Alongi 2008). Many of the disaster-damaged mangroves, particularly after the Indian Ocean Tsunami, naturally recolonized and recovered completely within a few years (DasGupta et al. 2015).

1.3 Future Uncertainties in the Delivery of Mangrove Ecosystem Services

While mangroves may be resilient to future natural disturbances, including those from sea-level rise and natural hazards, anthropogenic disturbances and direct deforestation continue to remain the primary concerns for their future sustainability. One notable study mentioned that climate change is likely to be responsible for a 10%–15% reduction of mangrove habitats in the future, particularly due to the changes in sea-level rise; however, the primary threat comes from anthropogenic disturbances (Alongi 2008). For instance, given no control measures, the current low productivity of shrimp aquaculture in many parts of Indonesia may escalate further mangrove conversion and result in the loss of a further 600,000 ha of mangroves over the next two decades (Ilman et al. 2016). Similarly, if the current trend prevails, agriculture expansion might annihilate mangroves from the Myanmar coast by 2050 or even earlier (Webb et al. 2014). Nonetheless, what is interesting to note is that the global, as well as regional approaches to mangrove conservation, are changing fast. While mangroves were viewed as mosquito-infested swamplands not too long ago, today they are increasingly occupying the center of various international discourses on climate change, sustainable development, and disaster risk reduction. Therefore, national commitments toward the protection, conservation, and restoration of mangroves are also rising. In countries like India, Bangladesh, the Philippines, and Thailand, governments have started regular mangrove afforestation programs and adopted more stringent mangrove conservation policies, and as a result, mangrove cover is consistently rising (DasGupta and Shaw 2013a). This is further supported by international finance and incentive mechanisms for mangrove protection, such as the UN-REDD+ program. In addition, owing to direct evidence of the protective role of mangroves during the Indian Ocean Tsunami, several communities also developed a positive attitude toward mangrove conservation, thus promoting community-based mangrove management in Asia (DasGupta and Shaw 2013b). Several countries started mangrove restoration as a national priority for their Nationally Determined Contribution (NDC) under the Paris Agreement and enforced legislation for the development of coastal green belts.

The current and future delivery of vital mangrove ecosystem services, such as the ability to store carbon, sediment retention, pollution control, and coastal hazard mitigation, nevertheless depends on a series of external factors, which can be broadly classified under the STEEP (Social, Technological, Economic, Environmental, and Policy) framework. The STEEP framework analyzes the manifestation of potentially important drivers that can transform the future extent and delivery of ecosystem services, such as mangroves. For instance, against the backdrop of Asia, social drivers such as per capita income, poverty and resource dependence, and wealth inequality are among the important factors behind mangrove sustainability. Similarly, among technical drivers, advanced monitoring frameworks, plantation techniques, and choice of species are among the critical factors. Economic factors such as incentive design, revenue sharing, economic gain from alternative use of mangrove, global food prices, demand for aquaculture products, etc. directly influence mangrove sustainability (DasGupta and Shaw 2017). In terms of environmental factors, pollution, oil spillage, port and urban development, and invasive species are important determinants of future mangrove sustainability. In addition, local development plans, conservation policies, and social development policies also determine the fate of mangroves, thus influencing the delivery of vital ecosystem services. In short, it is extremely difficult to pinpoint the future of mangrove ecosystem services, given the uncertainty in the different drivers and their complex interplay with mangroves.

1.4 Taking a Scenario and Modeling Approach to Understand Mangrove Sustainability

In Asia, mangroves exist in complex socio-ecological settings, and there are significant reasons to protect, conserve, or even expand mangroves to take into account human well-being in the face of climate change and the increasing frequency of natural hazards. Nonetheless, to determine the future for prospective mangrove cover, and to ensure the delivery of mangrove ecosystem services to a satisfactory level, quantitative information across space and time is necessary. Decision-makers, therefore, need to consider a wide range of uncertainties and the complex interaction of STEEP drivers, both at a regional and global level, to ensure the future of mangroves and the provision of their vital ecosystem services.

Over the past decade, scenarios have become powerful decision-making tools to assess long-term, nonlinear transformations of socio-ecological systems. Scenarios portray a range of imaginative futures, considering a variety of possibilities and the complex interaction between drivers. Despite scenarios have been widely used in contemporary climate change research, their application in biodiversity and ecosystem services is still in the nascent stage, particularly in Asia (DasGupta et al. 2019a; Hashimoto et al. 2019). Such applications are further limited in mangrove research, and to the best of our knowledge, only a handful of studies used scenario approaches for quantification of the future extent of mangroves. For instance, Webb et al. took a trend-based approach to depict a plausible alternative future of mangroves in Myanmar (Webb et al. 2014). Their research used the rate of mangrove deforestation over two different periods to depict the plausible alternative mangrove futures. Similarly, a story and simulation approach (SAS) was adopted to assess the mangrove future in the Indian Sundarban delta where four alternative storylines were developed to depict the likely state of the socio-ecological future of the delta (DasGupta et al. 2019b). To address future uncertainties in mangrove ecosystem services, scenario-based quantitative assessment of mangrove ecosystem services remains imperative for evidence-led decision-making and establishing a strong science-policy interface for decision-making.

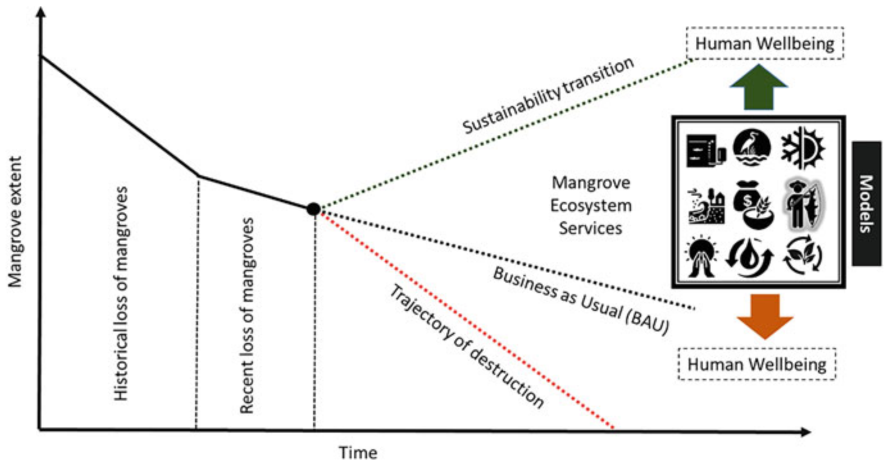

Fig. 1.1 A simple depiction of mangrove scenario analysis

As shown in Fig. 1.1, a typical set of exploratory scenarios generally depict three or more alternative trajectories, with one corresponding to the Business-as-Usual (BAU) scenario and depicting a plausible future following the historical trend. The other two outline the best and worst-case scenarios, depicting what can go right or wrong over a period. Scenarios can be built in several different ways; however, an analysis of the influential drivers is the first step to build a scenario. The art of scenario building conventionally follows five steps: (1) identification of scenario fields; (2) analysis of the influential drivers; (3) identifying the key factors; (4) developing scenarios; and (5) scenario transfer. Scenario analysis, which is often used in academic literature, can broadly include both developing scenarios and analysis of the alternatives. It is, however, important to note that, no scenario can cover all uncertainties; rather, a careful selection of the most influential driver is necessary to enhance the reliability of the scenario exercises.

To this end, models that quantify ecosystem services over space and time are extremely useful to guide decision-makers amidst uncertainty. Models address the effects of multiple changes in influential drivers, which in turn drive changes in the ecosystem and its services. Varieties of models are currently available to model biodiversity and ecosystem services, at a scale from local to global. According to The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), models can also be of three types, namely, correlative models, process-based models, and expert-based models. In addition, models can be classified as "dynamic," i.e., they are capable of projecting changes in ecosystem services over time, while "static" models provide a snapshot of ecosystem services at one point in time (IPBES 2016). A combination of scenarios and models often serve as the best recipe for informed decision-making. Nevertheless, as highlighted by IPBES, all scenarios and models have strengths and weaknesses, meaning that selection requires careful consideration in terms of research objectives and limitations of models.

1.5 About the Book

In the context of scenarios and models of ecosystem services as discussed above, this book's 16 chapters aim to increase understanding of the tools and techniques necessary for assessing, mapping, and modeling mangrove ecosystem services. Through thematic reviews and case studies, the book explores various methods and tools such as the use of geospatial technology and participatory stakeholder analysis to understand the past, present, and future of mangroves and their ecosystem services. Further, it outlines techniques for identifying influential drivers, econometric and spatiotemporal modeling of ecosystem services using state-of-the-art ecosystem assessment models. For ease of understanding, the book is divided into two sections.

In the first section, we discuss the case studies related to trend analysis, including both expert-based and process-based, scenario building, and methods of identification of influential drivers. In Chap. 2, for instance, Hussain and Rahman provide an estimate with regard to mangroves in four selected locations in Pakistan. Using the temporal Landsat satellite imageries and geospatial analysis, they report an increase of mangroves since 1986 in the four major mangrove habitats in the Southeast Asian country, particularly highlighting the recent increment of mangroves owing to the proactive plantation and restoration drives by several NGOs, institutions and local governments. In Chap. 3, Delos Santos et al. map the reverse transformation of abandoned aquaculture ponds to mangroves in Panguil Bay in the southern Philippines using Landsat data and Google Earth Engine (GEE). In this study, the authors develop a methodology using open-source Landsat data on a cloud-based processing platform, which can be adopted for restorative scenario planning and policymaking at the local level. Chapter 4 by Takahashi et al., on the other hand, provides a detailed study on narrative-based scenario development using a combination of literature review and stakeholder engagement. They studied the socio-ecological systems on Ishigaki Island and created four different alterative scenarios, by analyzing the status and trend of ten locally influential drivers. Such narratives can be used as the future storyline of assessing the state of natural capital in the Island, including mangroves. Similarly in Chap. 5, Joshy et al. analyze the influential drivers of mangrove degradation in Kerala, India, using a stakeholder-based participatory approach. In this expert-driven approach, they interviewed a large number of stakeholders, including residents, government officials from various concerned departments, and members from the village council. Such identification of locally influential drivers is important to understand the drivers and pressures on the mangrove ecosystems, together with the different use of mangrove ecosystem services and possible avenues for conservation. Dhyani et al., in Chap. 6, provide a similar case study from the

Bhitarkanika and Mahanadi Delta, India, where the authors provide an in-depth review of locally important and influential drivers and their trends.

In the second section, we focus on mapping and modeling of mangrove ecosystem services. This section has nine chapters, which deliver techniques and methods of assessing, mapping, and modeling different mangrove ecosystem services. Chapters 7–9 focus on regulating services of mangroves and, in particular, the ability of mangroves to store carbon. In Chap. 7, Akhand et al. provide a comprehensive review of different available techniques to assess blue carbon, i.e., carbon storage in aboveground biomass (AGB), belowground biomass (BGB), nonliving detritus, and sediment by coastal ecosystems, including mangroves. The chapter further describes both destructive and nondestructive approaches to blue carbon measurement. In Chap. 8, Nath et al. give a case example detailing the changes of carbon stock and its spatial variation in the mangrove ecosystems of the Andaman Islands. In this chapter, the authors used remote sensing techniques to estimate the AGB and provide a rigorous review of field-based AGB studies in different mangrove ecosystems of Southeast Asia. In Chap. 9, Dalimunthe et al. mention an interesting case study on how online news and media cover the Indonesian “blue carbon champion” initiative, which is a nationwide restoration drive for mangrove regeneration. Through a series of qualitative content analyses, the chapter analyzes public opinion regarding mangroves’ potential to be a blue carbon champion. Further, Chaps. 10 and 11 focus on the assessment of other important regulating services of mangroves. In Chap. 10, Naz and Chowdhury describe an eco-engineering technique for bio-shield design (using different suitable species) for wave and storm surge attenuation in the Indian Sundarbans. In Chap. 11, Chung et al. provide a detailed, spatiotemporal assessment of the ecosystem services of urban mangroves using the InVEST model. In particular, they mapped carbon storage (ton-C), habitat quality, nutrient (nitrogen) delivery ratio (NDR) (ton-N/year), and sediment delivery ratio (SDR) (ton/hectare/year) for the Tamsui River estuary mangrove forest in Taiwan. Chapter 12, on the other hand, provides a detailed analysis of the species diversity of mangroves in the six mangrove habitats of the Oriental Mindoro, Philippines. Following this, Chaps. 13 and 14 provide an outline of the cultural ecosystem services of mangroves. In Chap. 13, Bimrah et al. provide a synthesis of existing methods of mapping and modeling cultural ecosystem services of mangroves. Chapter 14 then outlines the role of capacity building to systematically identify and document indigenous and local knowledge (ILK) practices related to ecosystem conservation and coastal adaptation. In Chap. 15, Titumir and Paran narrate how both nature and humans coexist and are dependent on each other using the Sundarbans as a reference. Finally, Chap. 16 provides the operational challenge of fostering mangrove ecosystem services in light of various uncertainties, including recent advances in mangrove research, as well as detailing some gaps and challenges.

The book targets a wide audience, including students, researchers, and practitioners engaged in the field of mangrove conservation, landscape ecology and planning, natural resource, and coastal zone management. However, the book would also be helpful for disaster managers, local policy-makers, forest conservators, and general administrators. The knowledge shared in this book is expected to contribute toward scenario research in the Asia-Pacific and to further encourage evidence-led policy planning.

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Part I
Trend Analysis, Scenario Building and Identification of the Influential Drivers of Change

Chapter 2
Monitoring Spatial and Temporal Distribution, Pattern, and Trend Prediction of Coastal Mangroves in Pakistan Using Geospatial Techniques

Muhammad Hussain and Atta-ur Rahman

Abstract This chapter focused on monitoring spatial and temporal distribution patterns and trend prediction of mangroves along the coastal belt of Pakistan using geographic information system (GIS) and remote sensing (RS) approaches. Mangroves are considered significant for the ecology, environment, and livelihood of coastal communities and have high biological productivity. In Pakistan, mangroves are reported from the coastal belt of Baluchistan and Sindh provinces. Therefore, this chapter describes the spatial and temporal distribution pattern and trend prediction of coastal mangroves in Pakistan. To monitor spatial patterns of change in mangroves, Landsat temporal satellite data were used. The temporal Landsat data for the years 2020, 2011, 2001, 1991, and 1986 were acquired, and the NDVI-based classification technique was applied to demarcate mangroves. Besides, supervised classification with a maximum likelihood algorithm was used to identify the spatiotemporal patterns of mangroves. The analysis revealed a gradual increase of mangroves, i.e., from 48,331 ha in 1986, which increased to 55,621 ha in 1991, and further expanded to 79,254 ha (2001), 107,443 ha (2011), and 143,930 ha in 2020. Parallel to this, microlevel analysis at *Indus Delta*, *Sandspit*, *Sonmiani*, and *Kalmat Khor* was also carried out to validate the macrolevel results. It was found from the analysis that the gradual increase in area under mangroves is attributed to conservation strategies, sustainable regeneration, and initiation of afforestation projects by various departments, authorities, and organizations.

Keywords Indus delta · Mangroves · Trend prediction · Biological productivity · Afforestation

M. Hussain
Department of Geography, The Islamia University of Bahawalpur, Bahawalpur, Pakistan

A.-u. Rahman (✉)
Department of Geography, University of Peshawar, Peshawar, Pakistan
e-mail: atta-ur-rehman@uop.edu.pk

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2.1 Introduction

Mangroves are evergreen forests that are located alongside the coast of the tropics and subtropics and are generally found between latitude 25°N and 30°S (Rahman and Shaw 2017). Mangroves provide important environmental and socioeconomic facilities to coastal communities (DasGupta et al. 2018; Tong et al. 2004). The global area of mangroves is approximately 137,760 km^2 and connects 118 countries and borders of the world. These forests also have several important functions, such as preserving the quality of coastal waters, minimizing the occurrence of floods, protecting shorelines from erosion, and creating nurseries and feeding areas for many fish and crustaceans species (DasGupta and Shaw 2013; Parida et al. 2014). Mangroves provide various contributions including material and nonmaterial, which are very significant for human well-being and quality of life (Dasgupta et al. 2021). The only wood that exists at the confluence of land and the sea is the forest of mangroves, which are used for fruits, wood, fuel, medicine, etc. Mangroves are considered a valuable resource for the economy and the environment. Mangroves provide renewable woods and offer protection from coastal erosion (Alongi 2002). However, almost one-third of mangroves in the world has been destroyed over the last 50 years.

Asia, Africa, and South America are the most important regions where mangroves exist. There are approximately 41% of all mangroves that exist in five countries (Indonesia, Brazil, Nigeria, and Australia), while ten countries cover 60% of total mangroves (Valiela et al. 2001). The global distribution of mangroves is illustrated with the help of a map (Fig. 2.1).

The coastline of Pakistan is almost 1046 km long and spreads over Sindh (246 km) and Baluchistan (880 km) provinces, respectively, which is endowed with a significant amount of mangroves. The main area of mangroves in Sindh exists in two districts, i.e., Thatta and Badin. The most important place for mangroves in Sindh province is the Indus delta region, which covers almost 600,000 ha and extends between Sir Creek and Korangi Creek (Brah 1992). Indus delta covers almost 97% of mangroves in Pakistan (Amjad and Jusoff 2007). Baluchistan's coastline, on the other hand, stretches from the River Hub to Iran's territory and starts from the Sonmiani Bay to Gwadar Bay (Rasool et al. 2002).

Pakistan is rich in terms of natural resources, and the mangrove ecosystem is one of them that spread across the coastal areas of Pakistan. Pakistan has probably the tenth-largest mangrove ecosystem in the world with an area of 0.6 million hectares. In the past, the mangrove forests were considered useless, and their potential was overlooked. When researchers and scientists established their true economic value, particularly their role in soil conservation, fodder, fuel, as well as coastal fisheries benefits, many projects have recently started for the rehabilitation of mangroves in Pakistan (Qureshi 1993).

RS and GIS are considered important tools and techniques that are used to assess land use land cover studies (Rwanga and Ndambuki 2017), especially forest cover-related studies. Remote sensing is an important tool in mangrove biodiversity

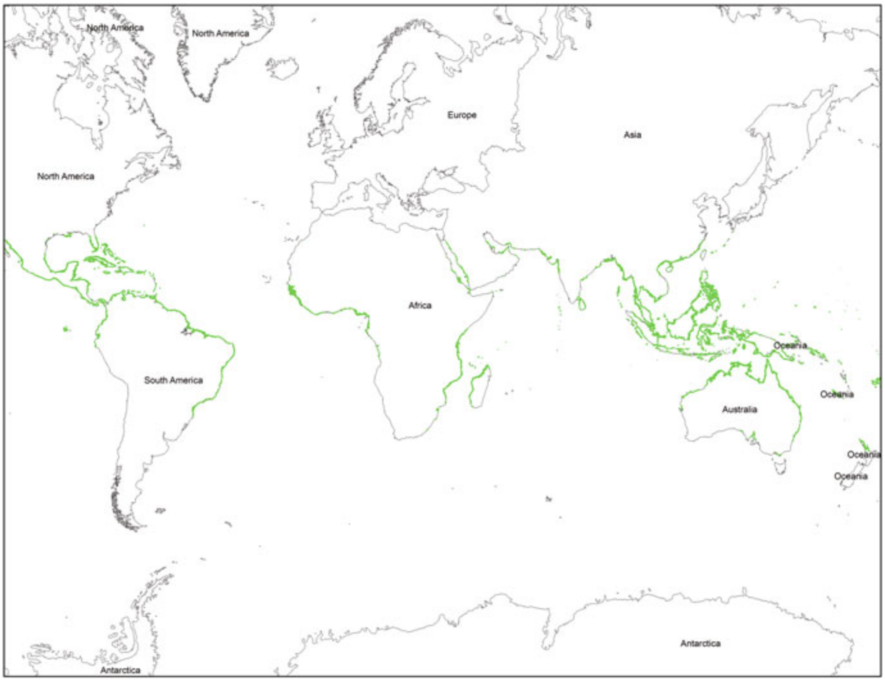

Fig. 2.1 Global distribution of mangroves modified by Author (2021)

assessment and monitoring, especially since a lot of mangrove sites are impossible or unsuitable for formal field surveys (Lucas et al. 2017). Earlier many national-level studies were carried out at the scale of 1:250,000 with Landsat 30 m spatial resolution data (Abbas et al. 2013).

According to Gilani et al. (2021), due to proper planning and plantation, mangrove forests in Pakistan increased in the last 30 years. Satellite data have been widely used in Pakistan for quantitative analysis and management of mangrove forests. However, due to the use of different imageries, image processing techniques, and inadequacy to collect ground data, the actual extent of the mangrove remained under scrutiny. In this study, we, therefore, attempt to provide a chronological trend to understand the past and future of mangroves in Pakistan. The study area and detail of mangroves forests concerning Pakistan are discussed in the following sections.

2.2 The Study Area

The coastline of Pakistan is 1046 km long and extends from India to Iran. However, mangroves exist in some small patches. In Pakistan, the following four sites are important for mangroves, namely, Indus Delta, Sandspit, Sonmiani, and Kalmat

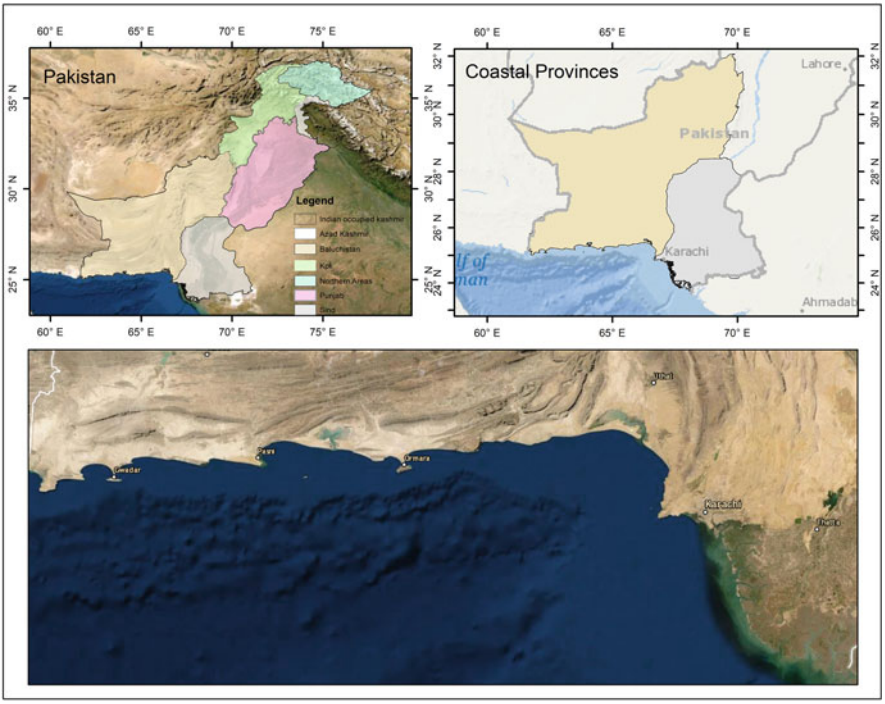

Fig. 2.2 Location of the study area

Khor (Fig. 2.2). In the Sindh province, mangroves occupy the Indus Delta and Sandspit, which are located southwest side of Karachi City. The two other places of mangroves in Pakistan are located in Baluchistan province, namely, Sonmiani Khor and Kalmat Khor.

2.3 Methods and Material

To monitor spatial and temporal distribution, pattern and trend prediction of coastal mangroves satellite images were downloaded from the USGS websites (United States Geological Survey). The area of study covers three separate Landsat archive paths/rows. Satellite images of suitable dates have been downloaded taking into consideration sea height (tide) and cloud cover percentages. A detailed description of satellite data is given in Table 2.1.

In Table 2.1, five different periods 2020, 2011, 2001, 1991, and 1986 are selected for this research. The Landsat image of 2020 was available in Landsat 8, the 30-m resolution with Operational Land Imager (OLI) sensor. The image of 2011, 2001, and 1991 was available in Landsat 5, the 30-m resolution with the thematic mapper (Fig. 2.3). In addition, the last image, i.e., 1986 image, was available in Landsat

Table 2.1 Description of satellite data

Year	Satellite	Sensor	Path/row	Acquisition date	Spatial resolutions (M)
2020	Landsat 8	OLI	152/43	18/11/2020	30
			153/42	09/11/2020	
			154/42	16/11/2020	
2011	Landsat 5	TM	152/43	27/02/2011	30
			153/42	22/03/2011	
			154/42	13/03/2011	
2001	Landsat 5	TM	152/43	05/06/2001	30
			153/42	11/05/2001	
			154/42	07/07/2001	
1991	Landsat 5	TM	152/43	24/03/1991	30
			153/42	15/03/1991	
			154/42	22/03/1991	
1986	Landsat 5	MSS	152/43	05/11/1986	60
			153/42	09/09/1986	
			154/42	16/09/1986	

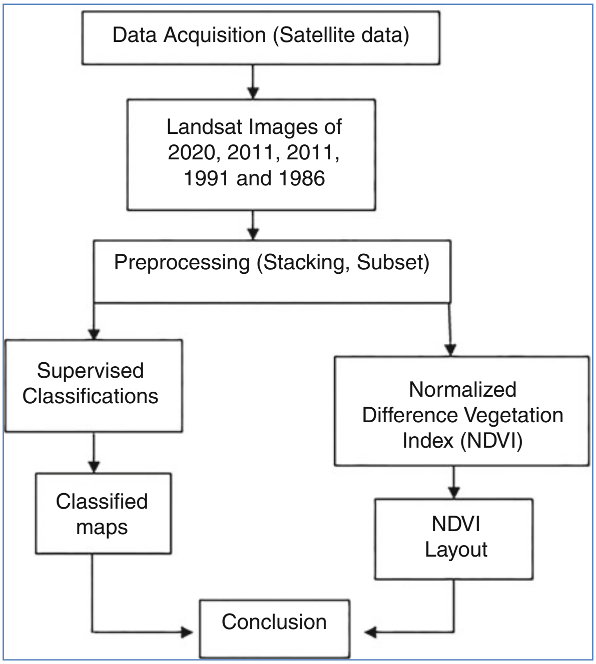

Fig. 2.3 Methodological framework

5, four bands with 60-m resolution in a multispectral scanner. Our idea was to start study time from 1981, but due to cloud cover and other data restrictions, the image of 1986 is selected. The complete methodology of this research is framed in Fig. 2.3.

2.3.1 Preprocessing, Supervised Classification, and NDVI

The next stage after acquiring Landsat images was image preprocessing. In this section, the data was separately extracted, and then layer stacking and subsetting of each year are performed in the Erdas Imagine. Then the satellite data was ready for analysis. We used the Normalized Difference Vegetation Index (NDVI) which is relevant to this study. NDVI shows the intensity of vegetation/forest area. Then, supervised classification is used to identify the temporal existence of mangroves for the years 2020, 2011, 2001, 1991, and 1986. The maximum likelihood classifier is used for supervised classification, which is reliable and recommended by the researchers. Five different layouts are generated with the results of supervised classification and then discuss based on these results. The microlevel analysis also discussed the basis of supervised classifications.

2.3.2 Tools and Techniques

The Erdas Imagine software is used for all analysis of Landsat images. In addition, ArcMap V.10.5 software is used for the generation layouts of the results. The small contribution of other software's including Endnote and MS Office also considered for data tabulation and writing of the manuscript.

2.4 Spatiotemporal Distribution of Coastal Mangroves

The major goals of our research were to understand how the distributions of mangroves have changed in the past and what the current extent is. The spatiotemporal changes in mangroves forest are analyzed with the help of the Landsat series, as we discussed above. Different techniques and methods are used to detect these changes. NDVI index is mostly applied to monitor the vegetation. It is an index that can be used to calculate the green density in a study area. NDVI is determined through the following equation:

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{RED}}{\mathrm{NIR} + \mathrm{RED}}$$

Red band and a near-infrared bandstand for the spectral red acquired reflectance measurements (visible) and near-infrared. These spectral reflection ratios are the ratios of radiation expressed in every spectral band individually; thus, the values between 0.0 and 1.0 are taken into account (Dall'Olmo et al. 2005). The NDVI results are shown with the values below.

The supervised classification is based on the knowledge of the user so that sample pixels can be selected from an image representing particular classes, and the image processing software can then be used as reference points for classifying all other pixels in an image. Based on researcher expertise, training sites are selected. The researcher sets the limits on how similar other pixels are to be clustered. These restrictions are also based on a particular increase (often based on "brightness" or reflectance intensity in specific spectral bands) in the spectral features of the training area. The researcher also shows how many classes the image is identified. For final performance analysis and classified maps, many researchers use a mixture of unsupervised classification and supervised processes. The findings are given in detail below.

2.5 Spatial and Temporal Distribution of Mangroves Using NDVI

Normalized difference vegetation index (NDVI) is applied in this research to detect the vegetation of mangroves in different periods 1986, 1991, 2001, 2011, and 2020, respectively. The layouts of the results are illustrated in Fig. 2.4.

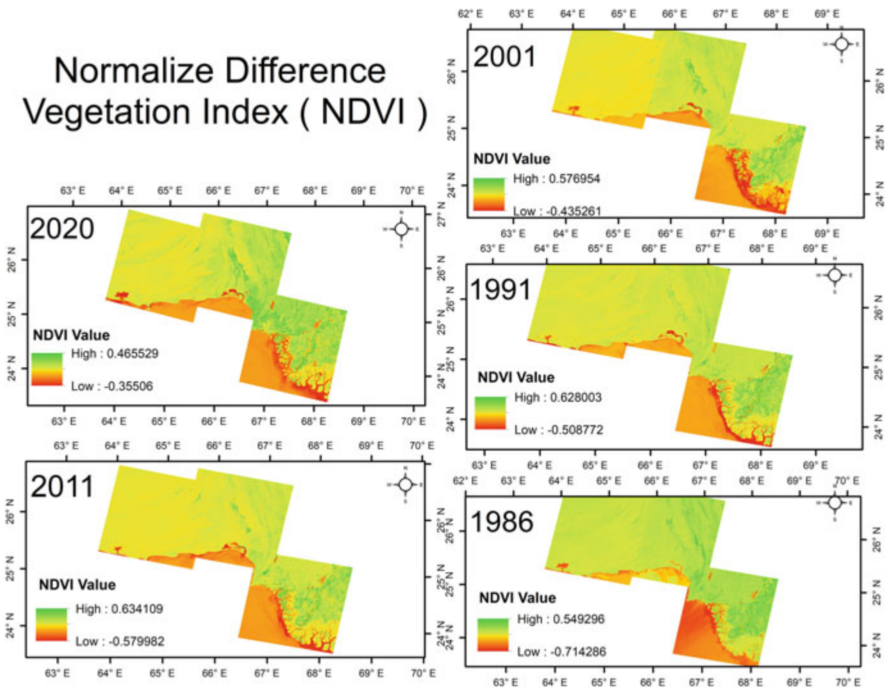

Fig. 2.4 Spatiotemporal distribution of coastal vegetation using NDVI

The focus in this research was mangroves of Pakistan, and the results of NDVI show that the mangroves in the year 2020 are highly dense as compared to previous years, and then 2011 is lower than 2020, 2001 is lower than 2011, 1991 is lower than 2001, and 1986 is also lower than 1986. In simple words, we can say that the density of mangroves is increased with time. The detailed and reliable results of supervised classifications are given below.

2.6 Spatiotemporal Analysis of Mangroves

The next step after NDVI analysis was selection of different bands 4, 3, and 2 in 1986, 1991, 2001, and 2011 image and 5, 4, and 3 in 2020 images, and maximum likelihood classifier (MLC) in supervised classification was applied to all Landsat images 1986, 1991, 2001, 2011, and 2020. The maximum likelihood classifier (MLC) method in supervised classifications is considered one of the most popular classifiers as compared to Mahalanobis distance (Mh.D) and minimum distance (MD). The results of supervised classification are illustrated in Fig. 2.5.

The results of the supervised classification show the positive changes in the mangroves of Pakistan with time. According to these results, forest cover area under mangroves is gradually increased. The study time started in 1986 and ended in 2020. With time as shown in layouts, the mangroves are flourished especially in Sindh province at the Indus Delta site. The statistics of mangroves in these 34 years are given in Fig. 2.6, which clearly shows the positive change.

The statistics of the results of supervised classification, as shown in Fig. 2.6, mangrove cover extended to 48,331 hectares in 1986, 55,621 hectares in 1991, 79,254 hectares in 2001, 107,443 hectares in 2011, and 143,930 hectares in 2020. The rate of mangrove growth was slow before 2000, but it speedily increased after 2000 and reached 143,930 hectares in 2020, and this was a positive change in forests due to healthy projects and favorable natural circumstances. Four sites, Indus Delta, Sandspit, Sonmiani, and Kalmat Khor, were chosen for this research, and almost all sites reported an increase, but the Indus Delta site is considered very important since it covers a large area of mangroves and it also increased speedily.

2.6.1 Microlevel Analysis of Coastal Mangroves in Sindh Province

In the Sindh province, two important spots of mangroves are Sandspit and the Indus Delta. In the coastal Delta zone created by the River Indus, the Indus delta covers approximately 600,000 hectares and almost 97% of Pakistan’s mangroves. The mangroves of the Indus Delta may be unique as the world’s biggest mangroves in an arid climate. They are approximately entirely dependent on freshwater from the Indus River and a limited quantity of freshwater from the domestic and industrial

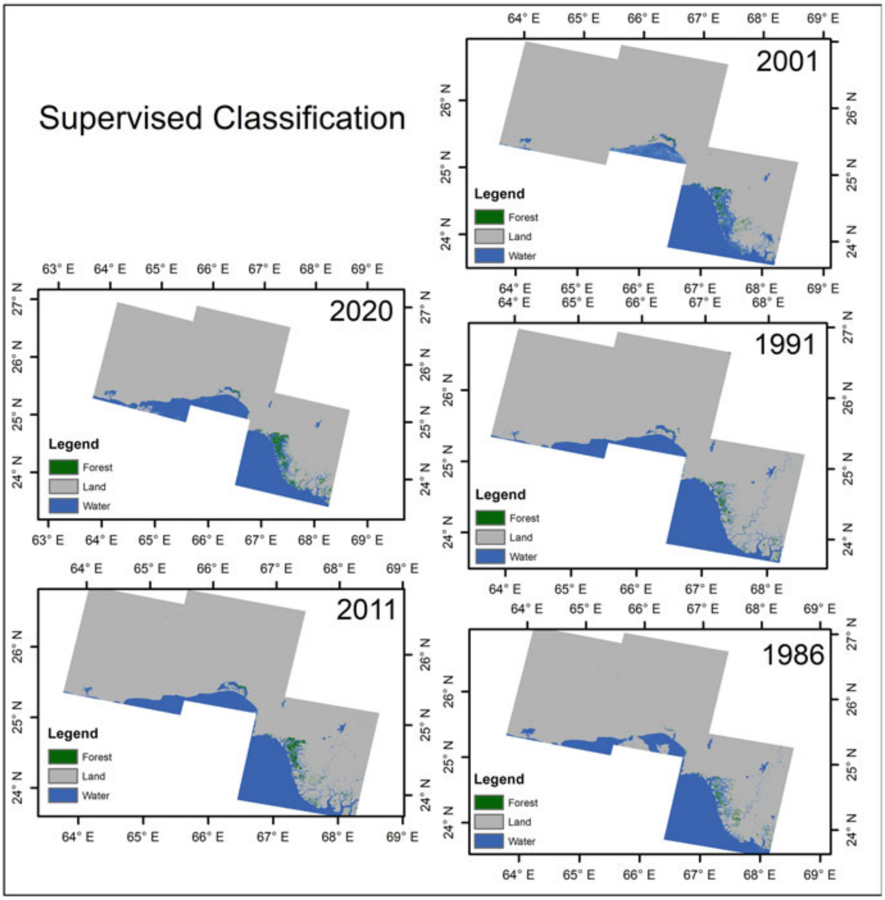

Fig. 2.5 Spatiotemporal analysis of mangroves using supervised classifications

wastewater in Karachi. More than 600,000 hectares of coastal land and muddy floors cover the Indus Delta most of which are submerged during floods. The Indus Delta is dominated by 17 large creeks and one of the largest arid mangrove forests in the world (Mukhtar and Hannan 2012). Mangroves are used as fuel, economic opportunity for coastal Dwellers, and fodder for livestock and camels.

The microlevel layouts of the Indus Delta image are given in Fig. 2.7. According to these layouts, the forest area of the Indus Delta is increased. The density of mangroves is very high in 2020 as compared to 2011, 2001, 1991, and 1986, respectively.

The second very important spot for mangroves in Sindh is at Sandspit which is located almost the end of the Sindh province near Karachi City. The microlevel layout of Sandspit is illustrated in Fig. 2.8. This figure clearly showed that the intensity and mangrove area are increased with time. The year 2020 is highly forested as compared to 1986.

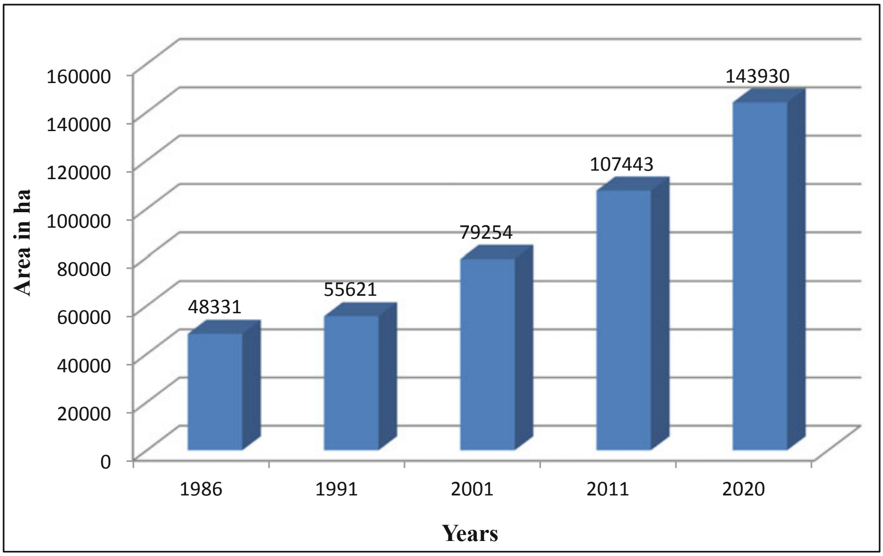

Fig. 2.6 Spatiotemporal distribution of mangroves

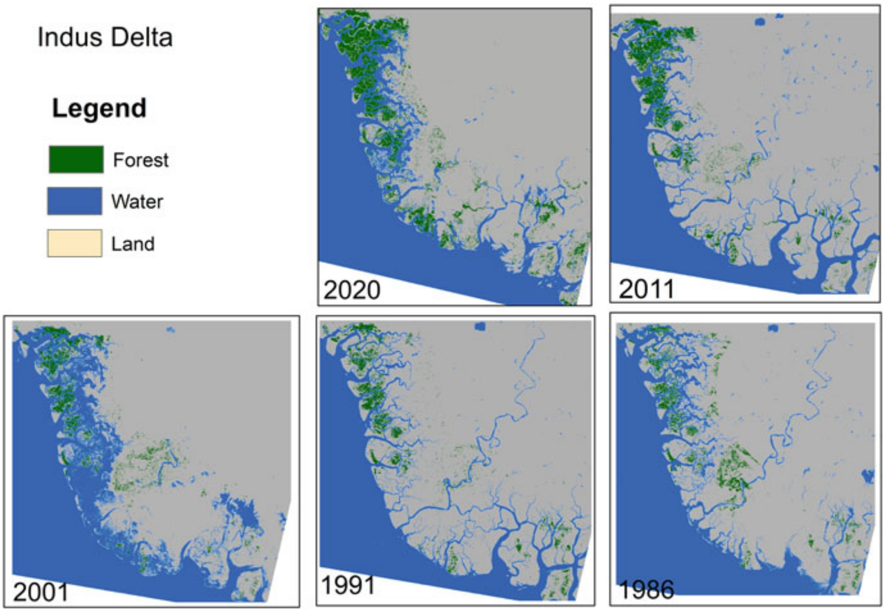

Fig. 2.7 Microlevel analysis at Indus Delta

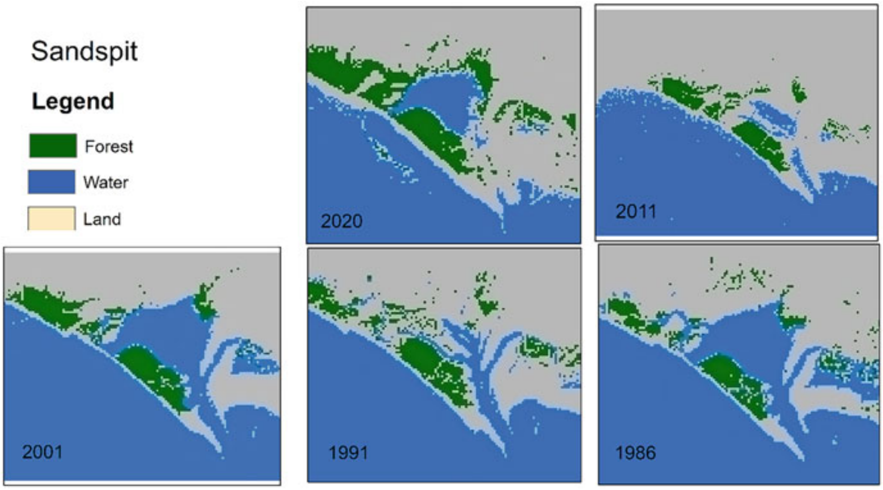

Fig. 2.8 Microlevel analysis at Sandspit

2.6.2 Microlevel Analysis of Coastal Mangroves in Baluchistan Province

The coastline of Baluchistan stretches from the mouth of the Hub River to the middle of the coasts of Gwadar Bay (the Lasbela and the Gwadar (Baluchistan Districts)). The coast of Baluchistan extent with a border of Iran occupies approximately 800 km. The coast of Baluchistan can also be subdivided into Miani Hor as its backwater lagoons are the Gwadar Bay, Gwadar West and Eastern Bays, Pasni Bay, and Sonmiani Bay. The coast of Baluchistan is hyperarid to tropical (sub) and has low hills and plains of piedmont. The Arabian sea drains on the mouths of seasonal rivers; there are locally limited, natural, and artificial tidal mangrove forests (Pakistan 2016). An uninhabited island, Astola, is 20 nautical miles from the sea in Pasni. Two important spots Sonmiani Khor and Kalmat Khor are observed for mangrove forests. First, we discuss Sonmiani Khor in Fig. 2.9.

Sonmiani Khor lies in the Lasbela district, Balochistan province. The word “Khor” or “Hor” for water channels is used in the local language of Balochi. This site is also known for mangroves. This is a very important site for fishing. A detailed picture and scenario of mangroves on Sonmiani Khor is given and shows the intensity of mangroves in different periods. The second spot is Kalmat Khor which is also located in Balochistan province (see Fig. 2.10). This is also a mangrove site but contributes a little portion of mangroves in all mangroves of Pakistan. Generally speaking, there is an inconsistent positive growth of mangroves over the years.

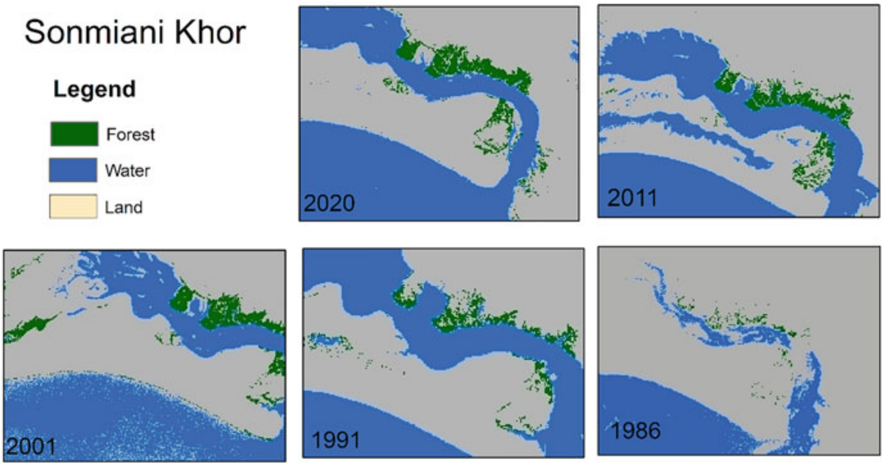

Fig. 2.9 Microlevel analysis at Sonmiani Khor

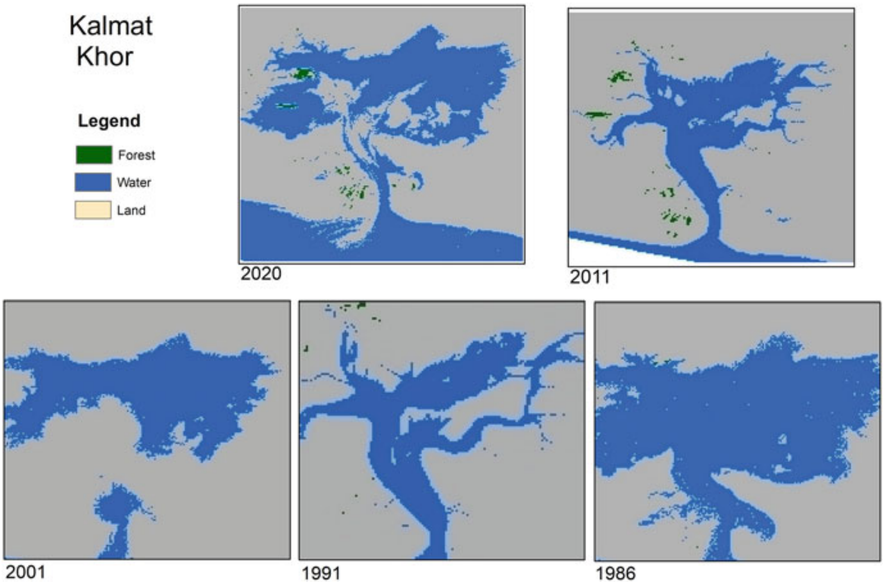

Fig. 2.10 Microlevel analysis at Kalmat Khor

2.7 Trend Prediction of Coastal Mangroves

Mangroves are an essential part of the coastal environment in Pakistan that act as the kidneys for the coastal waters. They are important fishing grounds for different types of fish and offer protection against coastal erosion. However, over the past years, it has been used as a source of fodder for livestock, a source of fuel, which are among the major causes of the degradation of mangroves. Another important factor contributing to the decline of mangroves is regular oil spills in the seas and oceans. Many reports reported a historical decrease in the population of mangroves along the Balochistan and Sindh coast. Hence, restoration research, activities, and awareness campaigns about mangroves are now being religiously carried out to conserve and regrow the mangroves along with multiple awareness activities carried out in collaboration with IUCN Pakistan, World Wide Fund (WWF) Pakistan, and National Rural Support Program (NRSP). Mangrove restoration activities have continued to increase the population of mangroves across the Indus Delta and Baluchistan coast, and as shown in the study, the trend looks promising. It is because of the constant endeavor by the government and NGOs. For example, in 2004, the Saudi Fund for Development (SFD) had restored 234,500 hectares of mangrove in both regions, while in 2005 IUCN, Department of Fisheries, Government of Baluchistan (BFD), and the Netherlands Embassy (RNE) had planted a total of 100,000 hectares. The “Pakistan Navy—Mangrove Plantation Campaign 2018,” a big restoration campaign, aimed at planting two million mangroves in Sindh and Baluchistan coastal areas.

IUCN Pakistan and Gwadar Development Authority (GDA) also planted mangroves in an area compromising 8 km at Shabi Creek, Gwadar. However, to restore functionality and sustainability, more plantations are required and recommended by the IUCN. Further, the restored mangrove ecosystem also does not always compare with natural mangroves; therefore, it is important to establish specific recovery objectives integrating the concepts of mangrove ecosystem services. After which, monitoring for long-term survival is recommended for which three strategies are suggested by the IUCN that include replantation, assisted by natural regeneration, and restoration of an alternate site to provide similar habitat for the mangroves. Syed Nasir Hussain Shah, the forest minister, recently declared that over two billion mangrove trees were planted in Sindh coastal zones and various regions of the province whose record has been computerized for the first time in the history of the country. Based on the developmental projects, the area of mangroves is preserved or increased with time. The regrowth of mangroves is central to many local departments, including the Sindh Forest Department, the Sindh Revenue Board, and Port Qasim Authority, as well as for the local researchers and institutions. The current state of mangroves is plentiful, and most probably, it will sustain and increase in the future.

2.8 Conclusion

The economic importance of Indus delta mangroves is well known as they provide significant ecosystem services, including breeding ground for commercially viable marine fish, shrimp, lobsters, and crabs, which, besides providing jobs and livelihoods for more than 100,000 fishing-associated people, enable national economies to obtain $100 million annually in foreign exchanges. It is estimated that 90% of the fish in mangroves, particularly creeks, are significant tropical marine species. For instance, up to 250,000 tons of fish were extracted from the Sindh coast which is affected by mangrove destruction in 1998 (IUCN), and 2.24 billion was received from fish exports in Pakistan. Thus, mangroves are of great socioeconomic interest.

According to the results of this study, the mangroves of Pakistan are increased over time especially at the Indus Delta due to proper planning and management. The contribution of researchers through regular monitoring, assessment, and use of technology further helped the development and preservation of mangroves. Management, protection, and conservation through sustainable use of mangrove resources are a key priority in Pakistan. To achieve the best economic and environmental benefits without damaging this precious habitat, knowledge of mangrove habitats is necessary. In addition, awareness and education for sustainable management of mangrove forests are pivotal for their future sustainability.

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Chapter 3
Assessment of Mangrove Colonization of Aquaculture Ponds Through Satellite Image Analysis: Implications for Mangrove Management

Kriselda Anna delos Santos, Ram Avtar, Severino Salmo III, and Masahiko Fujii

Abstract Mangroves are highly productive forest ecosystems recognized for several ecosystem services like carbon sequestration and coastal protection that can help in climate change adaptation and mitigation. Globally, mangrove forests have decreased and have become fragmented, especially in Southeast Asia where conversion to aquaculture ponds (AP) was the major driver of loss. When disturbed, mangroves can naturally recolonize their habitat. However, documentation and assessment of natural mangrove recolonization in former AP are largely unreported. Hence, in this study, we developed a methodology that detected and mapped mangroves in AP in Panguil Bay, southern Philippines. Using Landsat data and Google Earth Engine (GEE), we analyzed spatiotemporal mangrove distribution and extent in AP from 1993 to 2020. In general, the increase in mangrove cover was directly correlated to the decrease in AP. However, different rates and patterns of mangrove colonization in different periods were observed. Mangrove-recolonized ponds (MRPs) were ca. 25% (10.24 km^2) of the total mangrove area (40.20 km^2) in 2020. To our knowledge, this study showed the first mapping of mangrove recolonization in AP in the Philippines. The developed methodology used open access Landsat data on a cloud-based processing platform, which can be replicated in other regions for large-scale mangrove scenario planning and policy-making. Upscaling the developed methodology can provide national-level MRP information that can be used for evaluating the success of mangrove rehabilitation programs.

K. A. delos Santos (✉)
Graduate School of Environmental Science, Hokkaido University, Hokkaido, Japan

R. Avtar · M. Fujii
Faculty of Environmental Earth Science, Hokkaido University, Hokkaido, Japan

S. Salmo III
Institute of Biology, College of Science, University of the Philippines Diliman, Quezon City, Philippines

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Keywords Mangroves · Rehabilitation · Remote sensing · Canopy gap dynamics · Colonization · Panguil Bay · Philippines

3.1 Introduction

Mangroves are resilient ecosystems that can recolonize their habitat after major disturbances like typhoons and land-use conversion. Globally, mangrove forests have decreased in area (Valiela et al. 2001) and have also become degraded due to habitat fragmentation (Bryan-Brown et al. 2020). The major drivers of mangrove loss are aquaculture, agriculture, forest extraction, and urban development (Valiela et al. 2001; Richards and Friess 2016; Thomas et al. 2017; Goldberg et al. 2020).

Valuable ecosystem services are reduced when mangroves are degraded or lost. These services include coastal protection (Hochard et al. 2019), coastal erosion control (Gracia et al. 2018), and provision of habitat and nursery areas for commercially important organisms (Nagelkerken et al. 2008). Mangroves can also sequester large amounts of carbon in the biomass and sediment compartments (Inoue 2018).

The Philippines has one of the most diverse mangrove forests in the world, where 40 out of 54 true mangrove species can be found (Primavera 2000). Philippine mangroves have decreased in area from 4184 km^2 in 1951 (Primavera 1995, 2000) to 2278 km^2 in 2019 (Baloloy et al. 2020). Much of the mangrove loss in the Philippines is largely caused by conversion to aquaculture ponds (AP; Primavera 2000). Loans and grants from the Philippine government, international banks, and multilateral development agencies stimulated investments in aquaculture production which fueled pond expansion from 1950 to 1990 (Primavera 1995, 2000). The Philippine government also supported AP construction in mangrove areas by setting a low fishpond lease agreement (FLA) fee at only US\$2 ha^{-1} $year^{-1}$ (Primavera 2000).

Mangroves in the Philippines are still decreasing but at a slower rate of 14 km^2 per year (1990–2010) compared to the rate of loss of 50 km^2 per year from 1950 to 1970 (Long et al. 2014). The slowdown of mangrove loss may be attributed to the recognition of the importance of ecosystem services provided by mangroves in the Philippines which are valued at US$ 47.92 billion (in 2007 prices; Azanza et al. 2017). Studies confirming the importance of mangroves for climate change mitigation and adaptation, through coastal protection (Menéndez et al. 2018) and carbon sequestration (Salmo and Gianan 2019), emphasized the need to support mangrove conservation.

Several projects have been implemented since the 1990s to rehabilitate mangroves (Primavera and Esteban 2008). A review of mangrove rehabilitation projects in the Philippines, financed with international development assistance, showed that less than 20% of mangroves survived after 1–3 years from planting due to inappropriate species-substrate-site matching (Primavera and Esteban 2008; Garcia et al. 2014; Wodehouse and Rayment 2019). To address this problem, guidelines for science-based mangrove rehabilitation were developed, recommending the mid to high intertidal zone as mangrove planting sites. Mangroves planted in this zone have higher survival rates than those in coastal fringes due to less exposure to waves (Primavera et al. 2014) and less salinity and inundation stresses (Salmo and Juanico 2015). This zone is also where thousands of hectares of mangroves were cut down for pond expansion, but more than 50% of these ponds are now underutilized or abandoned (Primavera et al. 2011).

Many ponds were abandoned in the 1990s due to profit loss from mass mortalities and low market prices of shrimps (Macabuac 2005). Moreover, unsustainable aquaculture farming practices resulted in the degradation of soil and water quality and an increase in diseases. After a few years of abandonment, pioneer species mainly from the genera *Avicennia* and *Sonneratia* can naturally recolonize some ponds (Primavera et al. 2014; Proisy et al. 2018). Studies in some countries have also shown the capacity of mangroves to naturally recolonize abandoned aquaculture and salt ponds. Indigenous mangrove species were found among planted *Rhizophora* species in abandoned AP that have been reconnected to tidal flow through pond dike openings in Bali, Indonesia (Proisy et al. 2018). Similarly, mangroves naturally recolonized abandoned salt ponds in Ceará, Brazil, after tidal flow to the ponds was reestablished (dos Reis-Neto et al. 2019). Mangrove natural regeneration is possible if there is a nearby source of mangrove propagules (Lewis 2005), if hydrological connections to tidal flows are restored (Lewis 2005; Primavera et al. 2014), and if the substrate is conducive enough (e.g., not compacted and asphyxiated) for the propagules to establish (van Bijsterveldt et al. 2020).

Despite the high incidence of pond abandonment, pond reversion to mangroves is fraught with institutional and political issues, such as the lack of manpower to monitor and enforce policies (Ferrer et al. 2016). Nonetheless, reversion of AP is vital to effective mangrove rehabilitation due to its prime location. Mapping of abandoned, undeveloped, and underutilized (AUU) ponds in the Philippines, which are poorly documented, was proposed as an initial step to pond reversion (Samson and Rollon 2011; Primavera et al. 2014). Although these issues have been recognized as important to mangrove conservation, there are only a few studies that have addressed them (Samson and Rollon 2011; Primavera et al. 2014; Salmo and Juanico 2015; Duncan et al. 2016). Therefore, this study aims to contribute to the development of a national inventory and assessment of mangrove colonization in AP in the Philippines by providing a method for detecting these sites. The study used open-access satellite imagery and a cloud-based platform so that it can be replicated in other regions by anyone with access to the internet and basic knowledge in geographic information system (GIS) analysis. The methodology can be used as a preliminary step for evaluating the success of mangrove rehabilitation policies.

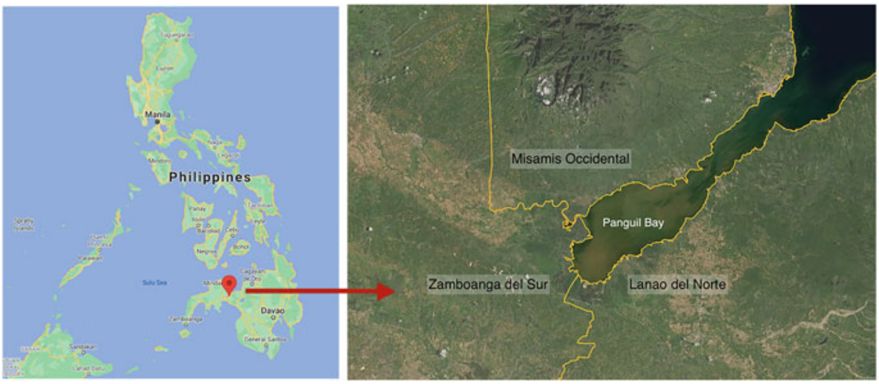

Fig. 3.1 Location of the study site in Panguil Bay, Southern Philippines. Panguil Bay is bordered by three provinces—Misamis Occidental, Zamboanga del Sur, and Lanao del Norte

3.2 Methods

3.2.1 Study Site

The study area is the coastal zone of Panguil Bay in the southern Philippines (Fig. 3.1). The coastal zone is defined here as 10 km on both landward and seaward sides of the coastline with less than 10 m elevations (Eastman et al. 2015). Panguil Bay was identified as one of the regions that had the most concentrated mangrove areal decrease from 1990 to 2010, driven by aquaculture expansion (Long et al. 2014). It was also one of the priority sites for a mangrove rehabilitation project financed with international development assistance from 1990 to 1994 (Asian Development Bank [ADB] 1999).

Panguil Bay forms a large estuary that is bordered by the administrative provinces of Misamis Occidental, Zamboanga del Sur, and Lanao del Norte (Fig. 3.1). It has a total catchment area of 3097 km^2 and a tidal elevation range of 0 to 1.2 m. Its salinity gradient ranges from 5 to 10 PSU at the inner bay portion near river mouths to 32 PSU at the mouth of the bay near the open ocean (Boco et al. 2014). There are eight major mangrove species and three mangrove associate species recorded in Panguil Bay (Rivera et al. 2017; Osing et al. 2019).

3.2.2 Data Preprocessing

Mangrove forests are difficult to access and navigate thereby making on-site change monitoring a difficult and time-consuming task. Remote sensing has been used to map mangrove extent and distribution globally and in different regions in 435 published studies (Wang et al. 2019). Mangroves have a distinct spectral signature that makes it easier to distinguish them from other vegetation types, particularly in the red, near-infrared, and mid-infrared spectral ranges (Giri 2016).

The processing and analysis of multiple satellite images take time and require large storage capacity and computing power. Open-access cloud-based platforms for geospatial analysis, like Google Earth Engine (GEE), significantly reduced the time and resources needed to process very large geospatial datasets (Gorelick et al. 2017). GEE provides access to Google's high-performance computing resources and its large data catalogue of satellite images.

This study used remote sensing, specifically Landsat datasets, and the GEE processing platform to map aquaculture ponds and mangroves in Panguil Bay, southern Philippines. The Landsat image collection is one of the main open-access earth observation datasets that is used for long-term and large-scale mangrove extent mapping. Other previous studies similarly used Landsat data to monitor the impact of aquaculture on mangroves in the Mekong River Delta, Vietnam (Hong et al. 2019), and to assess the change in mangrove areas and its causes in the Ba and Rewa Deltas in Fiji (Avtar et al. 2021).

Landsat 5 and 8 have a 16-day revisit frequency with 30-m spatial resolution. Landsat 5 and 8 Surface Reflectance Tier-1 (SRT-1) images, available from the GEE platform, were acquired and composited for the decadal mangrove forest change detection (Table 3.1). Images from these datasets have already been orthorectified and contain atmospherically corrected surface reflectance. Very few cloud-free images were available for the study site before 2010, and none were available before 1992. Cloud contamination was reduced by stacking all available images for each study period (1993, 2000, 2010, 2015, and 2020). For study periods that mostly had cloudy data, images from 1 year prior were added to the annual composites. Images from 1992 and 1999 were added to the 1993 and 2000 composites, respectively. Images from 2010 and 2020 were sufficiently cloud-free so additional data from other years were not needed. The land cover changes in 1993, 2000, 2010, and 2020 were compared. Only training data was collected from the 2015 composite image. Table 3.2 shows the number of images available for the selected periods.

Clouds and shadows were masked out using the *pixel_qa* band which is a quality assurance band provided with all Landsat surface reflectance datasets. The *pixel_qa* band contains pixel quality attributes generated from the CFMask algorithm. CFMask is a translation of the Function of Mask (FMask) algorithm (Zhu and Woodcock 2012; Zhu et al. 2015) into the C-programming language by the United States Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center. Pixels with the highest Normalized Difference Vegetation Index (NDVI) value from all available images for each study period were then composited into one image. NDVI uses red and near-infrared light to quantify vegetation growth and health (Eq. 3.1) because chlorophyll absorbs blue and red light and reflects green and near-infrared light (Table 3.1). Because clouds have a higher NDVI value than water, a threshold was added (Stuhler et al. 2016) so that all pixels with NDVI values less than 0.7 will use the median NDVI value instead.

Table 3.1 Landsat 5 and 8 surface reflectance Tier-1 band designations

	Landsat 5			Landsat 8		
Spectral region	Band	Wavelength (nm)	Resolution (m)	Band	Wavelength (nm)	Resolution (m)
Coastal aerosol	–	–	–	B1	435–451	30
Blue	B1	450–520	30	B2	452–512	30
Green	B2	520–600	30	B3	533–590	30
Red	B3	630–690	30	B4	636–673	30
Near-infrared (NIR)	B4	770–900	30	B5	851–879	30
Short-wave infrared 1 (SWIR1)	B5	1550–1750	30	B6	1566–1651	30
Short-wave infrared 2	B7	2080–2350	30[a]	B7	2107–2294	30
Temperature 1	B6	10,400 – 12,500	30	B10	10,600 – 11,190	30[a]
Temperature 2	–	–	–	B11	11,500 – 12,510	30[a]

[a]Resampled to 30-m

Table 3.2 Number of images used for the spatiotemporal analysis, 1992 to 2020

Year of acquisition	Data source	No. of images
1992	Landsat 5 SRT-1	3
1993	Landsat 5 SRT-1	4
1999	Landsat 5 SRT-1	4
2000	Landsat 5 SRT-1	12
2010	Landsat 5 SRT-1	8
2015	Landsat 8 SRT-1	45
2020	Landsat 8 SRT-1	41
Total		117

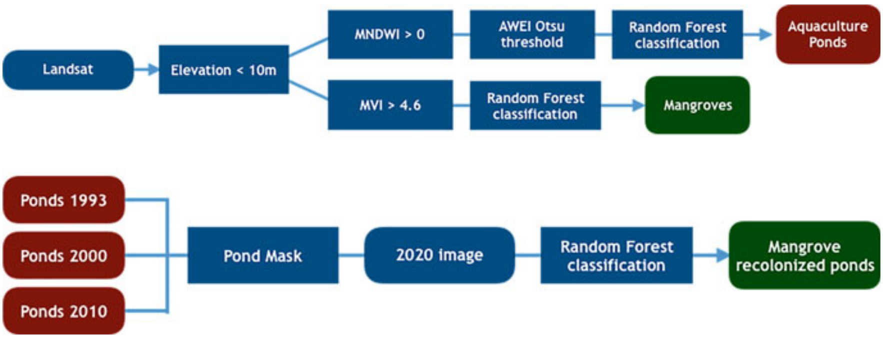

Fig. 3.2 Flowchart used for the spatiotemporal analysis and identification of mangrove-recolonized ponds. MNDWI refers to the Modified Normalized Difference Water Index, AWEI refers to the Automated Water Extraction Index, and MVI refers to the Mangrove Vegetation Index

$$\mathrm{NDVI} = (\mathrm{NIR} - \mathrm{Red}) \div (\mathrm{NIR} + \mathrm{Red}) \quad (3.1)$$

where NIR is the near-infrared band and Red is the red band of Landsat data (Table 3.1).

3.2.3 *Supervised Classification*

An elevation mask was applied to the composited Landsat images (1993, 2000, 2010, 2015, and 2020). The elevation mask was applied to limit the study site to areas with less than 10 m elevation where mangroves and ponds are likely to occur (Eastman et al. 2015). The elevation mask was created in GEE from the Multi-Error-Removed Improved Terrain (MERIT) Digital Elevation Model (DEM; Yamazaki et al. 2017). The flowchart developed by this study is illustrated in Fig. 3.2.

Training and validation points were created by selecting a sample of pixels from the 2015 composite image for six landcover classes, using a high-resolution Google Earth image of the site and the 2015 landcover map from the National Mapping and Resource Information Authority (NAMRIA) as a guide. The landcover classes used were pond, water, mangrove, built-up, cropland, and others. The "others" class includes other forest types, grasslands, shrubs, and open/barren land. A total of 500 points per landcover class was created to train a random forest (RF) classifier. The RF classifier is a machine learning classification algorithm available on GEE.

Water and vegetation indices were calculated and added as new bands to the composite images. Water pixels were separated from non-water pixels using the Automated Water Extraction Index (AWEI; Eq. 3.2; Feyisa et al. 2014) and the Modified Normalized Difference Water Index (MNDWI; Eq. 3.3; Xu 2006). The study also used the Mangrove Vegetation Index (MVI; Eq. (3.4); Baloloy et al. 2020) to extract the mangrove regions from the non-water pixels. The indices were calculated using the following equations:

$$\mathrm{AWEI} = 4 \times (\mathrm{Green} - \mathrm{SWIR2}) - (0.25 \times \mathrm{NIR} + 2.75 \times \mathrm{SWIR1}) \tag{3.2}$$

$$\mathrm{MNDWI} = (\mathrm{Green} - \mathrm{SWIR1}) \div (\mathrm{Green} + \mathrm{SWIR1}) \tag{3.3}$$

$$\mathrm{MVI} = (\mathrm{NIR} - \mathrm{Green}) \div (\mathrm{SWIR1} - \mathrm{Green}) \tag{3.4}$$

where Green, NIR, SWIR1, and SWIR2 represent the spectral regions of green, near-infrared, short-wave infrared 1, and short-wave infrared 2 of the Landsat data, respectively (Table 3.1).

Water absorbs red, yellow, and green light which makes it easily recognizable against vegetation and landmass. However, suspended sediments or particles in the water such as phytoplankton can alter its characteristics. On the other hand, MVI detects mangroves by measuring the greenness and moisture information of image pixels. It has been used to generate mangrove maps for the Philippines, Japan, Indonesia, Cambodia, Thailand, and Vietnam (Baloloy et al. 2020).

The composite images were then segmented using the simple non-iterative clustering (SNIC) algorithm. Thresholds were applied to create two separate layers for each image. SNIC segments images into superpixels which are small clusters of connected pixels with shared characteristics, like pixel intensity (Achanta and Susstrunk 2017). The water layer was created by setting an MNDWI threshold equal to 0 so that all pixels with MNDWI values below 0 were masked out. This step removed vegetation and other non-water pixels and improved the separability of different types of water, specifically pond and shallow water (Yu et al. 2020). The histogram and Otsu threshold of AWEI were then calculated from the water-masked images. The Otsu method (Otsu 1979) finds the optimal threshold to separate pixels into two classes, in this case, the pond class and other water types. Pixels with AWEI below the calculated Otsu threshold were removed to produce the final water layer. The vegetation layer was created by setting an MVI threshold of 4.6 (cf. Baloloy et al. 2020) for detecting mangroves from Landsat images. All pixels with MVI values below 4.6 were masked out. The water and mangrove layers were classified separately using the RF algorithm as the classifier to extract the pond and mangrove classes.

Two validation datasets were created to test the accuracy of the pond and mangrove classes. Following the method for accuracy assessment by Yu et al.

Table 3.3 Partial confusion matrix and summary of calculated Recall (Rec), Precision (Prec), and *F*-score

Class	CP	VP	TP	FP	FN	Rec	Prec	*F*-score
Pond	100	83	82	18	1	0.99	0.82	0.90
Mangrove	148	132	128	20	4	0.97	0.86	0.91

CP no. of classified pixels per class, *VP* no. of validation points per class, *TP* true positive, *FP* false positive, *FN* false negative

(2020), a partial confusion matrix was constructed to calculate the Precision (Eq. 3.5), Recall (Eq. 3.6), and *F*-score (Eq. 3.7).

$$\text{Precision} = \frac{\text{TP}}{\text{TP} + \text{FP}} \tag{3.5}$$

$$\text{Recall} = \frac{\text{TP}}{\text{TP} + \text{FN}} \tag{3.6}$$

$$F\text{-score} = 2 \times \frac{\text{Precision} \times \text{Recall}}{\text{Precision} + \text{Recall}} \tag{3.7}$$

where TP is the true positive which is the number of correctly classified pixels, FP is the false positive which is equal to the total number of classified pixels minus the TP, and FN is the false negative which is equal to the number of validation points minus the TP. A pond or mangrove pixel was considered correctly identified if a validation point landed on it. A total of 83 pond validation points and 132 mangrove validation points were used in the final accuracy computation (Table 3.3).

The mangrove-recolonized ponds (MRPs) were extracted by combining all classified ponds from 1993, 2000, and 2010 to create a pond mask layer that was applied to the 2020 composite image. The 2020 image with the pond mask was classified using the RF classifier. All pixels that were classified as mangroves within the pond mask were identified as MRPs.

3.3 Results

The accuracy of the classification results based on the F-score of the pond and mangrove classes was 90% and 91%, respectively (Table 3.3). The pond and mangrove maps for each period were paired with a false-color composite of their Landsat image to illustrate the geographical features surrounding the pond and mangroves (Fig. 3.3). The mangrove area increased from 24.91 to 40.20 km^2, while the pond area decreased from 35.28 to 26.51 km^2 from 1993 to 2020 (Table 3.4). The total area of MRPs was estimated at 10.24 km^2 and was ca. 25% of the study site's total mangrove area (40.20 km^2) in 2020 (Fig. 3.4). MRPs also occupied about 18% of the combined pond area (58.34 km^2) from the 1993, 2000, and 2010 maps (Table 3.5).

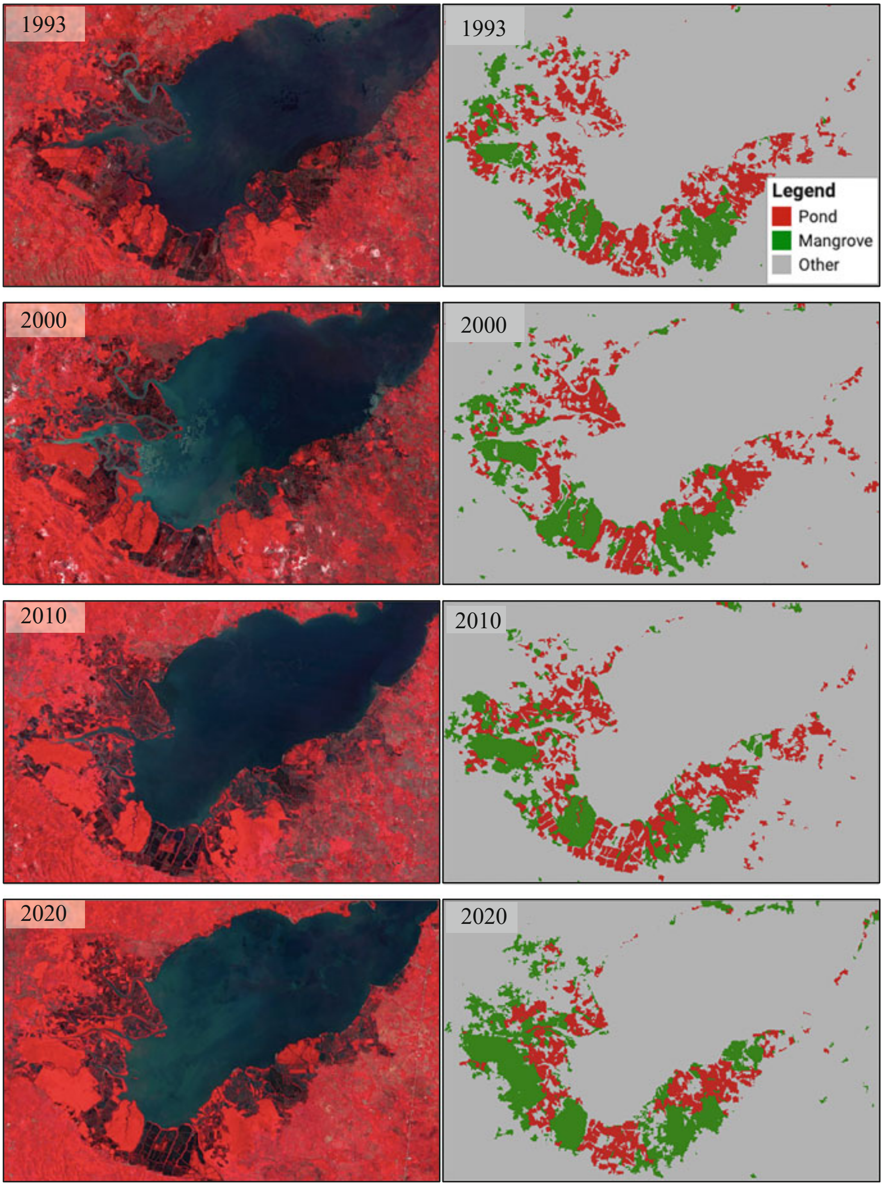

Fig. 3.3 False color composites of Landsat images in 1993, 2000, 2010, and 2020 of Panguil Bay, Philippines (left), paired with their respective pond and mangrove mapping results (right)

The change in spectral reflectance of MRPs from 2013 to 2020 was compared against the mean spectral signature of ponds and mangroves (Fig. 3.5). The spectral signature of MRPs approached that of mangroves as time progressed. The MRP reflectance in the red and green spectra were similar to pond reflectance but differed

Table 3.4 Summary of pond and mangrove area and area change (km^2) per study period. The values under the pond and mangrove change columns show the total area lost/gained per study period, from 1993 to 2000, 2000 to 2010, and 2010 to 2020

Year	Pond (km^2)	Mangrove (km^2)	Pond change (km^2)	Mangrove change (km^2)	Pond change (%)	Mangrove change (%)
1993	35.28	24.91	–	–	–	–
2000	31.87	34.77	−3.40	9.86	−10	40
2010	34.66	30.98	2.79	−3.79	9	−11
2020	26.51	40.20	−8.15	9.21	−24	30

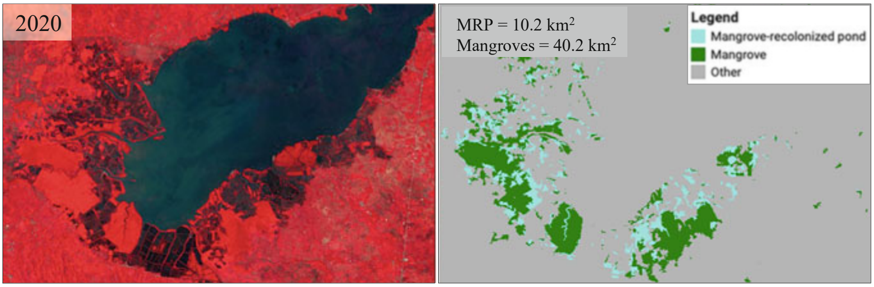

Fig. 3.4 A false color composite of the 2020 Landsat image (left) compared with the map of mangrove-recolonized ponds (MRP) in Panguil Bay in 2020 (right)

Table 3.5 Summary of new ponds detected per study period and the total area of mangrove-recolonized ponds (MRP). The combined pond area includes operational and abandoned ponds

Year	Pond (km^2)	Combined pond area (km^2)	MRP (km^2)
1993	35.28		
2000	12.41	47.68	
2010	10.65	58.34	
2020	6.39	64.73	10.24

significantly in the near-infrared (NIR) and short-wave infrared (SWIR 1 and 2) spectra (Table 3.6).

The changes over time in water and vegetation index values of MRPs were also compared against the pond and mangrove classes (Table 3.7). The mean value of the pond class was considered as the baseline, while the mean value of mangroves was the target. The AWEI showed a decreasing trend as MRPs transitioned from water-filled ponds to mature mangroves. AWEI values decreased from 70.40 to −1349.63. On the other hand, the NDVI showed an increasing trend indicating the transformation of MRPs from ponds to mangroves with greener and denser mangrove canopies. NDVI values increased from 0.52 to 0.79. The MVI values also showed an increasing trend but with dips in 2016, 2017, and 2019. The MRPs showed higher values than the mangrove class in 2015, 2018, 2019, and 2020. Unlike other vegetation indices, MVI is more affected by inundation and background moisture as it reflects the probability of a pixel being a mangrove rather than mangrove vigor (Baloloy

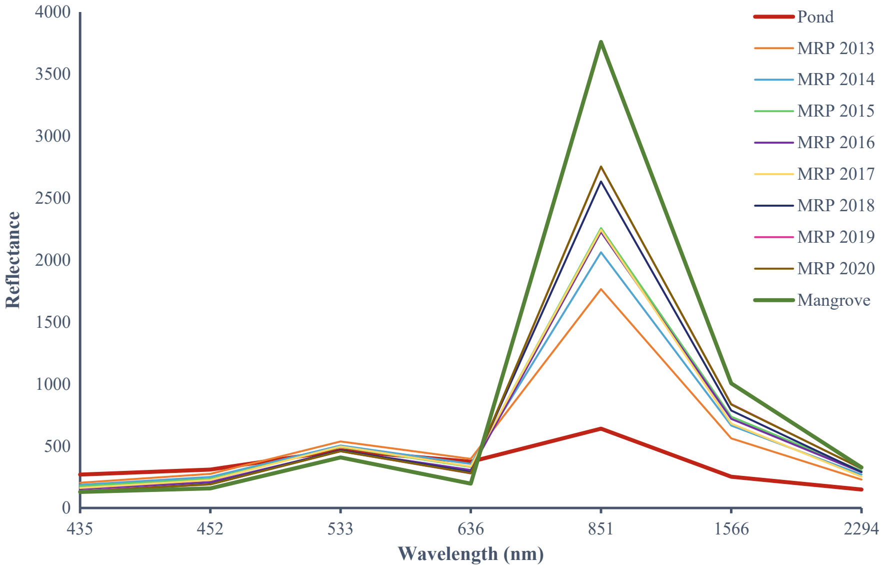

Fig. 3.5 Spectral signature of mangrove-recolonized ponds (MRPs) in 2013 through 2020 compared to pond and mangrove classes

Table 3.6 Average annual spectral reflectance of MRPs compared with the pond and mangrove classes

Class	Spectral region				
	Green (520–600 nm)	Red (630–690 nm)	NIR (770–900 nm)	SWIR 1 (1550–1750 nm)	SWIR 2 (2080–2350 nm)
Pond	465	373	640	252	149
MRP2013	537	396	1765	562	230
MRP2014	505	356	2062	666	269
MRP2015	492	331	2257	736	300
MRP2016	461	306	2226	719	289
MRP2017	495	334	2244	681	253
MRP2018	465	290	2633	786	290
MRP2019	458	280	2751	837	318
MRP2020	459	282	2755	835	320
Mangrove	408	197	3759	1005	328

et al. 2020). The MRPs showed higher background moisture (see AWEI values in Table 3.7) than the mangrove class.

By year 2014, the MRPs were more recognizable as mangroves with mean MVI of 4.65 (Table 3.7), exceeding the 4.6 MVI threshold (cf. Baloloy et al. (2020) for identifying mangroves in Landsat images). The mean spectral reflectance of MRPs in 2020 produced higher AWEI and lower NDVI values compared with the mean values of the mangrove class (Table 3.7). These reflectance values included

Table 3.7 Summary of spectral index values of mangrove-recolonized ponds from 2013 to 2020 compared with the mean spectral index values of the pond and mangrove classes

Landcover class	AWEI	NDVI	MVI
Pond	959.79	0.17	0.09
MRP 2013	70.40	0.52	3.98
MRP 2014	−449.50	0.59	4.65
MRP 2015	−751.11	0.66	6.03
MRP 2016	−814.12	0.68	3.75
MRP 2017	−625.98	0.67	4.33
MRP 2018	−1173.18	0.75	7.63
MRP 2019	−1357.81	0.79	6.34
MRP 2020	−1349.63	0.79	7.89
Mangrove	−2425.88	0.90	5.87

mangroves of different growth stages, from seedling to mature stage. The lower NDVI values of MRPs indicate that they are still in the early vegetation development stage.

3.4 Discussion

3.4.1 Mangrove Regeneration

Mangrove area increased from 1993 to 2020 due to mangrove expansion along the coastline, rivers, and into abandoned AP. Sediment deposition through increased siltation may have facilitated mangrove colonization in the study site (Jimenez et al. 2009). The deposited sediments increase the surface elevation relative to the mean sea level elevation which may have improved the conditions for mangroves to extend seaward in areas that were previously too inundated to colonize (Duncan et al. 2018). Moreover, abandoned extensive ponds located on the seaside are likely to have breached or eroded pond dikes which may have led to restored tidal flooding (Primavera et al. 2014). Mangrove regeneration in abandoned ponds is controlled by submergence time and sediment stability which are related to bed level elevation and pond drainage (van Bijsterveldt et al. 2020). When bed level elevation is raised and hydrological connectivity is restored, more sediments are delivered to the ponds. The sediments within the AP are subjected to less flooding which increased soil stability and allowed sediment consolidation (Newcomer et al. 2014). Mangrove seedlings have a higher chance for establishment when the sediment is stable and inundation stress is low (Salmo and Juanico 2015; van Bijsterveldt et al. 2020). Duke (2001) described the survival and growth strategies and the regenerative processes of mangroves after a disturbance. Mangroves use regular tidal flooding by producing abundant, buoyant, and self-planting propagules that can disperse and establish in exposed substrates and surrounding areas. Given favorable conditions, including exposure to full sunlight, mangrove seedlings will rapidly colonize and vigorously grow in available spaces for approximately 5 years. As the seedlings transition to trees, there will be gradual reductions in density, but biomass will continue to increase. These transitions are evident in the increasing NDVI values of MRPs in the study site from 2013 to 2020 (Table 3.7). After ca. 10 years, the canopy will be closed, and the forest will stabilize consistent with the vegetation and sediment restoration trajectories observed in planted mangroves in northwest Luzon and central and western Visayas in the Philippines (Salmo et al. 2013).

3.5 Impact of Policies on Mangrove Rehabilitation

Policies can have a huge influence on mangrove conservation and rehabilitation. Government financial incentives in the form of loans and low fees stimulated investments in aquaculture and fishpond construction (Primavera 1995, 2000). The co-occurrence of pond retraction and mangrove expansion in the study site between 1993 and 2020 may be related to the enactment of several mangrove conservation policies, specifically:

1. Department Administrative Order 76 in 1987 established mangrove buffer-zone areas as a form of coastal protection.
2. Republic Act 7161 in 1991 banned cutting of all mangrove species in the Philippines.
3. Department of Environment and Natural Resources (DENR) Memorandum Order 17 in 1998 prohibited further zonification of mangroves for fishpond development.

However, despite the strong legal framework supporting mangrove conservation at the national level, policy enforcement at the local level is weak and can be politically influenced. Moreover, the agencies in charge of environmental, agriculture, and aquaculture development have overlapping mandates and conflicting policies. Private owners who have strong political connections can illegally develop protected mangrove forests into privately owned ponds (Primavera 2000). As seen in the 2010 land cover map (Fig. 3.3), a patch of mangrove forest was still converted into fishponds despite the policies banning cutting of all mangrove species. On the other hand, the enactment of the National Greening Program in 2011 may have led to the large increase in mangrove area from 2010 onward (Table 3.4) because it provided financial incentives to coastal communities to participate in mangrove reforestation. Policies that legitimized the access and tenure rights of coastal communities over mangroves and coastal resources were also seen as critical to sustainable mangrove management (Song et al. 2021).

Song et al. (2021) noted that mangrove development is largely influenced by global views on conservation and mangrove valuation. Development assistance from wealthy countries influences the discourse surrounding the value of mangroves and how they should be utilized and consequently influences the policies that are created. From 1950 to 1990, large-scale overseas development assistance was offered to the Philippines to ramp up aquaculture production which resulted in policies that allowed the clearing of mangrove forests for fishpond construction (Primavera 1995, 2000). Similarly, since 2011, development assistance has been provided to advance carbon accounting and blue carbon programs which led to Philippine policies that aim to increase carbon credits through reforestation (Song et al. 2021).

3.6 Implications for Mangrove Management and Restoration

Mangroves, seagrass, and saltmarshes, called blue carbon ecosystems, have been recognized as important carbon sinks and incorporated in the Nationally Determined Contribution (NDC) mitigation actions of several countries (Herr and Landis 2016). The Philippines committed to lower its emissions by 75% for the period 2020 to 2030 when it submitted its NDC to the United Nations Framework Convention on Climate Change (UNFCC) (Climate Change Commission 2021). The conservation and restoration of mangroves can help the Philippines meet its NDC target. Restoring Philippine mangroves to its 1951 extent will increase carbon storage and could offset emissions from other sources. Aside from carbon emissions reduction, restoring mangroves also restores the ecosystem services that they provide like habitat and nursery for various organisms (Nagelkerken et al. 2008), food and raw material provision (Salem and Mercer 2012), and coastal protection (Hochard et al. 2019). Menéndez et al. (2018) estimated that Philippine mangroves protect about 613,500 people per year against floods and avert about US$ 1 billion in property damages. Moreover, an additional 267,000 people per year could be protected against floods and US$ 453 million avoided in property damages if Philippine mangroves are restored to their 1950 extent. Hence, aside from mangroves that are already declared as protected areas, the recolonized mangroves should also be protected and not subject to conversion for coastal development projects. Coastal development plans and policies should integrate the protection of recolonized mangroves in abandoned, undeveloped, and underutilized (AUU) ponds.

The Philippines has many AUU ponds that can be rehabilitated into mangroves. Primavera et al. (2011) estimated that about half of the 2320.65 km^2 of AP in the Philippines was abandoned in the mid-1990s. The Philippines could sequester large amounts of carbon if all AUU ponds are rehabilitated. Salmo et al. (2019) calculated the mean rate of carbon sequestration of newly established mangroves at 10.2 ± 0.7 Mg C ha^{-1} $year^{-1}$. Similarly, this study showed the huge potential of AUU ponds for restoring mangroves. About 17% of the AP in the study site were recolonized by mangroves, and the area could be much higher because this study only assessed mangrove recolonization of AP from 1993 to 2020.

3.7 Research/Management Gaps and Recommendations

In summary, mangrove-recolonized ponds (MRPs) have a distinct spectral signature that can be used to detect AUU ponds where mangroves are still in the early vegetation development stage. Mapping all MRPs in the Philippines using the methodology developed in this study is recommended. This can be used to prioritize areas for assisted mangrove rehabilitation since the presence of vegetation indicates that the substrate in the AUU ponds has become stable enough for mangrove establishment and that inundation stress has been reduced. The methodology can also be used to monitor and evaluate the success of mangrove rehabilitation programs.

The study also suggests conducting site inspections after mapping the MRPs to verify the actual presence and distribution of mangroves, measure the mangrove structure and composition, and study the conditions surrounding mangrove recolonization of AP (e.g., tidal inundation level, substrate stability). Moreover, future monitoring studies (from 2015 onward) should make use of the open-access Sentinel 1 and 2 datasets which have higher spatial and temporal resolutions. These high-resolution images can provide higher classification accuracies and can also discriminate between different mangrove species. Future studies should also use very high-resolution satellite imagery which may be able to distinguish naturally regenerated mangroves from planted mangroves by showing their spatial patterns.

The study further recommends interviewing local authorities and communities to document the history of mangrove management in the sites, determine the cause of mangrove regeneration (whether it was from natural regeneration or from reforestation), and document mangrove conservation and rehabilitation policies and practices that were implemented. In-depth policy analysis is recommended to determine which policies were the most effective in reducing pond expansion into mangrove forests and increasing mangrove cover.

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Chapter 4
Ecosystem Services and Their Future Scenarios Centering on Mangrove Ecosystem in Ishigaki Island, Japan

Yasuo Takahashi, Shizuka Hashimoto, and Huang Wanhui

Abstract This chapter contributes to a comprehensive understanding of the island socio-ecological system by a synthesis of the state and trend of, and the drivers of changes in ecosystems and their services, focusing on mangroves in Ishigaki Island. The current extent of mangroves on the Island is limited to small patches along a few river estuaries, which nevertheless provide critical habitat for several threatened species as well as important ecosystem services that mediate the Island's terrestrial and coastal systems. It however is subject to gradual change due to changing hydrological and sedimentation patterns affected by land uses within the upstream watershed. The chapter went further to identify plausible future island socio-ecological scenarios with concrete narratives and key metrics, building on downscaling existing scenarios on one hand, and on the other hand regional policies and periodic statistics over the past two decades. The scenarios are fourfold: (A) nature-sensitive integrated tourism and agriculture; (B) nature-centered tourism; (C) integrated tourism and agriculture; and (D) resort island scenarios. We also identified ten key quantitative metrics to gauge the four scenarios: (1) tourist number, (2) nature tour destination area, (3) residential area, (4) land development area, (5) coastal development, (6) dry and paddy field area, (7) grassland area, (8) conservation agriculture area, (9) protected area, and (10) restored area. The synthesis of the Island's socio-ecological system and the plausible future scenarios articulated in this chapter provide a robust basis for modeling future island ecosystems and their services centering on mangroves in Ishigaki Island. Furthermore, the chapter demonstrates methodological advancement in downscaling existing high-level scenarios

Y. Takahashi (✉)
Institute for Global Environmental Strategies (IGES), Hayama, Kanagawa, Japan
e-mail: yasuo.takahashi@iges.or.jp

S. Hashimoto
Department of Ecosystem Studies, University of Tokyo, Tokyo, Japan

H. Wanhui
The Research Institute for Humanity and Nature, Kyoto, Japan

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with the aid of regional periodic statistics and a comprehensive review of regional policy documents.

Keywords Island · Scenario · Model · Biodiversity · Ecosystem services · Mangrove · The Nature Futures Framework (NFF) · Natural capital

4.1 Introduction

Recently, mangroves are drawing global attention for their co-benefits to ameliorate climate change and its impacts, as well as for biodiversity and several other ecosystem services that underpin human livelihoods and well-being (Pörtner et al. 2021). Accumulating scientific knowledge revealed the likelihood to exceed the global warming of 1.5C and 2C during the current century (IPCC 2021). The impacts of climate change on different ecosystems and thus on people have become apparent in the past few decades (IPCC 2014). These impacts, particularly oceanic changes including sea-level rise, are projected to be exacerbated in the current trajectory (IPCC 2021). Mangrove, which lies at the interface between terrestrial and sea waters, is susceptible to these changes (Ward et al. 2017). Likewise, socio-ecological systems on small islands are, and will further be, exposed to climate change impacts (IPCC 2014). Hence, to support evidence-based sound decision-making on island mangroves, it is imperative to understand the present and future state of island mangroves in the socio-ecological contexts unique to such islands. Scenarios and models have become extensively used for future predictions, but their application to mangrove socio-ecological systems is yet limited. These limitations largely derive from extensive data requirements and the challenges in developing the scenarios and quantifying the ecosystem services that are salient to the local and regional priorities. In Japan, a set of national-scale socio-ecological scenarios was developed, which mainly considers uncertainties in population distribution and the use of natural and produced capitals, for future ecosystem services prediction (Saito et al. 2019). Further, these scenarios inspired the development of regional scenarios for the prediction of marine ecosystem services for the Yaeyama region, to which Ishigaki Island belongs. These scenarios, as well as the Nature Futures Framework (NFF), a heuristic tool of scenario building developed by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) task force on scenarios and models (Pereira et al. 2020), were available to understand future island ecosystems, particularly mangrove, and their services in Ishigaki Island.

Against this backdrop, this chapter aims to contribute to the holistic knowledge of the island socio-ecological system by a synthesis of the state and trend of, and the drivers of changes in ecosystems and their services, focusing on mangrove in Ishigaki Island. On these bases, and drawing on downscaling higher-level existing scenarios, the chapter goes further to develop plausible future island socio-ecological scenarios with concrete narratives and key metrics. With these, this work sets the scene for future scenarios and modeling of island ecosystem services, particularly focusing on mangroves, for Ishigaki Island and for other subtropical Japanese islands where the same approach is applicable.

The contents of this chapter rely largely on secondary sources, including policy documents, government statistics, and academic papers identified by key informant interviews and keyword searches on the internet. They partially include field data, such as exploratory pictures, collected through a preliminary site visit. We did not use a multi-stakeholder participatory approach to scenario development which now has become a widely practiced method (Kabaya et al. 2019). We instead relied on the analysis of existing policy documents in the relevant sectors to identify the scenarios and key metrics that are salient to the real-world policies and actions.

This chapter is composed of five sections. Following the current introductory section, the second section provides an overview of mangrove and other ecosystems, as well as services deriving from these ecosystems, on Ishigaki Island. The third section describes changes in different ecosystem types and direct and indirect drivers of these changes. The fourth section starts with an outlook of existing scenarios of socio-ecological systems and their interpretation in the Ishigaki Island's policy context. The section continues to identify plausible future scenarios for the island socio-ecological system focusing on mangroves, building on the synthesis of the Island's socio-ecological system as well as on downscaling the existing higher-level scenarios. The fifth section concludes the entire chapter by highlighting major findings, knowledge gaps, and possible ways forward.

4.2 Mangroves and Other Land Use and Land Cover on Ishigaki Island

The Ishigaki Island lays in the southwestern end of the Ryukyu archipelago in Japan, located between N 25.55, E 124.33, and N24.19, E123.27 in a subtropical climate. The island has the third-largest land area among other islands of Okinawa prefecture, i.e., 22,224 hectares (Ishigaki City 2017). Among other land-use and land cover (LULC) classes, mangrove covers 104 hectares, which is approximately 0.47% of the total land area on Ishigaki Island (Table 4.1). Nakasuga et al. (1974) confirmed 80 mangrove communities across Japan, which had the northern limit at the Kyushu mainland part of Kagoshima Prefecture, down south to Iriomote Island. Nakasuga (1976), by a more detailed survey, identified 21 mangrove communities across Ishigaki Island. Major mangrove communities on the Island were found mostly around river estuaries, particularly the Nagura, Miyara, and Fukido rivers (Fig. 4.1a). *Rhizophora mucronata* and *Bruguiera gymnorhiza* dominated these mangrove communities (Nakasuga 1976). More details of these mangrove communities are described in the following subsection. As for other LULC classes, broad-leaf forests had by far the highest coverage, followed by dry fields (non-paddy farmlands), grasslands, and buildings (Table 4.1, Fig. 4.1b). Grassland is used mainly for beef cattle and partially for cow milk production. Industrial crops including sugarcane (1084 ha in 2016) and tobacco (41 ha), vegetables (51 ha), and fruits (147 ha) were the main crops produced on dry fields (MAFF 2015). A patchwork of these LULC constitutes the watershed upstream respective mangrove stands.

Table 4.1 Land-use and land cover classification and area coverage in 2006

Class	Hectares	%
Broadleaf	10,080	45.1
Coniferous	890	4.0
Grassland	4150	18.6
Mangrove	100	0.5
Riverside, marsh, salt swamp, sand dunes	180	0.8
Natural bare land	140	0.6
Abandoned land	160	0.7
Paddy	380	1.7
Dry field	4480	20.0
Building	1240	5.5
Other	190	0.8
Open water	370	1.6
Total	22,360	

Note: Retrieved from the 2006 vegetation data of the Natural Environmental Information GIS, a vector dataset derived from aerial photograph interpretation and field surveys. The 2006 vegetation data has 51 vegetation classes on a 1:25,000 map, which were converted into 30 meters raster dataset with 12 land-use and land cover categories. The hectare numbers rounded off below the tens place, while the percentage numbers rounded off below the first decimal place

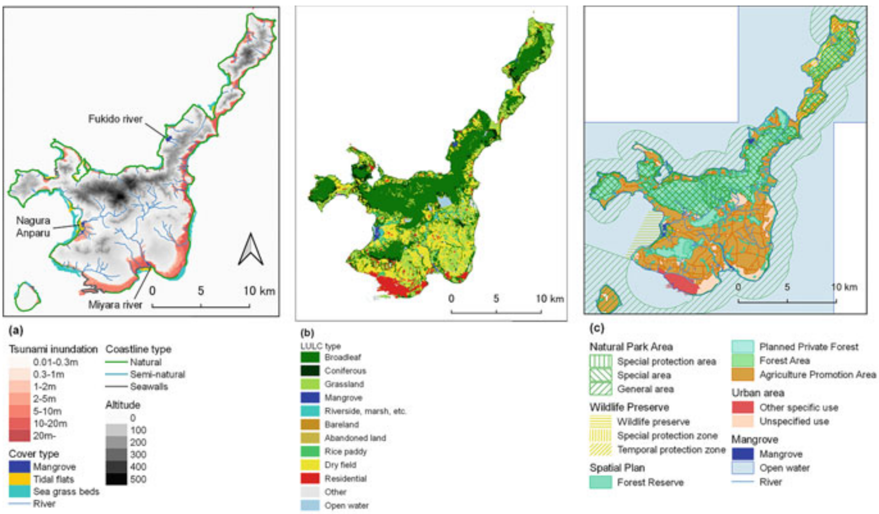

Fig. 4.1 Overview of mangrove, land use, and area protection on Ishigaki Island. (**a**) Tsunami inundation prediction, coastal cover/line type and topography; (**b**) land cover and land use type; and (**c**) area protection

The land-use regulations including protected areas of the Ishigaki City mostly agree with the current LULC, including the planned forest, agricultural and urban areas (Fig. 4.1c). The hilly terrain from the northeastern to the northwestern end of the island is mostly covered by forest. The forest is mostly protected as Natural Park Area, except for the forest patch at the southwestern part of the Island. Natural Park Area covers mangroves along Fukido and Nagura rivers but not the ones along Miyara River. Agriculture is promoted in the middle to the south part of the Island, while planned urban area is limited to the southwestern tip.

4.2.1 Mangrove Communities

4.2.1.1 Miyara River

Miyara river has the largest watershed range and is the longest among other rivers flowing out from the Island. The mangrove community extends from its estuary and up to lower tributaries. The mangrove stands along Miyara River are designated as a national natural monument. Whereas the Miyara river mangrove has long been affected by the deposition of red soil deriving from its upstream watershed, 46% of which is covered by farmland (Irokawa and Nihei 2008). The functions of mangroves to filter red soil and thereby contribute to reducing its impacts on coastal systems are reported (Irokawa and Nihei 2008). Mangrove, however, is also affected by red soil deposition that raises the ground level and thus can result in ecosystem succession to drier vegetation (Irokawa and Nihei 2008).

4.2.1.2 Nagura Anparu

Nagura Anparu ("Anparu" means net fishing in the vernacular term, implying the traditional use of the lagoon for artisanal fishing) is located at the central-western coastline of the Island. Nagura Anparu, a wildlife reserve of 1145 ha made up of a mix of multiple coastal ecosystems, encompasses mangroves (63 ha), dry fields (26 ha), open water (986 ha), and others (70 ha) (Nagura Anparu conservation and use promotion committee 2021). Mangroves, notably with *Bruguiera gymnorhiza*, *Kandelia obovata*, *Rhizophora mucronata*, *Lumnitzera racemosa*, *Avicennia marina*, and *Sonneratia alba*, dominate the vegetation over the Nagura reserve. It is designated as a wildlife reserve for its importance for the overwintering and stopover site for the birds migrating between eastern Asia and Australia. It is also an important habitat for several threatened species including black-faced spoonbill (*Platalea minor*) (EN), black-winged stilt (*Himantopus himantopus*) (LC, IB in the national red list), *Tringa totanus* (LC, II in the national red list), *Spilornis cheela* (LC, IA in the national red list), etc. Nagura Anparu, including the mangrove patches, is the most strictly protected among other mangroves in Ishigaki, as the Natural Park Special Area category I and Wildlife Preserve Special Protection Zone.

The Nagura Lagoon is a Ramsar site since 2005 (MOE 2010). Under these legal provisions, the site is commonly used for environmental education. However, the lagoon system has been changing gradually due to the deposition of red soil deriving from agricultural lands, particularly pineapples and sugarcane fields (Nakaza et al. 2011), that extensively cover the upstream watershed, and partly to the construction of drainage channels that had accelerated sediment transportation downstream.

4.2.1.3 Fukido River

Fukido river mangrove extends to 12 ha, which is dominated by *Rhizophora mucronata* and *Bruguiera gymnorhiza* (Terada et al. 2017). "Mangrove forest along the Fukido River" is designated as a special plant community, which also provides habitats for important crustaceans such as *Atyoida pilipes* and *Ryukyum yaeyamense*, listed as the near-threatened on the *National Red Data* book (MOE 2010). The mangrove stand belongs to the private forest under regional forest planning and is protected as Natural Park Special Area category I for its biological importance.

4.2.2 Mangrove Ecosystem Services

In the Yaeyama region, including Ishigaki Island, provisioning ecosystem services deriving from mangroves had traditionally played an important role in local livelihoods (Yoshimi 2011), but currently not as important as they were in the past. For example, Nagura Anparu, a coastal ecosystems complex with an extensive mangrove cover, was named after its use for net fishing ("Anparu") by local fishermen. Wood of *B. gymnorhiza* and *R. mucronata* was traditionally used for house construction materials. Barks from these trees are used for producing traditional reddish-brown dye. Mud crab (*Scylla* spp.) collected in mangrove waters is valued for local cuisine (Yoshimi 2011). Currently, these resources from mangroves are no more harvested for a commercial basis. Besides, efforts to the identification of potentially useful microorganisms from mangrove waters and soils have been made (Tokiwa et al. 2012).

Regulating ecosystem services of mangroves on Ishigaki Island are extensively studied. These include the regulation of creek and coastal water thermal environment (Nihei et al. 2002; Tamura and Nadaoka 2005), nutrient salt supply to coastal waters (Akamatsu et al. 2002, 2009; Kurosawa et al. 2003; Terada et al. 2017), dissolved organic matter sink and supply (Kida et al. 2019; Ohtsuka et al. 2020), aboveground and soil carbon storage (Okimoto et al. 2007; Kida et al. 2017; Iimura et al. 2019), river water purification (Terada et al. 2009), and sediment deposition (Akamatsu et al. 2004; Nihei and Seki 2006; Terada et al. 2017). Particularly nutrient and sediment retention are vital functions of mangroves in the Ishigaki Island. Turbid and eutrophic seawater caused by red soil and nutrient runoff from farmlands are known as major stressors on coral reefs, hindering the recovery and recruitment of coral reefs after breaching due to high seawater temperature (Hongo and Yamano 2013). Estuarine mangroves and associated organisms and soils have a vital function to reduce these stressors by filtering suspended soil and nutrients, particularly red soil deriving from upstream agricultural development for sugarcane and pineapple production (Nakaza et al. 2011). Red soil deposition, however, can have negative impacts on mangrove ecosystems through smothering mangrove root respiration (Ellison 1999) and accelerating succession to drier terrestrial vegetation (Ball 1980).

Cultural ecosystem services, or nonmaterial benefits of nature, are central to the ecosystem services provided by natural ecosystems in the Ishigaki Island, particularly coastal ecosystems including mangroves and coral reefs that attract a high number of tourists. Among the 70 tour operators that are members of the Ishigaki City Tourism Association and take tourists to outdoor activities, 11 (16%) advertise mangrove tours among their activity options on their website (Ishigaki City Tourism Association 2021). The Iriomote and Ishigaki National Park Management Plan (MOE 2010) specifies the recommended uses of mangroves along the Nagura and Fukido river lagoons for nature observation, bird watching, canoeing, clamming, and environmental education. These findings clarified the importance to capture the regulating and cultural services provided by mangrove ecosystems, and on the drivers that affect these services across the whole island including indirect drivers that derive from land uses within the upstream watersheds.

4.3 Historical Changes in Mangroves and Their Drivers

This section first explains historical changes in mangrove cover using the temporal LULC data and subsequently adds a qualitative account for these changes, as well as for their direct and indirect drivers[1] referring to the literature.

First, a comparison of the Natural Environmental Information GIS datasets between 1981 and 2006 yielded LULC changes between the two time points (Table 4.2). Mangrove cover gain between two time points was 56 hectares, and the loss was 25 hectares (Fig. 4.2), which made 25 hectares net increase and 88 hectares turnover. An increase in mangrove cover was most notably seen in Nagura Anparu (Fig. 4.2), which was the consequence of a mass deposition of red soil on the lagoon waterbody derived from upstream farmlands (Nakaza et al. 2011). Mangrove was lost mainly for broadleaf woodland (16 hectares) and open water (10 hectares). The replacement of broadleaf woodland by mangrove (14 hectares) is not probable and may contain errors in the identification of boundaries between these two classes.

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[1] Here we refer to the driver of biodiversity loss defined by IPBES (IPBES 2021): *Direct drivers ... have direct physical ... and behaviour-affecting impacts on nature. They include climate change, pollution, different types of land use change, invasive alien species and zoonoses, and exploitation. Indirect drivers are drivers that operate diffusely by altering and influencing direct drivers, as well as other indirect drivers.*

Table 4.2 LULC between 1981 and 2006

1981 LULC class	2006 LULC class												
	01	02	03	**04**	05	06	07	08	09	10	11	12	Total
01 Broadleaf	7110	360	680	**10**	30	50	40	30	520	150	40	90	9100
02 Coniferous	120	120	60	**0**	0	0	0	0	50	0	0	10	370
03 Grassland	1280	240	1620	**10**	30	20	20	20	750	160	40	40	4230
04 Mangrove	**20**	**0**	**0**	**50**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**10**	**80**
05 Riverside, marsh, salt swamp, sand dunes	160	10	120	**10**	30	20	10	40	140	10	0	20	570
06 Natural bare land	10	0	0	**0**	0	0	0	0	0	0	0	0	10
07 Abandoned land	0	0	10	**0**	20	0	0	10	0	0	0	30	70
08 Paddy	90	10	110	**0**	30	0	20	200	160	10	10	10	640
09 Dry field	1060	130	1390	**0**	40	0	70	80	2760	250	30	50	5870
10 Building	60	0	30	**0**	0	0	0	0	60	540	10	0	700
11 Others	40	0	90	**0**	0	0	0	0	40	60	20	10	260
12 Open water	130	10	60	**20**	10	50	0	0	10	50	40	110	470
Total	10080	890	4150	**100**	180	140	160	380	4480	1240	190	370	22,360
Summary	01	02	03	**04**	05	06	07	08	09	10	11	12	Total
No change between 1981 and 2006	7110	120	1620	**50**	30	0	0	200	2760	540	20	110	12,550
Gain (a)	2980	760	2530	**60**	150	140	160	180	1720	700	170	260	9810
Loss (b)	1990	250	2610	**30**	540	10	70	440	3110	160	250	360	9810
Net-change (a – b)	980	520	–70	**30**	–390	130	100	–260	–1390	540	–80	–110	0
Turnover (a + b)	4970	1010	5140	**90**	690	150	230	620	4830	860	420	620	19,620

Note: The 1981 vector dataset had 34 LULC categories on a 1:50,000 map, while the 2006 dataset had 51 LULC categories on a 1:25,000 map. These datasets were converted into 30 meters raster datasets with 12 LULC classes to assess LULC flow between the two time points. The hectare numbers rounded off below the tens place

4.3.1 Direct Drivers

We identified three likely drivers of mangrove cover change, out of the five common drivers of biodiversity loss (IPBES 2019), drawing on the temporal LULC data and field observations. These are anthropogenic land-use change, climate change, and pollution.

Fig. 4.2 Mangrove cover loss and gain between 1981 and 2006

Land-Use Change LULC flow from open water, riverside, marsh, salt swamp, and sand dunes to mangrove and subsequently to broadleaf woodland may indicate dry succession toward more terrestrial-type vegetation, whereas mangrove loss for open water may indicate natural disturbance that has been eroding mangrove stand frontier. Mangrove cover change in these two directions is not directly attributed to anthropogenic drivers but presumably indirectly to the two direct drivers explained below. Besides, we found the loss of a small patch of mangrove along Miyara River for constructing a new road for improving access to the new Ishigaki Airport from the Ishigaki City center (Fig. 4.3a). The Miyara River mangrove, which locates on unprotected private lands, is more prone to land-use change than the other two major mangroves that are protected as natural parks and/or wildlife preserve.

Climate Change Climate change is projected to exacerbate extreme climate events that impact mangroves. From field observations, we identified two incidents where extreme climate events affected mangroves. At Fukido river estuary, *Bruguiera gymnorhiza* was dying out due to massive sedimentation caused by a landslide in an upstream tributary (Fig. 4.3c). Along Nakama River in the adjacent Iriomote Island, strong typhoon wind fell and opened up *B. gymnorhiza* stands (Fig. 4.3d).

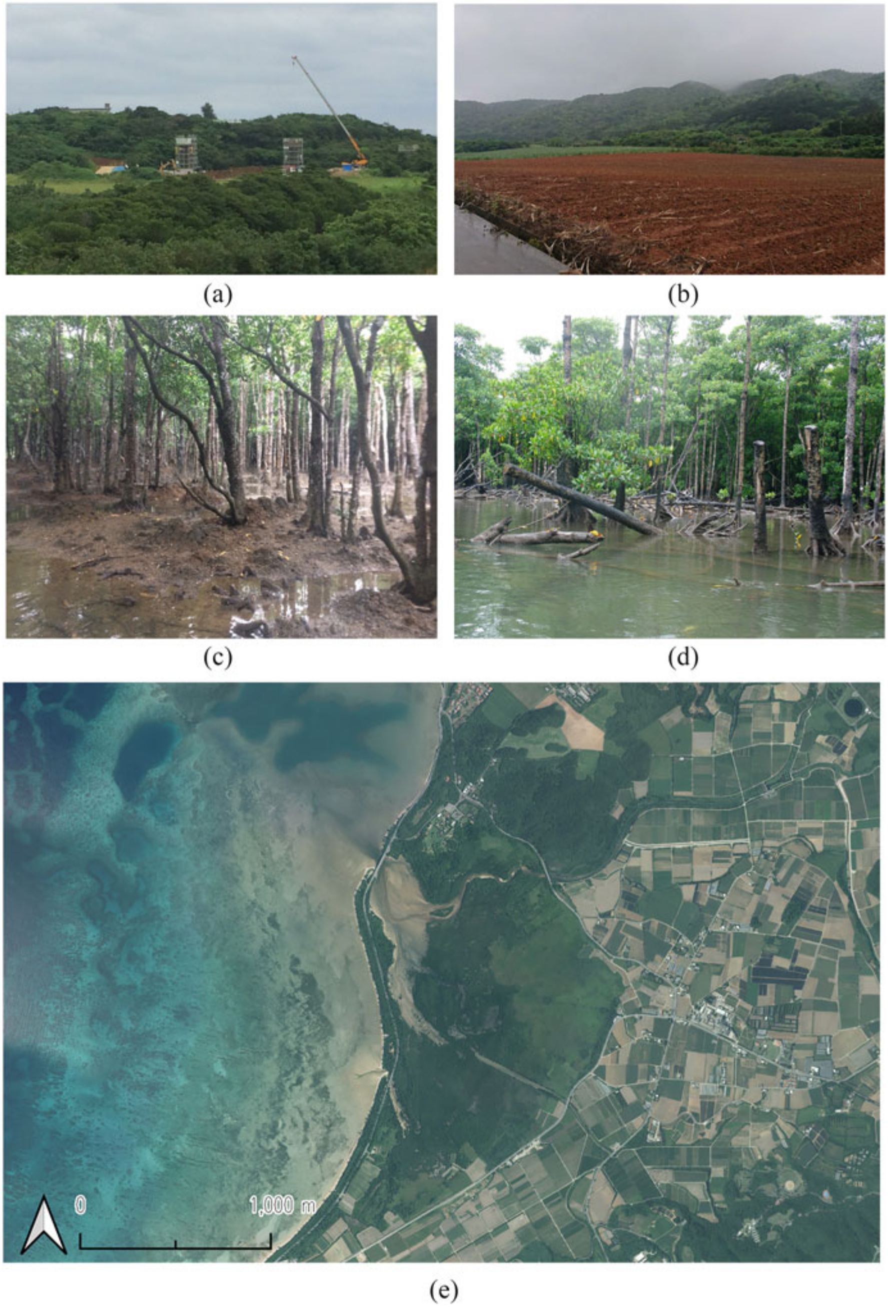

Fig. 4.3 Snapshots of the direct drivers of mangrove cover change. (**a**) Road construction across Miyara River mangrove corridor. (**b**) Bare red soil during sugarcane intercrop susceptible to soil runoff in heavy rains. (**c**) *B. gymnorhiza* dying off along Fukido River due to massive sedimentation caused by a landslide in upstream catchment. (**d**) Strong typhoon wind destroyed *B. gymnorhiza* stands along Nakama River in the adjacent Iriomote Island. (**e**) Aerial photo of Nagura Anparu, indicating red soil deposit in saline swamp (source: Geospatial Information Authority of Japan)

These indicate the possible negative impacts of climate change on mangroves in two different ways: accelerated dry succession as a consequence of increased sedimentation caused by heavier rainfall and a higher river flow velocity, and direct damage on mangrove trees by stronger typhoon wind and storm waves.

Pollution Red soil runoff from agricultural lands in the upstream catchment (Fig. 4.3b) affects downstream mangroves. For example, the Nagura Anparu swamp is undergoing rapid accumulation of red soil deriving from upstream agricultural lands (Nakaza et al. 2011) (Fig. 4.3d). The mangrove cover gain and loss map (Fig. 4.2) indicate expanding mangrove cover into previous open water and tidal flat areas in Nagura Anparu. Further sediment deposit is likely to drive its succession to terrestrial-type vegetation such as a broadleaf forest. Mangroves along Miyara River, as well as in Nagura Anparu, are likely to be affected by pollution deriving from the upstream catchments, particularly red soil and associated nutrients runoff such as nitrogen and phosphorous (Blanco et al. 2010) runoff from sugarcane and pineapple farms that dominate agricultural lands in Ishigaki Island. Historical spatial data analysis of the mangrove cover over Nagura Anparu (Nakaza et al. 2011) revealed that an extensive farmland development of the upstream watersheds combined with the construction of a land drain channel accelerated red soil deposition within the lagoon, which resulted in a dramatic increase in mangrove cover. Flood sediment transported into mangrove waterbody derives both from upstream and from the coastal floor (Akamatsu et al. 2004; Nihei and Seki 2006). The consequential land level rise is likely to cause future dry succession (Irokawa and Nihei 2008). In contrast, Fukido river mangrove is less likely to be polluted where the upstream catchments are mostly designated as planned private forests and protected as the Natural Park Special Area.

Direct use, i.e., mangrove wood extraction for house construction materials and dye, was common in the past (Yoshimi 2011) but is not practiced nowadays. The impact of invasive alien species on mangrove cover was not identified from the information we collected.

4.3.2 Indirect Drivers

The current population of the Ishigaki Island, the only inhabited island among the islands under the jurisdiction of the Ishigaki City government, is 49,704 (as of August 2019) (Ishigaki City 2019). The population of the island has been increasing since 1920 except for a temporal decrease from the late 1960s to 1970s and is projected to increase until 2025 (Ishigaki City 2016). This mainly is attributed to in-migration from other regions and can be contrasted to the overall population decline in Japan particularly in rural areas. Accordingly, the aggregated building floor area has been in a continuous gradual increase in the past two decades (Fig. 4.4).

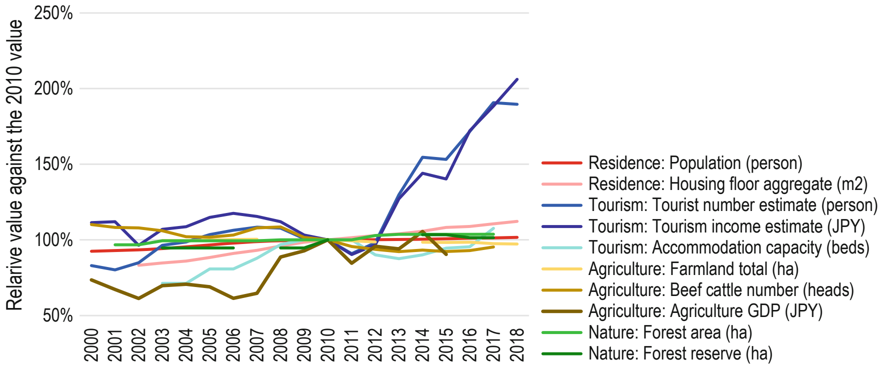

Fig. 4.4 Trends in key variables on population, tourism, agriculture, and nature conservation in the past two decades (Source: Ishigaki City 2021)

Service sector, including tourism, is by far the largest economic sector (396.61 million USD) in the Island, followed by public services (288.38) and construction (114.76) as of 2014 (Ishigaki City 2017). Tourist number and tourism income nearly doubled since 2012 (Fig. 4.4), which started immediately after the opening of the New Ishigaki Airport in 2013 that enabled the landing of longer-distance flights from the Japan mainland and abroad. The tourist accommodation capacity gradually increased since 2003 but by far slower than the increase in the tourist number, indicating a higher booking rate and a wider temporal distribution of tourist visits across months and seasons. The growing tourism sector may have various direct and indirect impacts on mangroves. Direct impacts may include the development of tourism infrastructure, such as roads across mangrove areas (Fig. 4.3a), and direct use of mangroves for boat or kayak trips. Indirect impacts may include land development, such as a golf course currently planned within the Nagura river watershed (Unimat Precious Co. 2018), that may change the hydrological and sedimentation scheme within the mangrove.

Agriculture is the seventh-largest sector, in which the share of beef cattle production is by far the largest (64.0 million USD[2]) in 2017, followed by industrial crops including sugarcane and tobacco (14.2), vegetables (6.0), fruits (4.8), and cow milk (4.7) (MAFF 2018). Agricultural stock represented by the total farmland area, including grassland, and beef cattle heads underwent continued slow decline in the past two decades. Nevertheless, GDP in the agriculture sector has been in overall increase, suggesting improved value addition in the sector. The direct impact of agriculture on mangroves, in such forms as the draining and converting mangroves into farmland, is negligible in the data we collected (Table 4.2). However, as explained in the previous section, farmland – particularly sugarcane field – affects mangroves through red soil and excessive nutrient runoff such as nitrogen and phosphorous (Blanco et al. 2010).

[2] Applied the exchange rate of 1 USD = 110.60 JPY as of 11 August 2021.

Forested land has been slowly increasing, which can be contrasted to a gradual decrease in farmland. The forestry sector in Ishigaki is small, according to its by far the smaller GDP than that of agriculture (0.47%). A large share of forest (32.5% in 2017) is protected as forest reserve (Ishigaki City 2021) or as a natural park, indicating a high nonmaterial value of forest across the island particularly for multiple regulating functions and for biodiversity conservation. Protection of natural ecosystems including forests has been in gradual increase (Fig. 4.4). In 2007, the Iriomote and Ishigaki National Park was expanded to include forested land on Ishigaki Island (MOE 2020a). The National Park area on Ishigaki Island was further expanded in 2016 which currently covers 7121 ha (32%) over the total terrestrial surface of Ishigaki Island (MOE 2020b). As described herein, the protection of forested land on the Island has been strengthened over the past decades, implying positive indirect drivers on biodiversity and ecosystem services on the Island.

4.4 Future Scenarios

This section explores future socio-ecological scenarios for the Ishigaki Island mangroves, other ecosystems, and their services by a three-step approach. It first provides an overview of relevant existing scenarios and identifies the point on which the different scenarios converge in the Island's socio-ecological context. It then maps different policy objectives across sectors over these scenarios to validate the policy relevance of the proposed scenarios. On these bases, the section finally proposes scenario narratives and key metrics that can potentially be used for modeling future ecosystems and their services focusing on mangroves on Ishigaki Island.

4.4.1 Hypothetical Scenarios for Ishigaki Mangroves Drawing on Existing Scenarios

Diverse scenario sets at different scales have been developed to forecast future ecosystem services. Among these, we identified three scenario frameworks that were relevant to the socio-ecological context of Ishigaki Island, i.e., a national scale PANCES scenarios for Japan (Saito et al. 2019), the local scenarios for the Yaeyama region (PANCES 2021), as well as the Nature Futures Framework (NFF) scenario (Pereira et al. 2020).

The PANCES national scenarios were developed through the Delphi method to assess future natural capital and ecosystem services in Japan up to 2050 (Saito et al. 2019). The scenarios are placed at four quadrants bound by two orthogonal axes (Fig. 4.5a). The vertical axis contrasts the societies in which natural capital- and produced capital-based infrastructure and products dominate over the other. The former end is characterized by high food self-sufficiency, ecological and short-

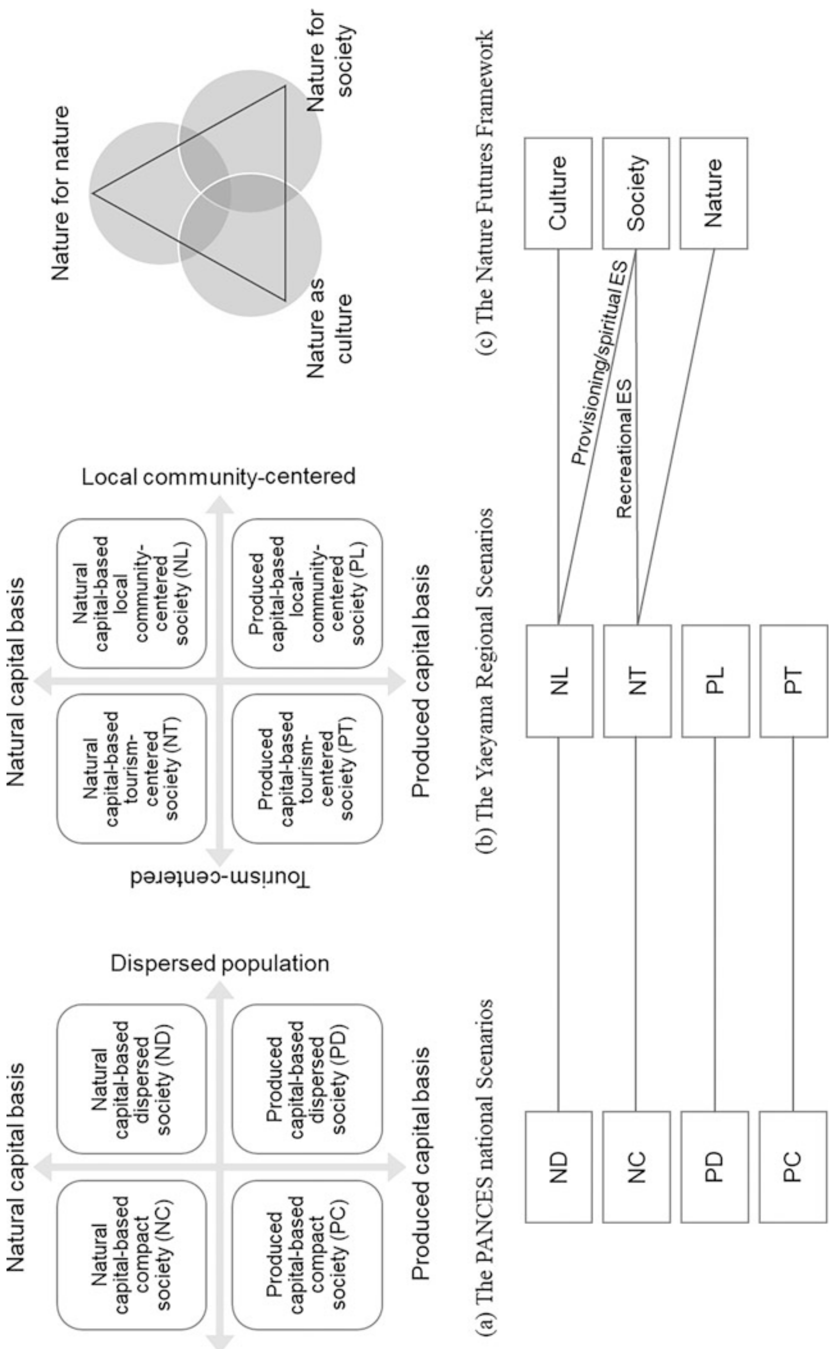

Fig. 4.5 Three scenario frameworks for the assessment of future ecosystem services at different scales

distance tourism, green infrastructure, and increased use of renewable energy, while the latter is characterized by increased imports, extensive use of ICT/AI for higher productivity, conventional gray infrastructure, etc. The horizontal axis contrasts concentrated (left) versus dispersed population (right). Dispersed population assumes counter urbanization, decentralized institutions, etc., while urban compactification is characterized by compact cities, rewilding/greening underutilized land, etc.

PANCES also developed a local-scale scenarios tailored for the Yaeyama Region, including Ishigaki, through a participatory process and with a focus on coastal and marine socio-ecological systems (Fig. 4.5b top) (PANCES 2021). The vertical axis of the regional scenarios space derived from that of the national scenarios which locates natural capital-based societies at the top end and produced capital- based societies at the bottom. The horizontal axis of the regional scenarios space, however, differs from that of the national scenarios which contrasts local community-centered and tourism-centered societies. The horizontal axis of the regional scenarios, however, can be logically related to that of the national scenarios (Fig. 4.5 bottom). Urban compactification across the nation may generate outbound trip demand, which is often met by rural tourist destinations such as Ishigaki Island. The local community-centered end of the horizontal axis assumes prioritizing local needs particularly fisheries, which could characterize a decentralized society as illustrated in the right end of the horizontal axis of the national scenarios. The fisheries element of the local community needs, however, should be interpreted into agriculture in the application of these scenarios to the Ishigaki Island's terrestrial context.

The Nature Futures Framework (NFF), developed by the IPBES task force on Scenarios and Models through an extensive international consultation process, provides a generic triangular framework for scenario development (Pereira et al. 2020). The three corners of the triangle correspond to the three value perspectives of nature (intrinsic, instrumental, and relational), i.e., nature for nature (NN), *in which nature has value in and of itself, and the preservation of nature's diversity and functions is of primary importance*; nature for society (NS), *in which nature is primarily valued for the benefits or uses people derive from it, and which could lead to an optimization of multiple uses of nature*; and nature as culture (NC), *in which humans are perceived as an integral part of nature, and therefore what is valued is the reciprocal character of the people–nature relationship* (Pereira et al. 2020).

A mapping of the PANCES national and the Yaeyama Regional scenarios into NFF indicates that the natural capital-based dispersed society (ND) of the PANCES scenarios and the corresponding natural capital-based local community-centered society (NL) of the Yaeyama Regional scenarios can be placed close to the NS and NC corners of NFF (Fig. 4.5 bottom). Here provisioning and spiritual ecosystem services constitute the main component of NS and NC, respectively. Likewise, the natural capital-based compact society (NC) of the PANCES scenarios and the natural capital-based tourism-centered society (NT) of the Yaeyama Regional scenarios can be located near NS and NN corners of NFF, where recreational services represent the NS component. NFF, as a scenario development framework focusing

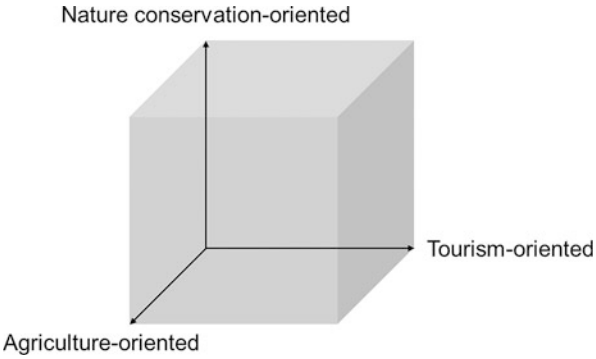

Fig. 4.6 Three-dimensional space to feature the Ishigaki Island scenarios

on people-nature relationships, does not entail the produced capital component of the Yaeyama Regional scenarios, as well as the PANCES national scenarios.

The Yaeyama Regional scenario set, among the three frameworks, is the handiest to explain the current and future mangrove change and its drivers within Ishigaki Island, as it captures the non-nature aspect and effectively explains the three major aspects of the Island's terrestrial socio-ecological system, i.e., tourism, agriculture, and nature conservation. It however has an issue in a real-world interpretation that the two ends of the scenario axes are not always mutually exclusive. For example, tourism can be compatible with agriculture; and produced capital can support natural capital. Taking these all into account, we mapped the Ishigaki Island scenarios in a three-dimensional space along the three axes that point the agriculture-oriented, tourism-oriented, and nature-oriented societies end (Fig. 4.6).

4.4.2 *Mapping Relevant Policies in the Hypothetical Scenario Space*

Next, we validated the policy relevance of the hypothetical scenarios by mapping relevant policies in the hypothetical 3D scenario space through the following four steps. First, we conducted a comprehensive review of relevant policy documents to extract relevant policy objectives (Table 4.3). Second, we weighed each policy objective by its relevance to the three scenario ends (2, obvious relevance; 1, implicit relevance; and 0, irrelevant). Third, using the average relevance scores among the policy objectives within each policy document, we mapped the 13 policy (documents) on the 3D space (Fig. 4.7). Fourth, the 13 policies were aggregated into a fewer number of groups that have similar traits with respect to their relevance to the three scenario ends by cluster analysis. This process identified five policy groups (Table 4.4) which are nature-centered and either production- or tourism-related, production-centered and nature-based, as well as nature-based or non-nature-based generic policies. As these, the hypothetical scenarios were shown salient to the policies related to mangrove and other ecosystem services in Ishigaki Island.

Table 4.3 Relevant policy documents and objectives

Document title	Date from	to	Mangrove	Spatially explicit	Policy objectives
National					
Iriomote Ishigaki National Park	Feb 2020	NS	Y	Y	(1) Strict preservation (special protection zone); (2) conservation and regulated use (special areas 1–3); (3) sustainable use (ordinary areas)
Nagura Anparu Wildlife Reserve	Nov 2004	Oct 2023	Y	Y	Wildlife preservation
Prefectural/regional					
Okinawa LBSAP	Mar 2013	Mar 2022	Y	N	(1) Protected areas; (2) endangered species conservation; (3) combat invasive alien species; (4) natural monument protection; (5) environment-friendly agriculture; (6) biodiversity conservation in forestry and greening
Land Use Basic Plan	Jun 2019	NS	Y	N	General land-use plan
Miyako Yaeyama Region Forest Plan	Apr 2018	Mar 2028	Y	Y	Production of timber and other public goods and services
Ishigaki city					
Fourth General Plan	Apr 2017	Mar 2022	Y	Y	(1) Forest and coral reef conservation; (2) urban gray and green infrastructure; (3) efficient land use
Economic Promotion Plan	Apr 2015	Mar 2022	N	N	(1) Economic integration across sectors including agriculture and fisheries; (2) resource development; (3) human resource and institution development; (4) strategic urban development
Marine Basic Plan	Apr 2013	Mar 2023	Y	N	(1) integrated coastal management; (2) marine bioresource uses; (3) marine mineral and renewable energy research and development; (4) tourism promotion; etc.
Landscaping Plan	Jun 2018	NS	Y	Y	Conservation and improvement of natural, rural, and urban landscapes
Land Use Plan	Dec 2013	Dec 2022	Y	Y	General land-use plan
Urban Planning Master Plan	Mar 2011	Mar 2030	Y	Y	General land-use zoning and guidelines, i.e., new urban zones; coastal resort zones; nature priority zones; forest conservation zones; coastal system conservation zones; freshwater zones; and resort zones

(continued)

Table 4.3 (continued)

Document title	Date from	to	Mangrove	Spatially explicit	Policy objectives
Tourism Basic Plan	Apr 2011	Mar 2020	N	N	(1) Tourism resource protection and development; (2) integrate tourism and local development; (3) sustainable nature and culture tourism

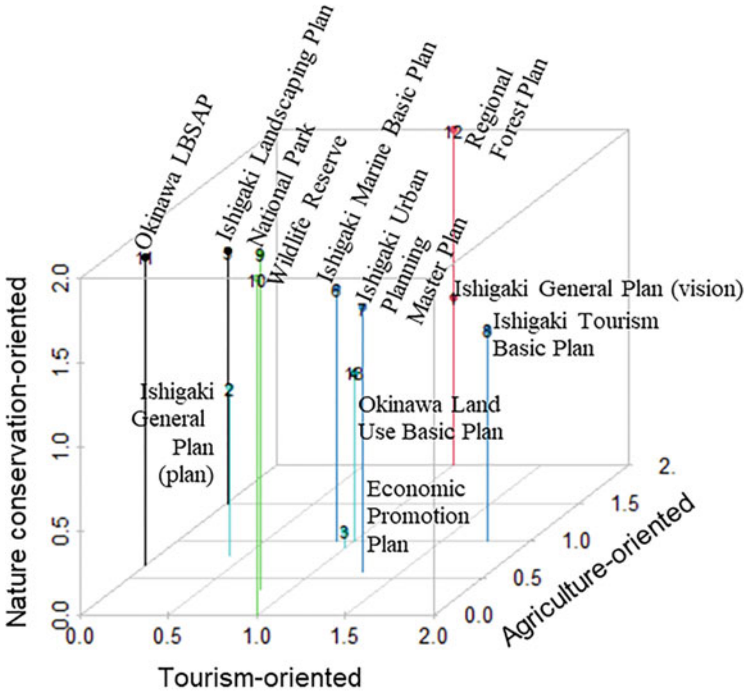

Fig. 4.7 Mapping relevant policies on a 3D space to explain the Ishigaki Island mangrove scenarios. *Note*: Point/bar colors indicate group of policies that have similar traits with respect to the three axes elements, which were identified by cluster analysis using the Ward method, with the Euclidean distance of 1.5

4.4.3 Scenarios and Key Policy Metrics for Ishigaki Island

Based on the hypothetical scenarios and the results of policy mapping against these scenarios as presented above, we first narrowed down scenarios to those highly policy-relevant and can be linked to specific policy outcome metrics. The scenarios that do not include tourism, i.e., policy groups (a) and (c) in Table 4.4, were dropped first. Considering the current primary and growing importance of tourism in Ishigaki's local economy, policy measures that support reduction in tourism are not reasonably presumed. In addition to the scenarios corresponding to the

Table 4.4 Policy groups that have similar traits regarding the three scenario elements

Policy group	Policy document title
(a) Nature-centered, agriculture-related	Ishigaki Landscaping Plan Okinawa LBSAP
(b) Nature-centered, tourism-related	National Parks National Wildlife Reserves
(c) Agriculture-centered, nature-based	Ishigaki General Plan (vision) Regional Forest Plan
(d) Nature-based, tourism- and agriculture-related	Ishigaki Marine Basic Plan Ishigaki Urban Planning Master Plan Ishigaki Tourism Plan
(e) Tourism- and agriculture-related	Ishigaki General Plan (plan) Ishigaki Economic Plan Ishigaki Land Use Plan Okinawa Land Use Basic Plan

remaining policy groups (b), (d), and (e), we included a scenario that does not consider negative impacts on nature to contrast it with other scenarios that are sensitive to nature. These steps identified four distinct scenarios (Table 4.5):

- *A. Nature-sensitive integrated tourism and agriculture scenario* assume maximum synergies between the three foci. It assumes maintaining the total agricultural land area including dry and paddy fields and grassland and expanding conservation agriculture such as red soil runoff prevention measures for sugarcane and pineapple production, and windbreak forests along farmland borders, which have been promoted under the Yaeyama Regional Plan for the Promotion of Agriculture, Forestry and Fisheries (Okinawa Prefecture 2017). The scenario further assumes the expansion of protected areas and ecosystem restoration efforts into unprotected forested or open areas, e.g., from the current level (32%) to 50%.
- *B. Nature-centered tourism scenario* prioritizes tourism over agriculture in scenario A. It assumes the decline in agricultural land, including by abandonment and nature restoration, where natural ecosystems are rehabilitated and protected to the level equivalent to the scenario A (50%). This may result in a wider option for nature tour destinations.
- *C. Integrated tourism and agriculture scenario* is less sensitive to negative impacts on the environment in scenario A. It assumes an increased number of tourists and associates increase in the development of tourism infrastructure, including accommodations, where possible within protected areas. It maintains total agricultural land area with weak environmental conservation measures. The scenario consequently can reduce nature tour destinations.
- *D. Resort island scenario* places higher tourist number and tourism revenue first. It increases land and sea surfaces converted for tourism infrastructure, including accommodations and other built recreation facilities. Such plans already exist on the Island, as the development of a new integrated golf resort on current forest and agricultural lands (Unimat Precious Co. 2018), as well as an offshore floating pier

Table 4.5 Four scenarios and the change in the relevant policy metrics assumed under the respective scenarios

Sector	Metric	Scenario: A. Nature-sensitive integrated tourism and agriculture	B. Nature-centred tourism	C. Integrated tourism and agriculture	D. Resort island	Assumptions	Modellable
Tourism	Tourist number (person)	→	→	↗*	↑	*BaU	Yes
	Nature tour destination (ha)	→	↗*	↘**	↘**	*abandoned agricultural lands rehabilitated and used for nature tourism; ** natural land/sea developed for tourism	No?
	Residential area (ha)	→	→	↗*	↑**	*replace natural land; **replace natural and agricultural land	Yes
	Land development (e.g. golf course) (ha)	→	→	→	↗*	*replace agricultural/abandoned land	Yes
	Coastal development (e.g. pontoon) (ha/km)	→	→	→	↗*	*replace natural coastline/ecosystem	No?
Agriculture	Dry and paddy field (ha)	↘*	↘**	↘*	↓***	*abandoned farmland replaced by grazing land; **forest restored on abandoned farmland; ***replaced by residence or tourism infra	Yes
	Grassland (ha)	↗*	→	↗*	↘**	*grassland replace dry/paddy field; **replaced by residence or tourism infra	Yes
	Conservation agriculture (ha)	↗	→	→	→		Yes
Nature	Protected area (ha)	↗*	↗***	↘***	↘***	*expand protected area to unprotected/rehabilitated natural ecosystems; **abandoned land rehabilitated and protected; ***weak enforcement	Yes
	Restored area (e.g. reforestation) (ha)	↗*	↗***	→	→	*rehabilitate degraded ecosystems; **restore ecosystems on abandoned agricultural lands	No?

Legend

↑	Increase
↗	Slight increase
→	Unchanged
↘	Slight decrease
↓	Decrease

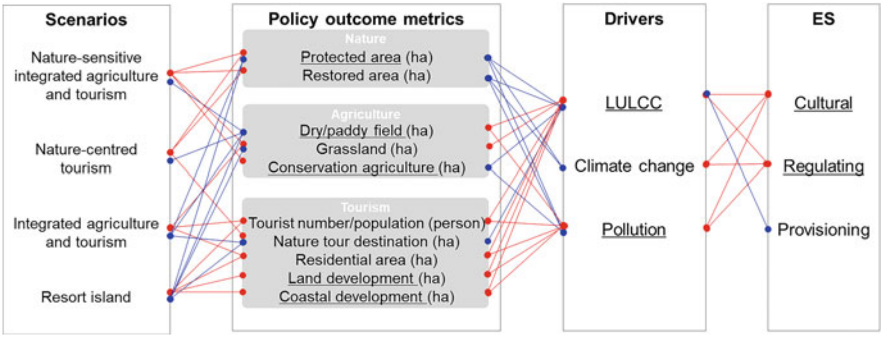

Fig. 4.8 A schematic diagram on the links between scenarios, key policy outcome metrics, drivers, and ecosystem services. *Note*: Blue nodes and lines between policy metrics and drivers boxes indicate probable positive contributions to addressing the drivers and thereby to increased ecosystem services, while the red nodes and lines indicate possible negative impacts that further deteriorate the drivers and thus reduce ecosystem services. Policy metrics, drivers, and ecosystem services that are found or likely to be relevant to mangroves are underscored

(pontoon) for more convenient marine leisure experiences (Yaeyama Mainichi Shinbun 2021). This scenario assumes less strict law enforcement that allows these developments within protected areas and thereby may result in reduced quality of nature tour destinations. Agricultural lands, including dry fields, paddy fields, and grasslands, may be replaced by tourist infrastructure.

Ten key policy metrics across the tourism, agriculture, and nature conservation sectors that can represent the four scenarios are also presented in Table 4.5. Among these, seven can be directly or indirectly translated into land surface change and thus relatively easily extrapolated into future ecosystem services modeling. Further, we illustrated how these metrics can be used for the assessment of the current and future drivers of change in the island ecosystem services in Fig. 4.8. A package of information on scenarios, relevant policy metrics, and their relevance to the key drivers of change in ecosystem services as presented in Table 4.5 and Fig. 4.8 provides a robust basis for evaluating future ecosystem services, including those deriving from mangroves, on Ishigaki Island.

4.5 Conclusion

This chapter contributes to a comprehensive understanding of the island socio-ecological system by a synthesis of the state and trend of, and the drivers of changes in ecosystems and their services, focusing on mangroves in Ishigaki Island. The current range of mangroves on the Island is limited to small patches along a few river estuaries, which nevertheless provides critical habitat for several threatened species as well as important ecosystem services that mediate the Island’s terrestrial and coastal systems. Hence, mangrove on the Island is critically important to the extent disproportionate to their range size and thus reasonably protected. It however is subject to gradual change due to changing hydrological and sedimentation patterns affected by land uses within the upstream watershed. This highlighted the importance to look into not only direct land conversion but also cascade effects on mangroves deriving from upstream land use including erosion control and river channel management. In this context, we pointed the potential negative impacts of developing large-scale tourist leisure facilities within the upstream watershed, as well as the importance of farmland erosion control measures.

The chapter went further to identify plausible future island socio-ecological scenarios with concrete narratives and key metrics, building on downscaling existing scenarios on one hand, and the other hand regional policies and periodic statistics over the past two decades. The scenarios are fourfold, which differently address the three key policy objectives for the terrestrial domain of the Island, i.e., tourism, agriculture, and nature conservation: (A) nature-sensitive integrated tourism and agriculture; (B) nature-centered tourism; (C) integrated tourism and agriculture; and (D) resort island scenarios. We also identified ten key quantitative metrics to gauge the four scenarios: (1) tourist number, (2) nature tour destination area, (3) residential area, (4) land development area, (5) coastal development, (6) dry and paddy field area, (7) grassland area, (8) conservation agriculture area, (9) protected area, and (10) restored area.

The synthesis of the Island's socio-ecological system and the plausible future scenarios articulated in this chapter provide a robust basis for modeling future island ecosystems and their services centering on mangroves in Ishigaki Island. Furthermore, the chapter demonstrated methodological advancement in downscaling existing high-level scenarios with the aid of regional periodic statistics and a comprehensive review of regional policy documents. This process, as we believe, will help strengthen the real-world rootedness of the proposed scenarios. Nevertheless, more dedicated field data collection including multi-stakeholder participation scenario building exercises will complement the scenarios we developed.

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Chapter 5
A Participatory Stakeholder-Based Approach to Assess the Drivers and Challenges of Mangrove Loss in Kochi, Kerala, India

Saniya Joshy, Jayshree Shukla, and Shalini Dhyani

Abstract Mangrove forests provide critical services around the globe to both human populations and the ecosystems they occupy. Mangroves have been heavily impacted by degradation and deforestation, with 20–35% of global mangrove extent lost over the last 50 years. Due to inadequate representation of the value of the mangroves in decision-making, mangroves have undergone a rapid decline in the last few decades. On the west coast of India, Kerala has thick mangrove vegetation along its coastline, with Kochi having the most diverse mangrove species in the state. Kochi is a fast-growing major industrial area in the state of Kerala. An extensive field survey was carried out followed by an extensive participatory stakeholder survey to understand various drivers of mangrove biodiversity loss in Kochi. This study provides some greater insights into the increasing pressure on mangroves of Kochi due to diverse direct and indirect drivers. This study is one of the few initial attempts to understand the urgent need of protecting the existing mangroves and developing place-specific policy interventions mainstreaming the drivers and strengthening participatory approaches for the preservation of the remaining dense and intact mangroves of Kochi. This primary attempt should be used as a baseline to understand the trends of loss, project the scenarios, and accordingly plan and implement interactive governance approaches to restore and halt the degradation of these valuable bioresources for aligning the efforts to achieve targets of the UN decade on restoration and post 2020 global biodiversity targets for reducing disaster risks and enhancing climate adaptations.

Keywords Kochi · Kerala · Mangrove · Ecosystem services · Drivers · Participatory approach

S. Joshy
Kerala University of Fisheries and Ocean Studies, Kochi, Kerala, India

J. Shukla · S. Dhyani (✉)
National Environmental Engineering Research Institute (CSIR-NEERI), Nagpur, Maharashtra, India

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5.1 Introduction

Mangroves are intertidal wetlands found along coastlines in much of the tropical, subtropical, and warm-temperate world (Bryan-Brown et al. 2020). Mangrove forests provide a range of critical economic and ecological services to surrounding coastal populations such as production of goods (such as seafood and timber), life support processes (such as pollination and water purification), and life-fulfilling conditions (such as beauty and serenity) (Barbier 2019; Goldberg et al. 2020). Wetlands contain around 40% of global soil organic carbon making them one of the major sinks of carbon, representing the most significant component of the terrestrial biological carbon pool (Shylesh Chandran et al. 2020). The ecosystem services of these include shoreline stabilization, stormwater management, water quality preservation, bioclimatic stabilization, groundwater replenishment and drawdown, flood regulation, sediment and nutrient retention, habitat protection, and ecosystem resilience, as well as tourism, and culture, recreation, fishing and hunting, and water transportation (Duke et al. 2007; Giri et al. 2014; Sahu et al. 2015; Sasmito et al. 2019; Spalding and Parrett 2019). Mangroves, salt marshes, and seagrass meadows are collectively termed as “Blue Forests”, which are counted among the most valuable and productive coastal ecosystems on the planet (Himes-Cornell et al. 2018). Mangroves are essential reproductive habitats for marine fauna, and many coastal populations rely on them for their livelihoods (Zu Ermgassen et al. 2021).

Despite their importance, mangroves are vanishing at a rate of 1–2% each year globally, with a 35% loss rate in the past two decades (Rani et al. 2016). Climate changes along with varying degrees of anthropogenic influence represent major threats for mangrove habitats (Ludwig et al. 2009; Rani et al. 2016; Carugati et al. 2018). Coastal development and other causes, such as global demand for mangrove products, significant infrastructure development, and governance failure, have put more than one in every six mangrove species in risk of extinction (Islam et al. 2018). According to the IUCN Red List of Threatened Species’ first-ever worldwide assessment of mangrove conservation status, none of the mangrove species so far is on the IUCN Red List (Bryan-Brown et al. 2020; Kadaverugu et al. 2021). Asia has suffered the largest loss of mangrove areas since the 1980s (Rasquinha and Mishra 2021). Rapid urbanization is the most common feature worldwide in recent years. The annual release of carbon into the atmosphere as a result of mangrove degradation is estimated to be 0.02–0.12 Pg, accounting for 10% of cumulative emission levels from deforestation (Thomas et al. 2017).

Southeast Asia shows a gradual degradation of the forest at a higher rate compared to the rest of the world because of both natural (Sea Level Rise) and anthropogenic causes (land-use changes) (Das 2020). In South Asia, mangrove forests grow along the tidal sea edge of Bangladesh, India, Pakistan, and Sri Lanka; these forests offer essential ecological benefits to the region’s dense coastal inhabitants, as well as supporting vital biosphere processes (Giri et al. 2014). Mangrove loss rates are linked to cumulative influences, such as population size, forest degradation, as well as the overall anthropogenic impact – as well as management measures (protected areas) (Turschwell et al. 2020). Overall, the mangrove cover of India is estimated to be 4639 sq. km, with over 56% of global mangrove species (Harishma et al. 2020; Ragavan et al. 2020).

Kerala lies in the southwestern tip of peninsular India with a shoreline of 590 km and rich mangrove patches (Harishma et al. 2020). The state of Kerala, situated on India's west coast, has lost 95% of its mangroves in the previous three decades (Sreelekshmi et al. 2020). Mangrove forests are being converted and destroyed at an alarming rate, particularly as a result of urbanization. Maintaining mangrove ecosystems is essential for protecting the coastal zone and the subsistence of the local population, particularly the fishing community. At present, the mangrove continuity is lost and is faced with destruction, urbanization, tourism development, and chemical discharge, which are some of the major common threats that are resulting in a steady decline in the mangrove ecosystem in Kerala (Surya and Hari 2018). As of 1975, some 700 sq. km. of mangroves in Kerala state had drastically shrunk to 17 sq. km. by 2013 due to habitat conversion (George et al. 2019). 80% of the mangroves in Kerala are under the custody of private owners and are therefore more susceptible to deterioration. An average of 2.95-tonne carbon/ha/yr. is the soil carbon sequestration potential of Kochi mangroves, which is equivalent to 10.62-tonne carbon dioxide, higher than tropical forests (Ghosh et al. 2021). Transformation for urban development, aquaculture, farming, salt farming, and other associated developments such as ecotourism, mining, distilleries, oil pipeline passes, harbour, dam, and road constructions, among others, continue to put pressure on mangrove forests. Changes in catchment hydrology, rising salinity, marine pollution, silting, fishing resource exploitation, and cow grazing are other drivers of decline in mangrove cover (Kathiresan 2018). Wide salinity gradients and a variety of habitat types, such as low-lying swamps, tidal creeks, and mangrove patches, define the Kochi backwaters, which sustain a rich flora and fauna (Apreshgi and Abraham 2019). Kochi is one of the fastest-growing industrial areas in the state of Kerala (Sahadevan et al. 2017).

Mangrove forests contain some of the greatest carbon densities of any environment, yet they have been extensively deforested due to aquaculture and agriculture. Mangroves have demonstrated parallel natural expansion with deforestation in several regions of the world, and significant expenditures have been invested in restoration initiatives (Richards and Friess 2016). Natural mechanisms like erosion can have a big impact on forest susceptibility, and anthropogenic loss hotspots all throughout Southeast Asia and the world have been labelled as critically endangered ecosystems (Goldberg et al. 2020). Forest conversion to aquaculture and rice fields were the major drivers of loss and fragmentation in Southeast Asia, a worldwide hotspot for mangrove decline (Bryan-Brown et al. 2020). Tropical cyclones have triggered the most mangrove loss worldwide, accounting for 45% of all reported global mangrove mortality during the last six decades (Sippo et al. 2018). However, a variety of anthropogenic stressors affect mangrove ecosystems, and the loss of this environment may be linked largely to human settlement of the coastal zone (Hayashi et al. 2019). Modern mangrove dynamics, on the other hand, are largely driven by manmade concerns such as pollution, overextraction, and conversion to aquaculture

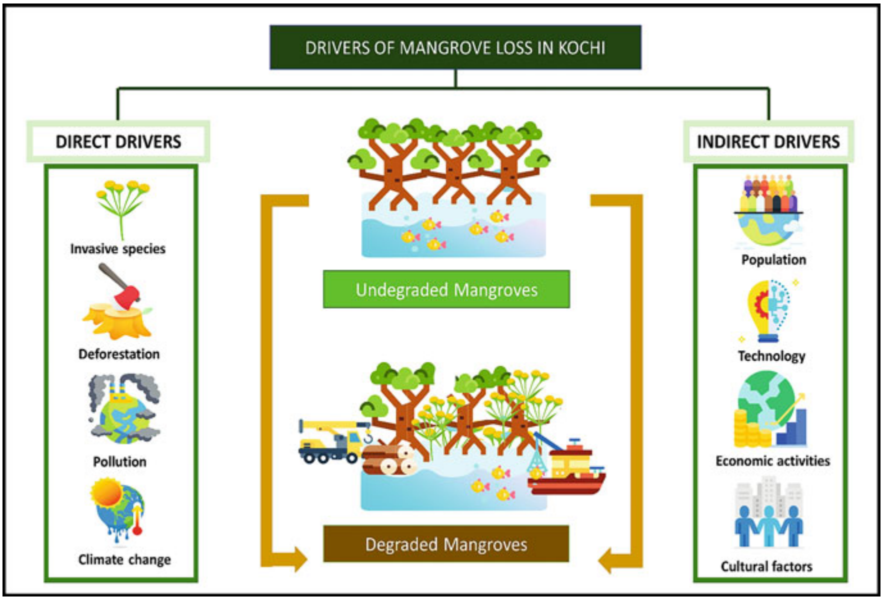

Fig. 5.1 Direct and indirect drivers of mangrove loss

and agriculture; while deforestation rates have decreased in recent years, the future of mangroves remains uncertain (Friess et al. 2019).

During 1980–2000 approximately 35% of mangroves' losses were recorded worldwide (Giri et al. 2011). Mangrove declines are regionally diversified, time-dependent, and connected to a variety of proximal practices and causative factors. Agriculture and aquaculture growth is a key proximate source of mangrove losses across the world. Urbanization, mining, and the overharvesting of timber, fisheries, crustacean, and shrimp are all important threats to mangrove habitat (Carugati et al. 2018) (Fig. 5.1).

The effect of societal decisions on human behaviour, whether driven by public or private sector leaders, has important implications for nature and the contribution of nature to humans. Land-use change refers to how the land has been used, with an emphasis on the functional significance of land in economic activity. Changes in land use modify plant and landscape patterns, causing changes in ecosystem structure and function, as well as changing the value of regional ecosystem services (Fei et al. 2018). Land-use changes are crucial for climate policy because native plants and soils hold the majority of carbon, and their losses from agricultural development, along with emissions from the agricultural output, account for 20% to 25% of total greenhouse gas emissions (Searchinger et al. 2018).

Plant and landscape patterns are altered as a result of changes in land use, resulting in changes in ecosystem structure and function, as well as a shift in the value of regional ecosystem services (Fei et al. 2018). Land-use changes are crucial for climate policy because native plants and soils store the majority of carbon, and their losses from agricultural expansion, along with emissions from the agricultural output, account for 20% to 25% of global greenhouse gas emissions. Sea-level rise is a key potential climate change hazard to mangrove ecosystems since they are vulnerable to fluctuations in inundation length and frequency, and also salt levels that exceed a species-specific metabolic threshold of tolerance (Friess et al. 2012). Prolonged floods can result in plant mortality and changes in diversity and abundance along seaward mangrove margins, lowering productivity and reducing ecosystem services (Ward et al. 2016). Coastal flooding is predicted to increase in the future, since global sea levels have risen at a rate of 3.2 mm per year in recent decades and are expected to rise by 0.28 to 0.98 mm by 2100. In India, diminished mangrove area and health would raise the threat of coastal hazards such as erosion, floods, storm waves, cyclones, and tsunami to human safety and shoreline development, as shown recently during the 1999 super cyclone in Odisha and the 2004 Indian Ocean tsunami (Sahu et al. 2015).

5.2 Study Area

The study area is the selected mangrove forests of brackish water environments in Cochin estuary of Ernakulam District on the Southwest Coast of India which extends from 9° 40′and 10° 10′N and 76° 10′and 76° 30′E (Rosmine and Varghese 2016). The climate is generally tropical, and the surface temperature ranges from 20 to 35° C. Heavy rains and thunderstorms are common due to southwest monsoon in June to September. The average annual rainfall is about 350 cm with an average of 132 rainy days annually. The soil type is a mixture of alluvium sediments, Teris, Brown sands, etc. Archean basic dykes, Charnockites, and Gneisses are the major rock types in the study area. Vembanad Lake (RAMSAR wetland in India) and connected backwaters are considered to be an example for many mangrove estuaries. Kochi houses 11 species of true mangrove belonging to four families. The Rhizophoraceae family comprises five species: *Bruguiera cylindrica* (Linnaeus) Blume, *B. gymnorhiza* (L) Savigny, *B. sexangula* (Lour.) Poir, *Rhizophora apiculata* Blume, and *R. mucronata* Lam.; three species of Acanthaceae family *Avicennia marina* (Forsk) Vierh., *A. officinalis* L., and *Acanthus ilicifolius* (L.) Engl.; two species of Sonnaratiaceae, *Sonneratia alba* J. Smith and *S. caseolaris* (L); and single species of Euphorbiaceae, *Excoecaria agallocha* L. (Sahadevan et al. 2017). *Avicennia officinalis* L. and *Rhizophora mucronata* Lam. are more dominant (Kumar et al. 2011). The district is endowed with the distribution of mangroves with 02 ha and above in the areas of Vypin, Panangad, Kannamali, Kumbalangi, Kumbalam, Nettoor, Mangalavanam, Panambukad, Pallipuram, Karumalloor, and Moothakunnam (Fig. 5.2).

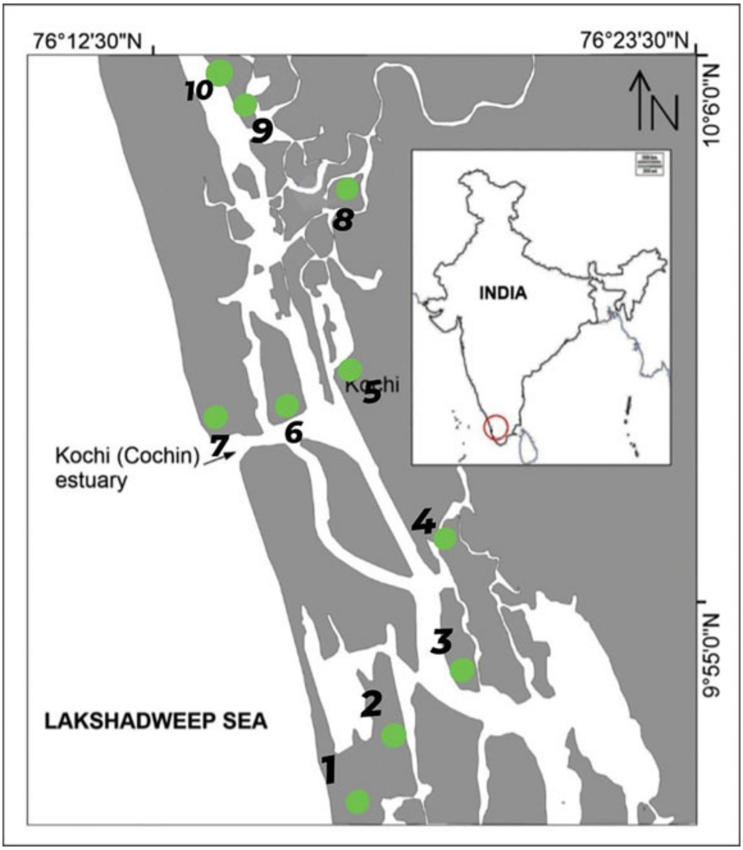

Fig. 5.2 Map showing mangroves in Kochi with an area of 2 ha and above (1) Kannamaly, (2) Kumbalangi, (3) Kumbalam, (4) Nettoor, (5) Mangalavanam, (6) Panambukad, (7) Puthuvype, (8) Karumalloor, (9) Pattanam, (10) Moothakunnam

5.3 Methodology

The information and data were collected through a field-based participatory stakeholder survey. Informal conversations with residents, officials of the state forest/agriculture/fisheries department, members of local panchayats, and natives in the localities cross-verified through personal observations were carried out for the purpose. The field survey was carried out from January 2021 to April 2021. A participatory survey was taken as the key approach for the collection of information about the current status of mangroves in the region. A semi-structured questionnaire survey was carried out by reaching out to potential respondents (those who live close to mangrove growing patches or are directly involved directly or indirectly) in the region. Online forms were initially stratified that was followed by a random survey by sharing the survey link with the local respondents as well as the government officials with a focus on those who had their residence close to the coastal area. A lot of respondents were reached out through this approach because of the lack of access and social distancing imposed due to SARS COVID-19 spread in the state. However, many informal discussions were personally carried out. The semi-structured questionnaire survey had 12 questions (Annexure) which were designed to capture the dimensions of drivers of mangrove loss in Kochi (due to urbanization, population growth, agriculture extension, coastal industries, illegal encroachment, ecotourism, roads and railways, natural disasters, etc.). The questionnaire combined multiple choice questions with predefined answers with a range of options from “no impact” to “very high impact” scale.

5.4 Result and Discussion

Kannamaly is a coastal suburb of Kochi and is a typical mangrove area; these mangroves protect the shore and serve as natural barriers. Kumbalangi is surrounded by backwaters and is an integrated tourism village. Mangroves separate land from water which in turn serves as a good breeding ground for prawns, crabs, oysters, and small fish. Kumbalam is a region bounded by Vembanad Lake that is a Ramsar site. It is a thickly populated area. About 46% of the true mangrove species are present in the Kumbalam village. Nettoor region is blessed with profuse mangrove forests (George et al. 2019). Mangalavanam Bird Sanctuary is located in the heart of Kochi city and has an area of 0.0274 sq. km. A large number of migratory birds visit this place. It is the only bird sanctuary in Kerala which is located in Mangrove forests. Panambukad is an island surrounded by estuarine waters of Kochi backwaters. This island is occupied by traditional fish and prawn farming, while Puthuvype is a fast-developing industrial area in Kochi. It borders Arabian Sea to the west and Vembanad Lake to the east. The population of Vypeen is estimated at more than 2 lakh, with one among the highest density of population in the world (Sahadevan et al. 2017). Karumalloor is a panchayat in Ernakulam district. It is directly connected by a backwater system, bounded by Periyar. The panchayat has a mainly rice-based economy. Pattanam is a village in the Ernakulam district. Due to habituation activities, it is a disturbing sight, and some parts are also partially destroyed due to sand quarrying. Moothakunnam comes in Ernakulam district and is a comparatively small village, an area surrounded by creeks on one side and backwaters on the other (Fig. 5.2).

According to the City Development Plan (CDP), Kochi is the epicentre of the state of Kerala’s commercial and economic activity. Kochi City has outgrown its limits in recent decades due to urban development. Kochi generates more than 60% of the state’s tax income, earning it the title of “Commercial Capital of Kerala”. The region’s communities have a scattered settlement layout with a high population density. During the last two decades, the immediate territory around the city has experienced tremendous expansion, particularly in areas near to key transportation routes. Kochi, according to the Kochi City Region Development Plan 2031, is

Table 5.1 List of dominant and rare mangrove species present in each study area

S. no.	Area	Dominant species	Rare species	Vernacular name	Family
1.	Kannamali	*Excoecaria agallocha* L.	*Bruguiera cylindrica* Blume	Kannampotti	Euphorbiaceae
2.	Kumbalangi	*Acanthus ilicifolius* (L) Engl.	*Bruguiera sexangula* (Lour.) Poir.	Chullikandal	Acanthaceae
3.	Kumbalam	*Avicennia officinalis* L.	*Bruguiera sexangula* (Lour.) Poir.	Oora	Avicenniaceae
4.	Nettoor	*Acanthus ilicifolius* (L) Engl.	*Kandelia candel* (L.) Druce.	Chullikandal	Acanthaceae
5.	Mangalavanam	*Avicennia officinalis* L.	*Bruguiera gymnorhiza* (L.) Savigny	Oora	Avicenniaceae
6.	Panambukad	*Rhizophora mucronata* Lam.	*Rhizophora candelaria* Wight and Arn	Pranthan Kandal	Rhizophoraceae
7.	Puthuvype	*Bruguiera cylindrica* Blume	*Excoecaria agallocha* L.	Kuttikandal	Rhizophoraceae
8.	Karumalloor	*Excoecaria indica* (Willd.) Mull.Arg	*Sonneratia caseolaris* (L.) Kuntze	Karimatti	Euphorbiaceae
9.	Pattanam	*Acanthus ilicifolius* L.	–	Chullikandal	Acanthaceae
10.	Moothakunnam	*Acanthus ilicifolius* L.	*Avicennia officinalis* L.	Chullikandal	Acanthaceae

experiencing unprecedented, mainly unregulated urban sprawl. The neighbouring panchayats and towns are experiencing a surge in construction activity, and local administrations are struggling to deal with infrastructural issues. Due to increased traffic volume, metropolitan roadways and regional road corridors are overburdened. Water supply, sewerage, surface water drainage, and solid waste management are all reported to be severely lacking. Water bodies occupy about a quarter of the city's territory, but they have not been exposed to planning and expansion and are likely underutilized for the city's advantage.

Kochi houses the maximum (ten) number of mangrove species in Kerala (Table 5.1). *Avicennia officinalis* L. and *Rhizophora mucronata* Lam. are more dominant mangrove species (Kumar et al. 2011). *Bruguiera sexangula* (Lour.) Poir. is the rarely observed mangrove species from Kochi.

In Kochi, mangroves have many benefits for local people such as *Bruguiera gymnorhiza* (L.) Savigny which is planted as a hedge or a boundary in some places. The flower of *Acanthus ilicifolius* (L.) Engl. is used as a medicine for blood pressure,

Fig. 5.3 Mangrove planted as a boundary to the coastal area in Edakochi at Kochi

and the fruit of *Excoecaria agallocha* is used as a medicine for leprosy. The mangrove species *Avicennia*, *Bruguiera gymnorhiza* (L.), *Bruguiera cylindrica* (L) Blume., and *Excoecaria* were used as home remedies (Hema 2014). The fruits of Avicennia were used against rheumatism and also as cattle medicine. The wood of *Excoecaria agallocha* L. and *Bruguiera cylindrica* (L) Blume. were mainly extracted for cork making (Hema 2014). The mangrove species *Bruguiera gymnorhiza* (L.) Savigny is planted along the boundary of homesteads to prevent soil and embankment erosion in fragile coastal areas (Fig. 5.3).

Land−/sea-use change, direct exploitation, climate change, pollution, and invasive alien species are the direct drivers of biodiversity loss which have a great impact on the species and their ecosystem (Fig. 5.1). Indirect drivers can be described as the influences that alter or play a role in activating the direct drivers as well as other indirect drivers (IPBES 2018). Changes in population, economic activity, and technology, as well as sociopolitical and cultural factors, are some important indirect drivers (GreenFacts n.d.).

The result is based on the field survey conducted in the Kochi area, from local people to government officials. Nearly 90% of the respondents felt that mangroves' wealth has depleted over time. The survey was conducted with 101 individuals among whom 51.5% were male and 48.5% were female between the ages of 20 and 70. The respondents included students to senior citizens including government officials. Most of the families living near mangrove areas are marginalized and live in fragile coastal areas.

As per the information shared by the respondents, the major pressures or drivers affecting the Kochi mangroves are urbanization, coastal industrial projects, population growth, deforestation, land use, land cover changes, and lack of awareness about the importance of mangroves. There has been a significant change in land use, land cover, and many other human-induced drivers which has affected the natural mangrove patches of the region. As per local informants, urban expansion, demographic changes, deforestation, increasing tourism, and lack of awareness are some of the crucial drivers of biodiversity loss in the Kochi district.

5.4.1 Population Growth

Biodiversity and ecosystem losses are worsening as the world's population grows and becomes more affluent, requiring more agricultural and forestry goods, and teleconnections in the global economy have led to more remote environmental stewardship (Marques et al. 2019). By 2030, an additional 1.2 billion people are projected to live in urban areas globally with a denser population in China and India. The urban population growth has had and will continue to have significant implications for land use, energy consumption and climate change, water security, food demand, and air pollution. Demographic changes have emerged as one of the mega drivers of the loss of the mangrove ecosystem in Kochi. Kochi became the industrial capital of the state in 2010, and people started migrating to Kochi for the job, trade, and business opportunities.

The projected population of the CDP (Census-Designated Place) area based on the natural growth trend was estimated to be 13.69 lakhs in 2021 and 14.29 lakhs in 2026, which showed a drastic increase according to the Kochi metro city population with 31.93 M in 2021 and estimated to be 41.55 million in 2031 (2021 World Population by Country n.d.).

Figure 5.4 explains the impact of population on the natural mangrove patches in Kochi. According to the information shared by the respondents, the exponential growth of population in the city is one of the potential drivers of mangrove loss in the Kochi area. Stakeholder responses show the impact of population growth on the loss of natural mangrove patches, indicating that about 80% assume that population growth is the main reason for mangrove degradation, of which 47.5% informed that population growth has a very high impact and 32.7% consider population as a high impact driver for mangrove loss. However, 14.9% of respondents believed population growth has a moderate impact on the degradation and loss of mangroves in Kochi.

5.4.2 Shrimp Farming/Aquaculture

For decades, mangroves have been exploited for shrimp farming, but as commercial shrimp farming expands and these systems necessitate total forest clearing,

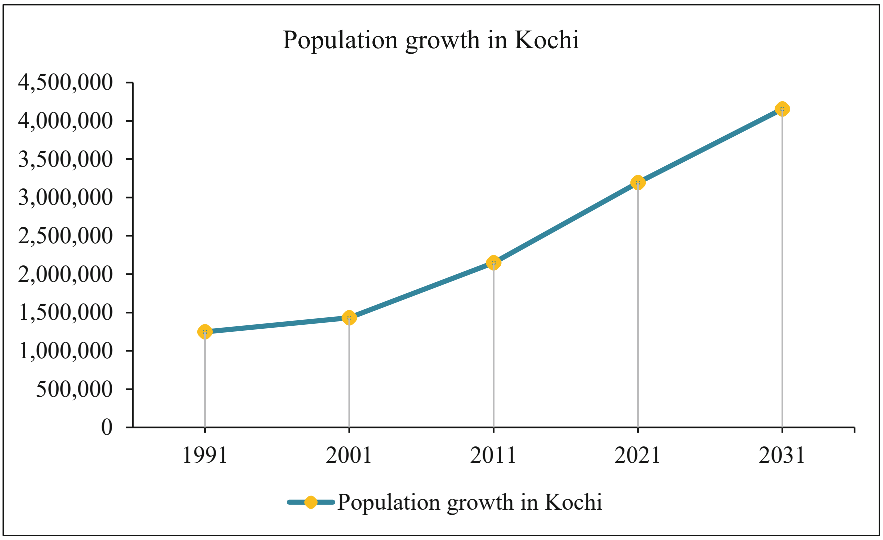

Fig. 5.4 Projected exponential growth of population in Kochi from 1991 to 2031

mangrove ecosystems are fast disappearing. Inadequate planning and management techniques, as well as a sloppy enforcement of preexisting restrictions, have exacerbated the detrimental effects of shrimp farming (Paul and Vogl 2011).

According to the information shared by the respondents, unscientific farming results in unscientific harvesting. Other than shrimp farming and aquaculture, unscientific pokkali (a local variety of paddy) cultivation is another threat to mangroves in Kochi. Most of the mangroves in the Karumalloor area are converted into coconut plantations. The majority of the respondents (46.5%) view shrimp farming and aquaculture as having a moderate impact on mangroves in Kochi. In Kochi, conversion of mangroves for shrimp farming and aquaculture is not so common and that is a reason that the majority of the respondents' opinion shows a moderate impact. Where 32.7% responded that this has a high impact on mangroves and 12.9% responded that shrimp farming and aquaculture have very little impact on Kochi mangroves. The very high impact was suggested by only 5.9% of respondents, and this might be because these respondents are elderly living very close to the mangrove areas and have observed the changing face of mangroves in Kochi in the last few decades.

Even though the majority of the respondents believe that shrimp farming and aquaculture have only a moderate impact, this is an upcoming threat to the Kochi mangroves. Aquaculture has developed into a highly economically profitable sector; therefore, more people are turning to this field. So, the shortage of availability of land for the purpose leads to the conversion of wetlands for these purposes that is degrading these landscapes.

5.4.3 Deforestation and Land-Use Change to Build up Expansion

Deforestation rates in mangroves are four times greater than in terrestrial tropical rainforests. When trees are chopped down, the top layer of the sediment is exposed to physical pressures, causing accelerated erosion, biochemical weathering, and decomposition rates. Clearing trees diminishes aboveground biomass, particularly aerial and prop roots, that limits OC sequestration. Deforestation is a major driver of mangrove biodiversity loss in Kochi. The developments in the last few decades have a significant role in deforesting the mangroves. Most of the coastal industries in Kochi are coming up by deforesting the land of its natural mangrove cover.

According to the information shared by the respondents based on their understanding, deforestation and land-use change are some of the potential drivers of mangrove loss in Kochi. The majority of respondents view deforestation as having a very high impact on mangroves, while 17.8% suggest it to have a moderate impact but will be damaging in the long run that can threaten these mangroves. Hardly a few responded to very little impact, and no one was suggesting for no impact. So, there was unanimous consent and consensus of local respondents of deforestation being the mega driver of mangrove loss in the district of Kochi.

5.4.4 Urbanization

The degree of or growth in urban character or nature is frequently referred to as urbanization, and it can apply to a geographical region mixing urban and rural areas, as well as the change of places to more urban development (Lee et al. 2006). Urbanization has been considered the important driver of mangrove loss all over the world. According to local informants, Kochi is facing a rapid urbanization trend and is one of the important coastal cities of India. Mangrove losses, which occur mostly 5–10 km from metropolitan areas, are intimately linked to increasing urbanizations. According to the study conducted by the National Centre for Earth Science Studies (NCESS), in 2000–2010, the Urban Intensity Index (UII) is at its peak in and around 0–2 km of the city region, and it shows a high intensification of urbanization within 2 km of the city region. In between 4 and 8 km, it shows a steady declining trend from the city centre because the zone is already well developed and the vacant space for expansion is negligible (Jayalakshmy and Mereena 2016).

Unplanned rampant infrastructure build-up and development of urban areas to meet the needs of the large population have significantly destroyed mangrove biodiversity. The increase in population and urbanization has been proportional to each other for the city.

5.4.5 *Coastal Industrial Projects*

Kochi is developed by the establishment of many industrial projects like LNG Petronet, Vallarpadam Transshipment Container Terminal, Cochin Port Trust, and Cochin Shipyard. Puthuvype has become the most attractive coastal industry. LNG Petronet and Vallarpadam container terminal are functioning in Puthuvype. A large area was taken by the government for the construction of these industries. LNG Terminal was commissioned in 2013, and it occupies an area of 33.4 ha for storage and gasification and 22 ha for marine facilities. The container terminal was commissioned in 2011 with an area of 40 ha (Fig. 5.5). These projects restrict the saltwater supply to these mangroves which results in mangrove degradation (Sahadevan et al. 2017).

According to the survey, urbanization and coastal industrial projects are the major drivers of the loss of mangroves in the Kochi area. Almost 85% of the respondents informed that urbanization and coastal industrial projects bring a high impact on mangroves. Of which 59.2% of respondents endorsed urbanization as having a very high impact and 25.5% mentioned urbanization having a high impact on mangrove degradation. Only 12.2% responded to urbanization as moderate impact and a trickle responded to very little impact and no impact.

5.4.6 *Dredging and Port*

Heavy metals, oils, and chemicals are frequently found in dredged debris. Dredging in vulnerable mangrove regions suffocates mangroves by preventing oxygen from reaching the root system by flooding the aerial roots. The sanctuary's physical environment has been deteriorating owing to severe sedimentation as a result of dredging activities on the shore, despite its small size of 2.74 hectares. An oil spill reported from Ennore, Tamil Nadu, in January 2017, released at least 2 tonnes of oil into the sea after two vessels collided, affecting 30 km of the coastline, leading to serious environmental damage and death of several turtles and hatchlings (Scroll.in n.d.).

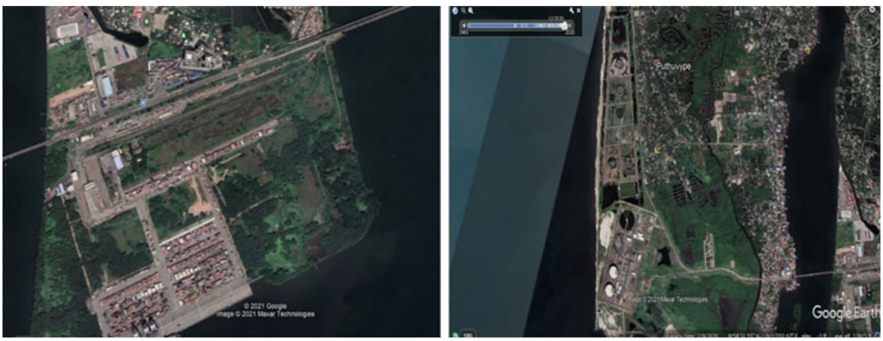

Fig. 5.5 LNG terminal and container terminal in Puthuvype, Kochi

Kochi has not reported any cases of dredging degrading mangroves even though the information shared by the respondents shows that 46.5% informed that dredging and port cause a high impact on mangroves and 31.7% have an opinion of moderate impact. And a few of 13.9% assert that port and dredging have a very high impact. 5% and a handful of respondents shared very small impact and no impact.

5.4.7 Tourism, Plastic Pollution, and Solid and Hazardous Waste Management

Mangalavanam Bird Sanctuary has become a hectic centre of real estate development because of its pristine and beautiful location. Large-scale stored tanks for petroleum products of Indian Oil Corporation are situated very close to this station. Oil spills and polluted water are the major threats. The mangrove in this region is facing the growing threat of oil pollution. On September 10, 2002, nearly 3000 L of diesel leaked from the Hindustan Petroleum Corporation Ltd. (HPLC) subterranean pipeline near the ecologically sensitive Mangalavanam (The New Indian Express [11-9-2002]). A thick film of diesel could be seen above the water mass of Mangalavanam, the feeder canal, and also some parts of Vembanad Lake near Bolgatty Island (Kaladharan and Nandakumar 2003). Its rich mangroves are being sucked dry by the burgeoning city-waste that clogs its water bodies that are regularly being dumped in the coastal zones. Most of the city waste is dumped in the landfill site that is close to Manglavanam. Plastic production and usage have extensively increased in an uncontrollable manner globally, and microplastics are plastic fragments smaller than 5.0 mm in size. Microplastics were identified as having more abundance in the Mangalavanam region during the pre-monsoon season (Nair et al. 2021). The green lungs of Kochi are being choked at an alarmingly fast pace and are now on verge of a shutdown.

According to the information given by the respondents, tourism and waste management is a growing driver of mangrove loss for Kochi. According to the information shared by the respondents, about 73% of people have an opinion that tourism and plastic pollution has a major role in the degradation of mangroves. They have an equal opinion with 36.6% of very high impact and high impact on mangroves. 26.7% count on moderate impact, and only a handful believe that it has no impact. Microplastics and chemicals used in agriculture are significantly affecting Kochi coasts.

5.4.8 Construction of Roads and Waterways

Because of urbanization, many mangrove areas have been subjected to degradation. Many mangrove patches in Kochi are also deforested for the construction of roads and waterways. The container road is a national highway 966A from Kalamassery to Vallarpadam international container transshipment terminal with a length of 15 km. About 46.4286 ha in seven villages have been acquired, evacuating 183 families for construction of this roadway.

According to the participatory survey, 47.5% have an opinion that the construction of roads and railways has a high impact on the loss of mangroves because of the construction of the Vallarpadam container terminal road. 31.7% stick to the opinion that it has only a moderate impact on mangroves. 13.9% of respondents presume it has a very high impact on mangroves. And some of the respondents have opinions that have a very small impact. So, overall, most of the respondents despite not being from scientific fields are convinced that roads and waterways can affect the mangrove and damage them in the long run.

5.4.9 Encroachment and Coastal Policies

A waterfront stadium is located in a coastal regulation zone (CRZ) that is ecologically sensitive. The Edakochi Stadium, which was built to international standards, has ran afoul of environmental regulations. The Board of Control for Cricket in India (BCCI) bought roughly 10 hectares (ha) of land in the Vembanad Lake, which is protected under the Ramsar Convention. According to the responses, the region was once covered with mangroves; however, for the stadium, the whole stretch has been cleared of vegetation.

According to the reviews from the participatory survey, the majority (34.7%) have an opinion that encroachment and coastal policies have only a moderate impact on mangroves in Kochi where 33.7% respond that this has a high impact on the mangrove ecosystem and 21.8% of respondents consider that it has a very high impact on mangroves. 7.9% and a few assume that encroachment and coastal policies have no impact.

5.4.10 Natural Disaster Climate Change and Sea-Level Rise

Even though Kerala state has relatively been free from severe cyclonic storms, still Ochki in 2015 was the most intense tropical cyclone which affected the Kannamali and Chellanam areas in Ernakulam district. The storm struck Kerala’s coasts on November 30, 2015, leaving a path of damage in its wake as hundreds of people were displaced from their flooded houses and relocated to relief shelters (The Hindu n.d.). This cyclone was considered the deadliest cyclone to have hit the state. Mangroves in the area decreased the high risk on the land, even though a large area of mangrove has been degraded due to the cyclone.

Kochi also has to deal with rising sea levels. Mangroves can’t survive in seas that rise more than 7 mm each year. In the coastal model, the Kochi islands are shown as being in a high-risk zone for sea-level rise. They found that Kochi experienced a 12–14 cm sea-level rise in the last 80 years. This would average about 1–1.2 cm per year. As per the information shared by the respondents, 47.5% said that sea level and climate change have a high impact on mangroves in Kochi. 24.8% and 23.8% of respondents had an opinion that it has a very high impact and a moderate impact on mangroves. And 4% responded that natural disaster and climate change have only a small impact on mangrove.

Natural disasters are nowadays common on the Kerala coast, and the mangroves have played a major role in protecting the shoreline. But due to the continuing pressure on mangroves, they are on the verge of destruction. There is a growing need and demand for reducing and halting destruction while restoring the mangroves by the involvement of all stakeholder groups.

5.4.11 Eutrophication and Coastal Acidification

Under current and future climate circumstances, increased instability associated with coastal eutrophication has far-reaching implications for several dimensions of mangrove ecological processes (Lovelock et al. 2009). Heavy metal contamination has grown significantly in the Cochin estuary over the last three decades, resulting in a reduction/adaptation in the concentration, variety, and enzyme expression pattern of bacteria, which could have negative consequences for ecosystem functioning (Joseph et al. 2019).

Most commercially fixed nitrogen and mined phosphorus go into the production of fertilizers. The rising demand for fertilizers has come from the need to meet the nutritional demand for our rapidly expanding human population (Coastal Wiki n.d.). Phosphorus levels in the freshwater bodies are escalating, and this poses a serious threat to the ecosystem. About 1.5 tetragrams of phosphorus is dumped into the freshwater globally. Carbon dioxide after dissolving in water causes pH reduction leading to coastal acidification which eventually affects the livelihood of phytoplankton which is a prime food source for aquatic organisms and also harms ecosystems like coral reefs. Agriculture contributes significantly to eutrophication and coastal acidification by discharging enormous amounts of agrochemicals, organic waste, drug residues, debris, and salty discharge into water bodies, causing mangrove deterioration (Food and Agriculture Organization of the United Nations n.d.).

According to the information shared by the respondents, the majority of the respondents assume that eutrophication and coastal acidification have a moderate impact on mangroves. 32.7% of respondents' opinion is that it has a high impact and 18.8% assume that it contributes a very high impact. A very small impact on the mangroves was assumed by a few respondents.

5.4.12 Lack of Awareness

Even though the city has its development, the people living near the coast are not properly aware of the benefits that are acquired by mangroves. Other than the shoreline protection from high waves, they have no idea about other benefits. So, during the survey, the lack of awareness was also projected high as the driver of the mangrove ecosystem.

The majority (57%) of the respondents said that lack of awareness is one of the major reasons for the impact on mangrove degradation, of which 29% with very high impact and 28.7% with high impact. The moderate impact was assumed by 28.7% of respondents. 9.9% and a few have an opinion that awareness does not affect the degradation of mangroves.

Even though Kochi is a developing city, the people often forget the values of the ecosystem. The local residents need to be given more awareness of the importance of mangroves. But the educated people that are aware of the benefits of mangroves are degrading mangroves for wealth and profit.

5.4.13 Introduction of New Species

Invasive alien species are biological species that have been introduced outside of their natural range and have a detrimental influence on native biodiversity, ecosystem function, health, and human welfare. After habitat degradation, they are the second-leading driver of biodiversity loss. Invasive species in mangrove forests are a major concern, with unintentional introductions being the most common cause. Invasive species in mangrove forests have been reported to inhibit the establishment and growth of mangroves, change the composition of existing native vegetation, prevent regeneration, and have a negative impact on ecosystem functioning. Exotic plants like Brazilian pepper, Australian pines, and carrot wood can essentially invade and suffocate native mangrove species. The invasive plants possess the traits of salinity tolerance, tolerance to anaerobic conditions, high fecundity, and rapid growth (Biswas et al. 2018). Lacking a common evolutionary line, species introduction would result in an unbalance in the ecosystem's interaction since introduced organisms often outcompete native species resulting in a drastic reduction of biodiversity.

According to the information gathered in the survey, 38% of respondents said it had only a moderate impact on Kochi mangroves. The majority of the respondents have an opinion that the introduction of new species does not cause a high impact on mangroves. 18.8% have an opinion that it has a high impact, and only 8.9% said that it has a very high impact on mangroves in Kochi. The introduction of new species is a serious threat to the mangrove ecosystem. The alien species reproduce rapidly, and they can completely destroy the native species. Even though the residents of Kochi are not familiar with this term, this is a serious problem faced globally.

5.5 Conclusions

According to the stakeholder survey, population increase, urbanization, coastal industry, tourism, plastic pollution, deforestation, land-use change, and a lack of knowledge are the primary drivers of mangroves in Kochi. Despite the fact that Kochi has the second-largest area of mangroves in the state, 36% of mangroves are deteriorating or damaged. The main reason for this is that 60% of the mangrove area is privately owned and these areas should be protected. The conservation of these ecosystems is essential for preserving their rich biodiversity, the long-term viability of fisheries, forestry, and other industries, and the protection of coastal areas from natural disasters.

According to the Forest Conservation Act of 1980, no forest land may be converted for non-forestry use without the prior consent of the Indian government. This law has proven to be highly efficient in keeping mangrove forest lands from being diverted for non-forestry activities. The Environment (Protection) Act of 1986 has played a critical role in mangrove ecosystem protection and management. To preserve the coastal environment, it establishes a Coastal Regulation Zone in which industrial and other activities such as discharge of untreated water and effluents, dumping of trash, land reclamation, and bunding are banned; mangroves are included in the most ecologically vulnerable category.

The Forest Department of the respective State/Union Territories protects mangrove forests designated as Reserve Forests, Reserve Lands, or Sanctuaries in India. The Central Government has the ability to adopt laws and measures to preserve and enhance the environment, according to Section 3 of the Environment Protection Act. The most sensitive CRZ I zones are those where no developmental activity is authorized. All states in India have designated all vegetative community areas in mangroves as CRZ I. All mangrove forests having a size of 100 m^2 or greater are designated as CRZ I, with a buffer zone of at least 50 m, according to this notification. In their attempt to offer protection against sea storms and other natural dangers, national governments have prioritized mangrove regeneration. Restoration has piqued the interest of governments, coastal ecologists, international and national NGOs, local CBOs, and coastal communities. India is a party to the Ramsar Convention on Wetlands, and in 2010, it adopted Wetland (Conservation and Management) guidelines, which incorporate conservation and management techniques for the country's mangrove ecosystems. Following the recent flooding and landslides, the Kerala government has decided to construct green infrastructure (coastal green belts including mangroves) as a cost-effective method of strengthening resilience against the consequences of hazard occurrences. In this environment, effective governance, climate change adaptation and mitigation alternatives, improved planning for the rehabilitation of damaged mangroves, and raising community awareness are all critical to conserving, protecting, and restoring the important mangrove wetland ecosystems.

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Conflict of Interest Authors declare no conflict of interest for writing this book chapter.

Presentation of Annexure

Participatory survey to discover the drivers/reasons of biodiversity loss of mangroves in Kochi.

List the drivers/reasons that you believe can affect (both positive and negative) in future conservation functioning of Kochi mangroves.

Use the score of 1–5 to identify their impact.

(1) No impact; (2) very little impact; (3) moderate impact; (4) high impact; (5) very high impact.

S No	Drivers of loss	1	2	3	4	5
1	Population growth					
2	Shrimp farming/aquaculture					
3	Deforestation and land-use change to build-up expansion					
4	Urbanization and coastal industrial project					
5	Dredging and port					
6	Tourism plastic pollution solid waste management					
7	Construction of roads and waterways					
8	Encroachment and coastal policies					
9	Natural disasters climate change and sea level rise					
10	Eutrophication and coastal acidification					
11	Lack of awareness					
12	Introduction of new species					

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Chapter 6
Understanding Potential Drivers of Mangrove Loss in Bhitarkanika and Mahanadi Delta, India, to Enhance Effective Restoration and Conservation Efforts

Shalini Dhyani, Muktipada Panda, Rakesh Kadaverugu, Rajarshi Dasgupta, Pankaj Kumar, Sunidhi Singh, Jayshree Shukla, Paras Pujari, and Shizuka Hashimoto

Abstract Mangrove ecosystems have attracted immense attention because of their unique ability to withstand and protect the fragile coastal ecosystem by supplying diverse ecosystem services in the warming world. To appropriately understand and predict the plausible alternative futures of mangroves in India, it is pertinent to understand the potential drivers of mangrove loss. The chapter focuses on the second most diverse mangrove patches in India Bhitarkanika and Mahanadi delta in Odisha. Changes in the local mangroves can help to understand the magnitude, trends, drivers, and scenarios of long-term changes. The present chapter provides a broader overview of direct and indirect drivers that have substantially affected the long-term protection, functioning, and restoration of mangroves. The chapter presents a critical review to understand key knowledge gaps and constraining conditions that have affected the conservation of mangroves in the region. An exponential increase in population, immigration, aquaculture ponds, infrastructure development, and poor socioeconomic condition of locals followed by increasing frequency of cyclones are key drivers. Improving interactive governance approaches and opportunities for locals in evidence-based decision-making, including their livelihood concerns, can improve conservation efforts. Sensitive coastal zone in the region should be declared

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S. Dhyani (✉) · R. Kadaverugu · S. Singh · J. Shukla · P. Pujari
CSIR-National Environmental Engineering Research Institute (NEERI), Nagpur, Maharashtra, India

M. Panda
Banki (Autonomous) College, Banki, Odisha, India

R. Dasgupta · P. Kumar
Institute for Global Environmental Strategies (IGES), Hayama, Kanagawa, Japan

S. Hashimoto
Department of Ecosystem Studies, University of Tokyo, Tokyo, Japan

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as a "no-go zone" for large-scale industrial and developmental projects that significantly affect coastal and marine ecosystems. The chapter highlights the implications of mangrove vulnerability and prospects for resilience for Bhitarkanika and Mahanadi Delta and argues ensuring the unrestricted flow of ecosystem services from the coupled socio-ecological system that can be ensured by a comprehensive understanding of the bidirectional linkages of ecosystems and arrangement of anthropogenic drivers of loss.

Keywords Mangroves · Odisha · Bhitarkanika · Drivers · Biodiversity loss · Ecosystem services · Climate change · Aquaculture

6.1 Introduction

High-value mangrove forests are present along the tropical and subtropical coastal areas of 118 countries across the world (Thomas et al. 2018). Mangroves are known to help to secure livelihood and ensuring nutritional security for the marginalized coastal communities. Mangroves offer provisioning benefits in the form of fisheries, protecting them from extreme climate events, and are also rich blue carbon sinks with the highest biomass carbon densities than any terrestrial forest ecosystem (Richards and Friess 2016; Dasgupta and Shaw 2017; Kumar et al. 2021; Kadaverugu et al. 2021). These high-value ecosystems provide supporting services in the biogeochemical cycling of carbon, which can help to reduce the vulnerabilities due to global climate change (Kadaverugu et al. 2021). Rapid decline in mangrove patches has been regularly observed by many ongoing and completed global assessments, and this decline is alarming than the loss of any inland tropical forests (Castillo et al. 2021). Human-induced pressures are the mega drivers accelerating loss of sensitive mangrove ecosystems across the world. Increasing settlements and rapid demographic changes in coastal regions with insufficient regulations have resulted in massive loss of mangroves (Turschwell et al. 2020). Degraded mangrove hotspots across Asia characterize mangroves as highly threatened ecosystems due to anthropogenic interferences, though the natural processes of coastal erosion are also enhancing forest vulnerability (Goldberg et al. 2020). There are multiple indirect and direct drivers that are accelerating the pace of mangrove losses, and the nature and dynamics of these drivers of mangrove loss vary across S. Asia and especially in different local contexts (Fig. 6.1).

To understand and address the socio-ecological and economic dimensions of mangroves, there is a growing need to understand the underlying drivers and stressors of mangrove losses and how they are interacting at the local levels (Chowdhury et al. 2017). The Global Assessment Report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) shortlisted five direct drivers of biodiversity loss, viz., changing sea and land use, direct extraction and unsustainable use of wild species, climate variability and associated vulnerabilities, pollution, and invasive species that can replace native species. The two indirect drivers of loss that can accelerate the pace of mangroves'

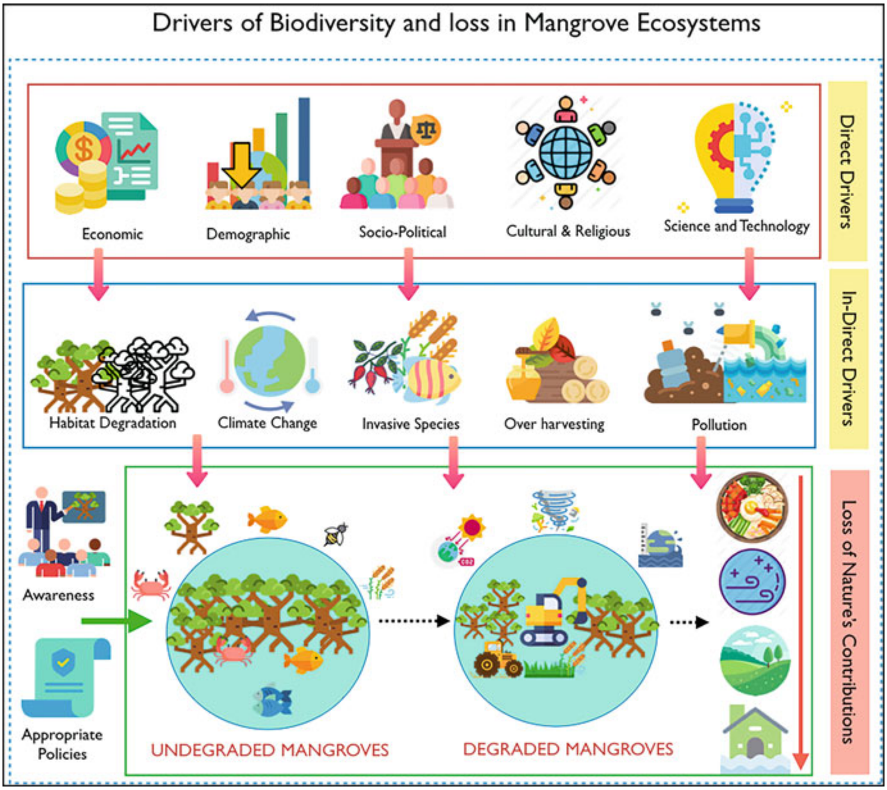

Fig. 6.1 Graphical presentation of different direct and indirect drivers affecting natural mangrove diversity

loss are people's disconnecting with nature, along with the lack of understanding of the immense value and importance of nature (Bongaarts 2019). Though deforestation rates for mangroves are studied at a global scale, still there are insufficient attempts to understand the mangrove deforestation drivers that vary across the regions. Continuous global and national mangrove monitoring can provide a broader overview of changes faced by mangroves, threats associated, and impacts of the ongoing restoration programs (Chowdhury et al. 2017). India is home to approximately 2.7% of the world's diverse mangrove cover that accounts for 0.67% of the total designated forest area of the country in 4662 km^2 of its 7516.6 km long coastline on the east and west coast followed by sensitive island mangrove patches (Giri et al. 2008; Dasgupta and Shaw 2013; FSI 2019). Mangroves along the east coast of India are vulnerable to the increasing frequency of extreme climate events, rise in sea level, enhancing salinity, human-induced pressures mainly due to unsustainable extraction of bio-resources, aquaculture, demographic changes especially settlement of migrants, commercial tourism, urban sprawling, increasing number of industries in the coastal zones, cattle grazing, etc. (Dasgupta and Shaw

2013; Kadaverugu et al. 2021). Bhitarkanika mangrove ecosystem is the second largest mangrove ecosystem in India that is facing threats from human encroachment, change of land use to agriculture, aquaculture, etc. which are some of the mega drivers affecting the mangrove populations in the region (Das and Vincent 2009). Though enhanced restoration efforts and assisted nature regeneration in the last few years have helped the natural patches of Indian mangrove ecosystems to recover and reduce the rampant loss, there is an emerging need to protect these high-value ecosystems in developing and underdeveloped countries (Castillo et al. 2021). Information on mangrove forest loss and its drivers is critical to support the decision-making by resource managers, planners, and policy-makers. To accurately predict the future of Indian mangroves, it is crucial to appropriately understand the local drivers of mangrove loss which can enable policy-makers for proactive planning and enforcement of policies. The chapter largely covers all the important direct and indirect drivers as per IPBES Asia-Pacific assessment of biodiversity and ecosystem services that have resulted in the loss of mangrove patches in the region (IPBES 2018). This will help in the effective restoration and rehabilitation of the degraded mangroves and achieving targets for UN decade on restoration (2021–2030), Sustainable Development Goal 15, and upcoming post-2020 global biodiversity targets.

6.2 Study Area

The mangroves forests on the east coast of Odisha are located between 19°12′–21°36′ N and 84°51′–87°29′ E (Fig. 6.2). The region has diverse estuarine habitats and deltas formed by major rivers of the state, viz., Mahanadi, Brahmani, Baitarani, Budhabalanga, Subarnarekha, Rushikulya, and Bahuda, which creates a suitable habitat along the coastline supporting diverse mangrove genetic resources. Most of these areas host scattered patches of mangroves except the mangrove ecosystems at Bhitarkanika. The dominant mangrove cover in the state is concentrated in the delta of Brahmani-Baitarani and Mahanadi in Kendrapara district (Roy et al. 2019).

The former delta is established by the rivers Brahmani and Baitarani, especially the Brahmani river which is a major contributor to the mangrove development in the region. Bhitarkanika is legally protected and holds four important protection designations. It was declared a wildlife sanctuary in 1975; Gahirmatha area got marine sanctuary status in 1997; Bhitarkanika was declared National Park in 1998 under Wildlife Protection Act, 1972, and Ramsar Wetland in the year 2002 under Ramsar Convention, 1971; and it was also proposed for a World Heritage status in UNESCO Man and Biosphere Programme by Govt. of India. Bhitarkanika Wildlife Sanctuary covering 672 km^2, in the Kendrapara district of Odisha, is home to India's second-largest mangrove forest, after the Sundarbans. Forests on the east coast of Odisha are dominated by exclusive mangrove species, viz., *Avicennia officinalis*, *Avicennia marina*, and *Excoecaria agallocha*, and are home to 62 species of mangroves (Chauhan and Ramanathan 2008) (Chauhan and Ramanathan 2008) (Fig. 6.3). The

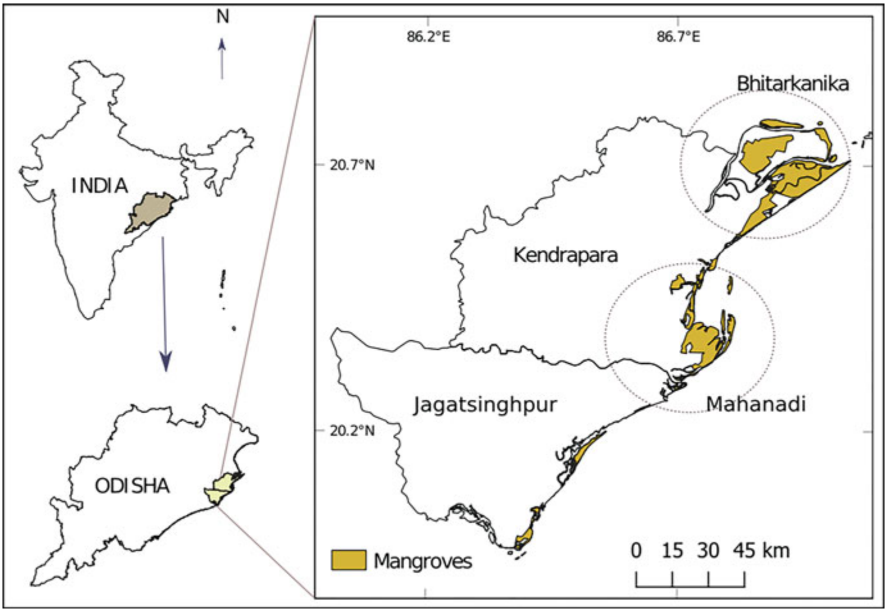

Fig. 6.2 Map showing mangrove patches in Bhitarkanika and Mahanadi delta in the east coast of Odisha

National Park is free of human habitations, whereas the Sanctuary is interspersed with 336 villages (Hussain and Badola 2010). Various forestry products like timber (*Avicennia*, *Bruguiera*, *Phoenix*, *Heritiera*, *Excoecaria*, *Tamarix*, and *Sonneratia*), honey, weaving and thatching species (*Myriostachya wightiana* and *Phoenix paludosa*, respectively), and fodder (*Porteresia coarctata*, *Myriostachya wightiana*) are frequently collected by the local villagers (Kadaverugu et al. 2021). The mangrove area of Mahanadi delta (20°15′ to 20°70′ N latitude and 87° to 87°40′ E longitude) extends from the southeastern boundary of Mahanadi river to the river mouth of Hansua (a tributary of Brahmani) in the north, from the northeastern end of Mahanadi river up to Jambu river in the east. These flowing rivers bring a significant amount of freshwater, sediment, and nutrient that supports suitable habitat for the growth and development of mangrove ecosystems.

6.3 Methodology

In the present chapter, a comprehensive review of existing information from both peer-reviewed and gray literature was carried out using three different established search engines (SCOPUS, Google Earth, and Web of Science) to explore and understand the larger impacts of complex drivers for Bhitarkanika and Mahanadi delta in the east coast of Odisha. The chapter attempts to examine diverse

Fig. 6.3 An overview of mangroves of Bhitarkanika and Mahanadi delta of Odisha: (**a**) A river site mangrove in Bhitarkanika; (**b**) an old patch of monospecific *Avicennia officinalis* in Mahanadi delta; (**c**, **d**) *Suaeda* infested forest sites in Bhitarkanika; (**e**) exposed mangrove roots due high tide surge in Odisha coast; (**f**) dying out old plants in Bhitarkanika

environmental and socioeconomic stresses based on critical analysis of available information and field-based observations to highlight the mega drivers of deforestation, degradation, and fragmentation of mangroves in Odisha. To identify and list the potential drivers related to the loss of mangrove ecosystem services and biodiversity the IPBES Asia-Pacific Assessment, 2018 was referred to as reference assessment. Direct drivers of biodiversity and ecosystem loss (i.e., economic, demographic, sociopolitical, and cultural drivers) and indirect drivers (including habitat degradation, climate change, invasive species, overharvesting, and pollution) were considered for this review chapter (IPBES 2018). There is evidence that direct drivers may result in massive loss of biodiversity and ecosystem services if they work in combination with the indirect drivers. IPBES global assessment, 2019, suggests two important categories of drivers which are planet (changing use of land and use direct exploitation of organisms, climate change, pollution and invasive, and nonnative species) and people that include the people's disconnect with nature and lack of importance and appreciation toward nature that is also attempted to be explored through this review for Bhitarkanika as a regional effort for a global issue (Bongaarts 2019). A critical review of the available information was further also cross-checked from our field-based observations from 2019 to 2020. The supervised land-use classification analysis has been performed on the cloud-free Landsat imageries of 30 m spatial resolution to understand the land-use land cover changes.

6.4 Drivers of Mangrove Loss in Bhitarkanika and Mahanadi Delta

Direct and indirect drivers of mangrove loss in Bhitarkanika and Mahanadi delta have been discussed in detail under specific heading for a better understanding of the severeness and complex situation the coastal area on the east coast of Odisha is facing.

6.4.1 Demographic

Demographic data from government records show that the coastal part of Odisha is having high anthropogenic pressure especially the mangroves of Bhitarkanika (Pattanaik et al. 2008; Hussain and Badola 2010; Roy et al. 2019). The fertile land in the coastal zone of Odisha that supports agriculture, fisheries, and tourism in the region for local livelihood is facing tremendous demographic pressure (Bahinipati and Chandra Sahu 2012). Though Bhitarkanika is a notified protected area under Wildlife Protection Act, 1972, more than 1,50,000 inhabitants live and are significantly dependent on natural mangroves for their substance requirements (Bhomia et al. 2016). Population in five coastal districts of Odisha was already eight million as per the last Census in 2011 by Govt. of India. This alarmingly indicated toward population density of 600 people/km^2 and annual population growth of 1.4% that has exponentially grown in the last decade (Hazra et al. 2020). High population density and their dependence on rich mangrove forests are the cause of serious disputes between local small farmers, fisherfolks, illegal aquaculture owners, and the conservationist community. Despite Bhitarkanika having protected area status, as per the 2011 census, there were 310 villages with 145,301 people living inside the

Bhitarkanika Sanctuary boundaries, and this sums up to a high population density of 216 persons per km^2.[1] The population density in the coastal district of Kendrapara is also rapidly rising. It was reported to be $435/km^2$ in 1991, 492 in 2001 that was $545/km^2$ in 2011, and recently it is reported to be 595 villages with a population of 50,6930 (Pattanaik and Narendra Prasad 2011; Thakur et al. 2019). The reported demographic growth rate in the region was at 13.27% from 1991 to 2001 that further reduced by 10.63% from 2001 to 2011.[2] The region has also seen large immigration and subsequent settlement of Bangladeshi refugees after the 1999 super cyclone resulting in enhanced anthropogenic pressure on the regional mangroves (Pattanaik and Narendra Prasad 2011). The exponential rise in population pressure in Bhitarkanika has resulted in increasing human settlements from an area of 27.33 ha to 46.19 ha within a span of 15 years (2000–2015) and accounts for around 69% of land use contribution (Banerjee et al. 2018). The increase in human population around estuarine areas may also affect the ecology of mangroves that are expected to deteriorate the health of the mangrove ecosystem of Bhitarkanika and Mahanadi delta including shrinkage in the area (Upadhyay and Mishra 2008).

6.4.2 Local Socioeconomics

The rich mangrove cover of Bhitarkanika provides immense provisioning benefits to support the subsistence requirements and livelihood of locals (Behera and Nayak 2013; Kathiresan 2018; Kadaverugu et al. 2021). Mangroves and other coastal forests are already reported to be overexploited for diverse provisioning needs of locals for fuelwood, fodder, NTFPs, timber, medicinal purposes, and livelihood (Hussain and Badola 2010; Panda et al. 2013; Roy et al. 2019). The socioeconomic condition of the locals is also a potential driver which is capable to transform the natural landscapes including the mangrove patches in the region (Dhyani and Dhyani 2020). Provisioning ecosystem requirements and dependence from Bhitarkanika mangrove patches depend on the availability of alternative products, roadways, accessibility to markets, settlement density, and tree composition of the mangroves. The presence of economically important mangroves also determines the degree of pressure these mangrove patches face (Ambastha et al. 2010). Direct dependence of local inhabitants for provisioning benefits due to the paucity of alternatives has stressed these rich biodiverse ecosystems. Nearly 30% of these forests close to easily accessible areas are facing high human-induced pressure. Complete lopping of branches for NTFP harvesting has been the most prominent cause of tree mortality observed in all the four forest blocks of the region having more than 84% of mangrove trees (Upadhyay and Mishra 2008). Impacts are directly

[1] https://ejatlas.org/conflict/land-and-livelihood-conflicts-in-bhitarkanika-wildlife-sanctuary-odisha-india.

[2] https://censusindia.gov.in/2011-common/censusdata2011.html.

proportional to the pressure on mangrove forest resources, and the reasons are both commercial and personal that are driving these pressures. Locals living in 100 adjoining villages to the mangrove forest blocks are dependent on the mangrove ecosystem for their livelihood. These local livelihood patterns and requirements directly or indirectly affect the very existence and survival of the natural resources, biodiversity, and ecosystem health in the region. Marginalized communities depend on mangroves for their fishing and fuelwood demands and also for livelihood by selling fuelwood and fishes to nearby urban centers. Socioeconomic driver and marginalized status of communities living close to coastal enhance encroachment by agriculture expansion and intensification, fuelwood collection, etc. Fishery is the major livelihood for locals in these areas whom landless, and despite being a National Park, illegal fishing is frequently reported and observed in Bhitarkanika. Mangrove deforestation and degradation is also because of high demand for wood charcoal (from mangrove wood) to fulfill the demand of nearby urban centers and also for subsistence requirements of local communities. Despite being notified as a protected area, harvesting of biomass is regularly reported from the region. It has been reported that approximately 14% of fuel wood consumed by each household (approximately 312 kg) is from nearby mangrove forests used for construction of house, NTFPs, fuelwood, fodder, construction of jetties, tracks inside forests, small bridges, fish traps, boats, etc. (Ambastha et al. 2010; Banerjee et al. 2018). Locals also earn livelihood and harvest NTFPs (non-timber forest produce, like baskets, mats, etc.) from mangrove tree leaves and bark. However, restrictions by forest department have ensured less fuel wood dependency on natural forests and crop byproducts meeting 78% of the energy demands (Banerjee et al. 2018). 14.2% of the household level fuelwood demands and 14.5% of the economic benefits were fulfilled by mangroves, while this contribution was more than 30% for the households living close to the mangroves (Hussain and Badola 2010). An overview of resource dependency of local inhabitants in Bhitarkanika is presented in Table 6.1.

It is important to note that after the declaration of Bhitarkanika as a protected reserve, tremendous decline in fuelwood harvesting is observed as well as reported (Bahinipati and Chandra Sahu 2012). Grazing pressure on mangroves is also undeniable in the region with more than 70,000 local livestock dependence during cropping season exerts pressure on especially *Avicennia* growing patches. Fishing is another important provisioning benefit from the region. However, this was also posing threat to the local ecosystem as this was restricting the migration of fishes and also the free movement of brackish water crocodiles. Fishing is also known to be the closure of creeks and hampers the tidal inundation significantly.

Das and Chatterjee (2020) confirmed that ecotourism has helped in creating a diverse livelihood opportunity and has helped in improving the socioeconomic conditions of locals. It was observed that eco-development committees (EDCs) recognized in 2001 have now increased to 31 in numbers on the fringe areas of Bhitarkanika and have helped in income diversification. However, lack of education, skills, and interest among the locals, mainly because of their preference to traditional livelihoods of farming and fishing, has been a key constraining factor to achieve fruitful results (Banerjee et al. 2018; Das and Chatterjee 2020).

Table 6.1 Resource dependency of local communities on Bhitarkanika conservation area, India

Resource use		Mean quantity (kg/hh/year)
Fuelwood	Total consumption of fuelwood	2205.0 ± 104.2
	Fuelwood from the Bhitarkanika	312.0 ± 32.2
Fish	Fish caught from the Bhitarkanika	98.0 ± 28.3
Timber	Used as rafts	343.0 ± 36.9
	For rooftop provisions	27.0 ± 4.3
NTFPs	Honey	525.0 ± 239.7
	For roof thatching (*Phoenix paludosa*)	49.0 ± 8.7

Source: Ambastha et al. (2010)

6.4.3 Governance

Historically, mangroves in Bhitarkanika were cleared for agriculture and human habitations after the end of the *Zamindari* system (Indian version of feudalism) in 1952, and clearing was rampant till the late 1970s. This was further accelerated by the influx of immigrants from the neighboring state of West Bengal in the early 1950s. Conversion of dense to open mangroves was also due to a lack of strict law enforcement (Shrestha et al. 2019). The Forest Rights Act (FRA), 2006,[3] by the Government of India has not been acknowledged and implemented resulting in unrest among locals. Constraining conditions that restrict the process of interactive governance add to conflicts between locals and the forest department by negatively affecting the process of long-term conservation and management of mangroves in the region (Banerjee and Pasha 2017). Wherever government policies are framed by keeping local livelihood and mangrove conservation in the center of the decision-making and planning process, favorable outcomes have been achieved.

6.4.4 Land-Use Change Due to Buildup Expansion

Reduction in mangrove cover due to land use in the study area is associated with the increasing shrimp culture, the exponential rise in population, and settlements followed by construction of Paradip port in the southern boundary and Dhamra port at the northern boundary. Over 30 years (1973–2004), monitoring in Bhitarkanika reported 51.76% of land use of the protected area was occupied by agriculture (Reddy et al. 2007). Loss of 1534 ha of the area under mangrove and increase of 2436 ha under agriculture indicate change in land use as a mega driver of biodiversity loss. Another study that monitored the National Park boundaries from 2000 to 2015 reported 73.29% of the land use under mangroves and agriculture in 14.80%, but these results were contradictory to that reported by Reddy et al. (2007)

[3] https://tribal.nic.in/FRA/data/FRARulesBook.pdf.

(Banerjee et al. 2018). Only 1.02% of the land use in this duration is reported to be encroached and occupied under the aquaculture ponds, 0.76% under human habitations, 0.34% under roads and trails, and 5.83% drainage, whereas 3.38% scrub forest followed by 0.58% of grassland mostly on the mudflats. Initiatives and efforts of the state forest department and Park authorities have been instrumental to control the loss of mangroves for 15 years (2000–2015). Increasing aquaculture in 0.35 km^2 that corresponds to 56.47%, settlements by 0.19 km^2, i.e., 40.83% and 0.80 km^2, i.e., 64. 39% increase in the scrub forest area, reflects changing land use. Increase in scrub forests reflects degradation and opening of fringe mangrove forests and increase in human-induced pressure in and around the National Park boundaries (Banerjee et al. 2018). Increasing connectivity through roads not only enhances support to the forest department for monitoring remote inaccessible locations but also enhances market influences and enhanced access to human-induced interferences, but compromises the sustainability of existing mangroves. Decreasing mudflats in the national park boundaries reported from 1973 to 2004 indicate enhanced mangrove plantation efforts by the forest department (Reddy et al. 2007). The total loss of dense mangroves from the Bhitarkanika was 9.28 km^2 in one decade (1995 to 2004), while from 2004 to 2017, the loss was significantly high corresponding to 21.44 km^2 (Shrestha et al. 2019). However, an increase in total mangrove cover in the park boundaries from 185.73 km^2 in 1990 to 238.71 km^2 in 2015 was reported because of continuous efforts of forest managers and park administration in mangrove restoration, plantation on mudflats, fringe areas, and enforcing coastal zone management plans and policies (Roy et al. 2019). The historical land-use changes from 2008 to 2018 at the district level (including Kendrapara and Jagatsinghpur districts) indicate that agriculture and built-up have been increasing (Fig. 6.4). The cumulative land area of these two districts is about 4451 km^2. Agricultural land in these two coastal districts has increased from 61% to 64%, while the built-up area has increased from 2.4% to 4.1%. It was observed that aquaculture has marginally gained from 1.6% to 1.7%; also mangroves have gained from 4.1% to 4.4%, but water bodies and other vegetation classes have been declining.

6.4.5 Aquaculture

Mangroves provide favorable conditions for aquaculture, but this has resulted in increasing aquaculture ponds (gheris) in Bhitarkanika and adjoining mangrove areas (Mishra et al. 2008). Due to ongoing changes in coastal ecosystems, the marginalized local communities are not able to earn a livelihood from seasonal agriculture; hence, a shift of income from nonfarm sources, especially from aquaculture, has been observed in the recent decades (Banerjee and Pasha 2017). Aquaculture was reported in the region since the early 1990s that has affected the hydrology and sediment transport because of the use of very fine mesh that covers the pond and

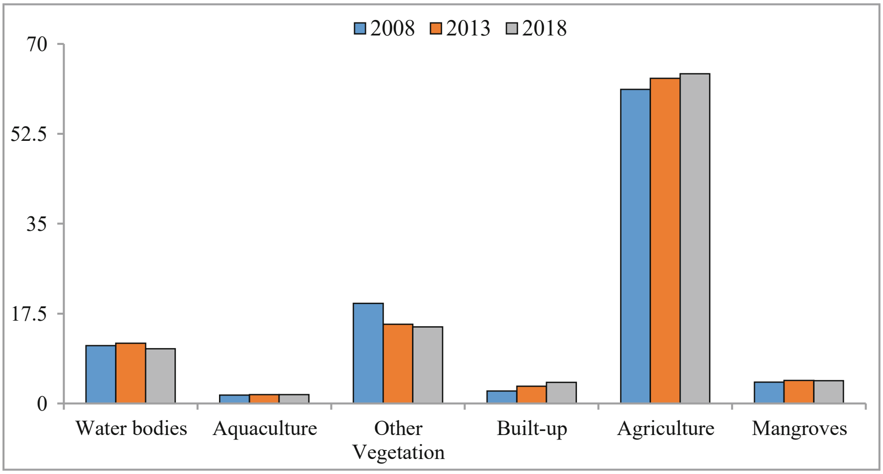

Fig. 6.4 Land-use change in Kendrapara and Jagatsinghpur districts of coastal Odisha (area in km^2)

restricts the free flow of the sediment. Between 1973 and 2006, net loss of more than 26 km^2 of mangroves was reported due to land-use changes with aquaculture being the predominant driver of loss. More than 9.39 km^2 of dense mangroves were reported to be converted to gheris, and land-use change to aquaculture was highest between 1973 and 1990 with more than 9.70 km^2 used in aquaculture land (Pattanaik and Narendra Prasad 2011). A twofold rise in aquaculture from 20.76 to 44.86 km^2 (216.08%) between 2002 and 2017 was reported in Bhadrak and Kendrapara coastal districts (Singh and Parida 2018). An extensive increase in illegal aquaculture close to natural mangrove patches exerts pressure and has been the key driver of overall mangrove loss of 7.10 km^2 between 1988 and 2013. Approximately more than 4 km^2 in 19 km^2 of Mahakalapada forest range of Bhitarkanika is lost due to illegal aquaculture (Barik 2019). Change in physicochemical properties of water laden with chemicals discharged from aquaculture ponds is harmful to the ecosystems and wildlife (Mishra et al. 2008). Though aquaculture without registration at Coastal Aquaculture Authority (CAA) is a punishable offense under Coastal Aquaculture Authority Act and Rules, 2005, and invites imprisonment and fines or both still, more than 2000 illegal gheris are already functioning in Bhitarkanika. Odisha Marine Fishing Regulation Act, 1982, also gives power for eviction and demolition of illegal aquaculture structures, and this has legally supported in reducing the impact of aquaculture of the region. Armed police patrol have been stationed close to the mangrove patches and creeks to reduce illegal clearing of mangroves for aquaculture in Bhitarkanika (Barik 2019).

6.4.6 Deforestation and Degradation

As per the state of forest reports by the Forest Survey of India, decadal change patterns in mangrove cover of the state from 1999 to 2019 show increasing trends (Table 6.2). This is also confirmed by our land-use change analysis for the two coastal districts of Odisha (Fig. 6.5). Still, there are diverse drivers of mangrove loss that are a threat to natural ecosystems and are forcing the site-specific loss of mangrove areas, compromising ecosystem health by disturbing community compositions and degrading habitat quality.

District-wise mangrove cover confirms dense mangrove cover restricted to only Kendrapara (Fig. 6.5). 80% of the mangrove cover is present in only Kendrapara district which includes both Bhitarkanika and Mahanadi delta mangroves followed by 14% in Bhadrak district of Odisha (Fig. 6.6).

It has already been projected that impacts of coastal zone degradation can lead to the extinction of *Sonneratia* sp. and *Bruguiera cylindrica* in the near future (Polidoro et al. 2010). However, habitat change is an alarming issue for Bhitarkanika. *Suaeda maritima* and *Acanthus ilicifolius*, two common invasive species, are observed to have fast proliferation indicating a threat to natural and native mangrove species. Many forest areas in the region are now having monospecific patches of low salinity-tolerant species which is a matter of concern. If the trend continues, Bhitarkanika may lose its status as the highest mangrove species ecosystem in India. The remaining mangroves are regenerating and comparatively young populations, largely monospecific, and are less diverse in nature. Significant reduction in nutrient-rich freshwater to mangroves in the region was further confirmed from long-term field studies. Due to mass felling and clearance of mangroves in the past, Sunei Rupei protected forest area is the most deforested mangrove patch in Bhitarkanika. Frequent removal of healthy mangroves and *Pandanus tectorius* that stands along the backshore and riverbanks of the Subarnarekha estuary on the east coast of Odisha has also been regularly reported (Roy and Datta 2018). These

Table 6.2 Change of mangrove cover in Odisha state from 1999 to 2019

Year of estimation	Very dense mangrove (km^2)	Moderately dense mangrove (km^2)	Open mangrove (km^2)	Total (km^2)
1999	–	–	–	210
2001	0	194	25	219
2003	0	160	47	207
2005	0	156	47	203
2007	82	97	42	221
2011	82	97	43	222
2013	82	88	43	213
2015	82	95	54	231
2017	82	94	67	243
2019	81	94	76	251

Source: State of forest report; http://www.fsi.nic.in

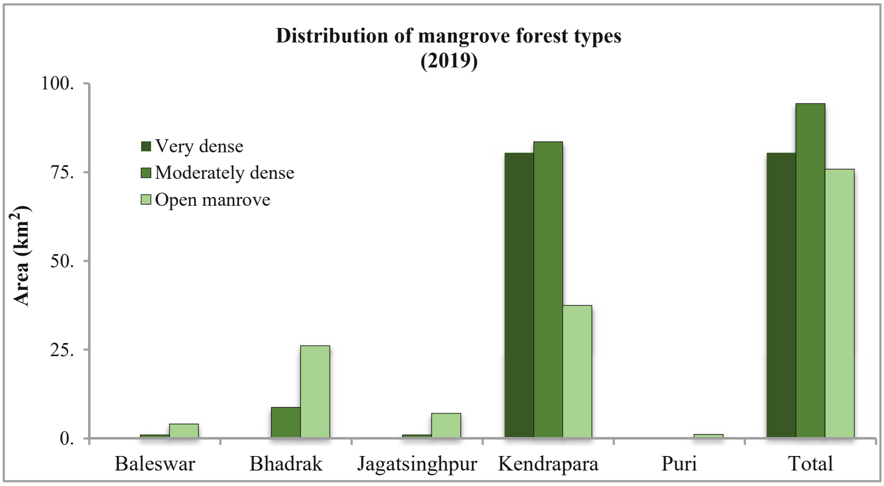

Fig. 6.5 District-wise distribution of mangroves (Odisha). (Note: Data adapted from, ISFR 2019)

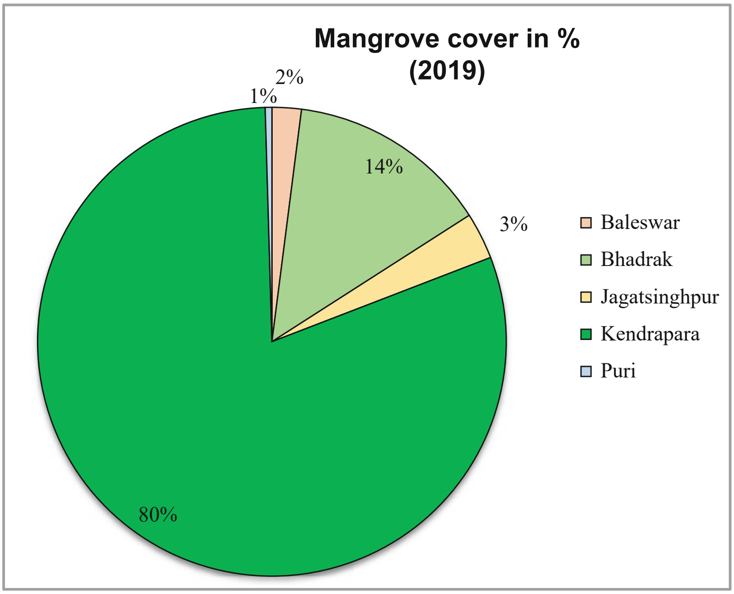

Fig. 6.6 District-wise percentage contribution to the total mangrove cover of Odisha. (Note: Data adapted from, ISFR 2019)

observations stress and indicate the alarmingly poor status of biodiversity and ecological composition of mangroves in the region due to the remaining monospecific stands of *Avicennia*. However, biodiverse old mangrove patches of *Avicennia officinalis*, *Avicennia marina*, *Excoecaria agallocha*, *Acanthus ilicifolius*, *Heritiera* *fomes*, and occasionally *Aegiceras corniculatum* are also reported to be existing in the region. Degradation and fragmentation diminish the capacity of natural mangroves to reduce the intensity of cyclones and storms resulting in the higher flow of tidal waters and greater erosion of sediment. This is especially alarming for Odisha where the frequency of coastal cyclones has increased and is expected to further increase due to climate change. Erosion and loss of sediment may also compromise the ability of mangroves to protect the shorelines from sea level rise that is again a risk for the coastline of Odisha (Bryan-Brown et al. 2020).

6.4.7 Agriculture Intensification

The use of fertilizers and synthetic pesticides in agriculture close to the mangrove growing areas has increased in the last few decades (the early 90s). Rampant use of chemicals is common both in paddy cultivation and aquaculture. There has already been an extension of agricultural land of 1115 ha in the area (Pattanaik and Narendra Prasad 2011). Other studies have also supported the extension of agriculture in Bhitarkanika by providing more evidence of this extension by 2436 ha (from 1973 to 2004) on the cost of dense (16 ha) and open mangrove cover (1518 ha) (Reddy et al. 2007). Between 1973 and 2004, 473 ha of dense mangroves were converted to 89 ha of agriculture expansion, whereas between 1988 and 2004, another 577 ha of dense mangroves were converted to largely 286 ha of agriculture. Loss of 1534 ha of mangroves and expansion of 2436 ha of agriculture inside the protected area boundaries indicate rampant enhancement of human-induced pressure in the last five decades. This also indicates limited livelihood opportunities available for coastal communities and settlement of immigrants that have affected the natural ecosystems and warrants attention from the government for income diversification efforts. It is important to mention here that if the business-as-usual (BAU) scenario continues in the region for a long time, there are clear projections that by 2030, there will be around twofold to threefold expansion in agriculture on the cost of 48% of mangrove patches with that of 2011 levels (Kebede et al. 2018; Hazra et al. 2020).

6.4.8 Port, Jetty, and Coastal Industrial Projects

Ports and jetties are other relevant drivers of mangrove loss in the region (Badola and Hussain 2005; Ambastha et al. 2010). The mangroves in Mahanadi delta, Devi estuary, Rusikulya estuary, Subarnarekha estuary, and Chilika lagoon have been degraded severely because of increasing human settlements, construction of Paradip port, Paradip Phosphate factories, and increasing aquaculture. Paradip port was developed after felling a large chunk of dense mangroves in Mahanadi delta (Nanda 2011). Presently one can only observe the remaining traces of past vegetation in the region (Panda et al. 2013).

6.4.9 Road and Waterways

The development of jetties and ongoing road construction is some of the emerging drivers of mangrove loss. Though roadways construction and settlement are mostly negligible in nature, an increasing trend of roadways in the last few years is a threatening indicator for the existence of existing mangroves in the region. 0.34% of the land use in Bhitarkanika is reported to be occupied by the roadways. The total change in the area occupied by roads between 2000 and 2015 in Bhitarkanika was 0.0185 km^2 which is about 9.90% of the total area (Banerjee et al. 2018).

6.4.10 Encroachment

Coastal zones and habitats of mangroves are legally protected from construction and are strictly prohibited because of the Coastal Zone Regulation Act, 2019.[4] However, land encroachment by shrimp mafias, land grabbing for tourism purposes by private operators, and brick kilns though at a small scale cannot be denied that was also observed during our field surveys. Encroachment of swampy areas for aquaculture, fish, and shrimp farming is increasing which is affecting the pristine mangrove patches significantly. Strict enforcement of government policies and regular patrolling of park forest officials can only handle and control the land grabbing and encroachment activities in Bhitarkanika and adjoining coastal areas. In the encroached areas, the tidal creeks are mostly blocked by bunds, which can prevent the influx of water natural tide and gradually result in loss of mangroves.[5]

6.4.11 Extreme Climate Events (Ex., Tsunami, Cyclones, and Floods)

In the last few decades, Odisha has been frequently facing the enhanced intensity of extreme climate events (e.g., tsunamis, cyclones, and floods, etc.) due to climate vulnerability that may further worsen because of widespread poverty (Bahinipati and Chandra Sahu 2012). Every year, the coastal areas of Odisha face severe cyclones and storms which result in a huge loss of coastal mangrove cover. Storm surge impact is highly pronounced in areas where mangrove patches have been lost or are facing degradation (Needham et al. 2015). According to a report by India Meteorological Department (IMD), Odisha has been hit by more than one-third of the cyclones (106 out of a total of 306 events) between 1891 and 2007 (Bahinipati

[4] http://www.indiaenvironmentportal.org.in/files/file/Final-CZMP-guidelines.pdf.

[5] http://odishawildlife.org/bhitarakanika.html.

and Chandra Sahu 2012). Tropical cyclones mostly emerge from the Bay of Bengal and have affected the entire eastern and southern Indian coast than the Arabian Sea (Sahu et al. 2015). Mangroves in the region are a defense to these strong cyclones, tsunamis, and high tides and have protected land and life along the coast of Odisha. It was reported that mangroves saved 0.0148 lives/hectare that otherwise would have been 1.72/village if mangrove width was reduced to zero (Das and Vincent 2009). However, in this process, the mangroves were substantially damaged and uprooted. Most of the uprooting was mostly observed for casuarina, palm, and coconut trees than mangroves, so, there is significantly less impact of natural drivers than exponentially rising anthropogenic and economic drivers on the loss of mangroves in the region. Odisha is also one of the most flood-prone areas, and Mahanadi delta faces frequent floods and waterlogging due to floods (Hazra et al. 2020). Storm surges reached as high as 6.1 m close to Bhitarkanika that have resulted in the submergence of around 2000 km^2 land area (Sahoo and Bhaskaran 2019). Around 45 villages around Bhitarkanika were worst affected in 2021 due to the Yaas cyclone.

6.4.12 Sea-Level Rise

Sea-level rise due to climate change is a serious concern as it may jeopardize not only the human well-being of coastal communities but will also affect the rich mangrove in the coming years (Hazra et al. 2020). Mangroves on the east coast of India have a gentle slope that makes the region extremely vulnerable to sea-level rise (Kathiresan 2018). The 480-km long coastline of the state along with Bhitarkanika is vulnerable to regularly increasing erosion of coastline (Kumar et al. 2010). The mean width of mangroves in 1999 was reported to be 1.2 km for 409 villages which was significantly less than 5.1 km of width reported in the year 1944 (Das and Vincent 2009). Around 10% of the littoral mangrove forests is approximately 15.44 km^2, 7% of the scrub forests corresponding to 0.366 km^2, and 12% of evergreen non-mangrove forest areas of approximately 0.251 km^2 of the total area in Odisha are in the very highly sensitive zone of inundation (Sahu et al. 2016). Kendrapara is already facing threat due to coastline erosion at the rate of 10 m/year increasing to a medium risk of 0.1–1.0 mm/year (Kumar et al. 2010). Four potential coastal erosion hotspots have been identified from the state with three of them Pentha, Gahirmatha, and Satabhya are close to Bhitarkanika. In a recent study, 26 coastal blocks (representing 30% of the total blocks in coastal districts of Odisha) were projected to be vulnerable to rapid erosion by 2050 (Mukhopadhyay et al. 2018).

6.4.13 Tourism, Pollution, Solid, and Hazardous Waste

In a recent study, ecotourism was endorsed and highlighted as an economic rescue option for many local villages in Bhitarkanika (Das and Chatterjee 2015). Many village-level institutions such as eco-development committees (EDCs) have been established in adjacent villages with locals as members of these committees. Many resorts in the region are managed by the Forest Department for eco-tourism purposes. Private operators and resorts in the park boundaries are having a considerable impact on the mangroves and their pristine environment. In an extensive study, prevalence and distribution of microplastics with an average size of 258.7 ± 90.0 particles/kg were confirmed from the beach sediment of Odisha coast (Patchaiyappan et al. 2021). Contamination of marine sediment at Paradip port, East Coast of India, was confirmed with the highest contamination factor and enrichment factor for Cd than other toxic trace metals (Satpathy et al. 2020). It is important to mention that total coliform bacteria and total viable bacterial load in sediment negatively affect the organic carbon, silt, and clay content of the sediment. In another study by Chauhan and Ramanathan (2008), a high concentration of dissolved trace metals was reported from Bhitarkanika. This confirms and provides evidence that mangroves in Bhitarkanika are experiencing enhanced threats from industrialization in the coastal zones. Brahmani with a drainage basin of 8570 km^2 has a peak discharge of 14,150 m^3/s, whereas Baitarni having a drainage basin of 8570 km^2 has a peak discharge of 14,150 m^3/s. These rivers are now the source of untreated domestic and industrial wastes to mangroves that include persistent organic pollutants, oil, and heavy metal from upstream areas (Chauhan and Ramanathan 2008). Untreated effluents discharged from aquaculture are equally affecting and having a damaging impact on aquatic fauna and the natural mangroves. Hormones and chemicals used in aquaculture also affect the wildlife residing in mangrove fringe forests. Aquaculture ponds in the fringe areas of Bhitarkanika regularly use brackish water from the Brahmani-Baitarani River system which is discharged into nearby mangrove patches. In a water quality assessment by Mishra et al. (2008), the aquaculture ponds in Bhitarkanika are required to follow permissible physicochemical parameters according to the standards of Bureau of Indian Standard (BIS) and Central and the State Pollution Control Board (PCB) that are violated many times.

6.4.14 Eutrophication and Ocean Acidification

Aquaculture requires brackish water supply that flows through feed channels and also supports irrigation of agriculture fields, which has become the driver of increasing soil salinity. Soil salinity has been continuously increasing which is negatively affecting soil fertility and promoting extensive use of fertilizers to enhance agriculture productivity (Mitra and Hazra 2017). High nitrate and phosphate have been reported from estuarine waters because of agriculture intensification as well as fertilizer plant at Paradip. Agriculture in the region involves heavy use of urea and diammonium phosphate-based fertilizers to enhance paddy productivity (Chauhan and Ramanathan 2008). The fertilizer plant at Paradip which is close to Bhitarkanika National Park produces around two million tons of DAP/NPK, 7000 TPD of sulfuric acid, and 2650 TPD of phosphoric acid per year[6] that might also be affecting water quality and degrading coastal mangrove diversity including marine and freshwater biodiversity. Extensive usage of pesticides like malathion, chlorpyrifos, and dieldrin; chemical additives like dioxins and polychlorinated biphenyls; antibiotics cephalothin, cephalexin, and tetracycline; and chemicals discharged in effluents like sulfides, nitrites, and ammonia were most commonly reported from local aquaculture to rivers flowing close to Bhitarkanika which are not only affecting the mangroves and wildlife but are also a potential threat to human health (Pattanaik and Narendra Prasad 2011). This continuous discharge of pollutants has already polluted the estuarine, and more focused research is required to assess their impact on the mangrove ecosystems (Upadhyay and Mishra 2008). The estuarine ecosystem of east coast also holds high concentrations of carbon dioxide (4–34,026 μatm) which is an alarming situation (Srichandan et al. 2019). Ocean acidification has been reported in the Bay of Bengal and cannot be ignored near Bhitarkanika with the presence of a fertilizer plant at Paradip, which might enhance the impacts (Ghosh 2019). Increasing sulfate and nitrogen aerosol deposition over the Bay of Bengal mostly during winters is increasing ocean acidity, and hence, the west coast that was earlier an important carbon sink is changing into the source of carbon dioxide to the atmosphere (Sarma et al. 2015). This has been further confirmed by increasing eutrophication on the west coast, and situations might be no different near Bhitarkanika (Yadav et al. 2016).

6.4.15 Invasive Species and Insects Pests

Existing mangrove strands in Bhitarkanika are having stunted growth, and many of these are monospecific dominated by mostly one species. Presently, a large part of Bhitarkanika during our field survey was observed to be covered by invasive and exotic halophytes. It is important to note here that increasing salinity due to aquaculture will further provide more suitable conditions for the invasion of these exotics in natural patches and that will be devastating for the existing mangrove species. Nearly 26 out of 80 potential Indian marine wood borers are also reported from the coastal mangroves of Odisha which are significantly affecting the mangrove tree wood in the region (Pati et al. 2013). *Hibiscus tiliaceus* in Bhitarkanika was reported to be substantially affected by the attack of *Sylepta derogata*, a leaf roller. The damage due to this leaf roller pest was reported to be more than 15% (Roychoudhury 2017).

[6] https://www.iffco.in/index.php/productionunit/index/paradeep.

6.4.16 Other Drivers

Changes in atmospheric chemistry, inundation frequency, temperature fluctuations, etc. are some of the emerging concerns for the region along with the main concerns. Mangroves of Odisha are river water supported; hence, reduced quantity and frequency of freshwater supply will significantly affect the species diversity, forest structure, and biomass production of mangrove trees (Selvam 2003). Due to the gradual decline in freshwater and tidal influx to the deltaic areas, most of the patches are already facing long periods of dryness that sometimes stretch to more than 6 months in a year. This long period of dryness has affected the populations of many exclusive mangrove species that were dominant historically. Across the coastal mangrove patches including Odisha, increasing coastal salinity has affected the existing populations of low salinity-tolerant mangroves and has led to their gradual loss, while *Avicinnea marina*, a high and broad range of salinity-tolerant species, has become dominant in the region (Selvam 2003). This is observed in Odisha where the natural populations of mangroves are sensitive to high salinity, viz., *Sonneratia apetala*, *Heritiera fomes*, *Xylocarpus granatum*, and *Nypa fruticans* are now not present in mangroves of Jagatsinghpur and Baleshwar, however, are only sparsely present in Bhitarkanika (Rajawat et al. 2015).

6.5 Endorsing Ecosystem Health Assessment

The present chapter provides a comprehensive analysis and in-depth information on the drivers and their locations where they are affecting the mangroves on the east coast of Odisha with a focus on Bhitarkanika and mangrove patches in the Mahanadi delta. Our analysis supports undertaking a systematic health assessment for Bhitarkanika according to the IUCN guidelines on the Red List of Ecosystems (RLE) to better understand the vulnerability status of the mangroves for proactive planning (Keith et al. 2013; Bland et al. 2019). This assessment will not only help to better understand the vulnerability of the ecosystem but also help to understand if the ecosystem is facing a situation of hidden collapse which is sometimes not obvious. The hidden collapse has been defined as a condition where an ecosystem appears to be intact, but prolonged degradation of ecosystem structure and functions, when coupled with long lag times for restoration, reflects collapse of the ecosystem structure and functions (Sato and Lindenmayer 2018). Regional conservation priorities that cover forest loss rates many times overlook fragmentation along with reduction of ecosystem functionality. Management of drivers of deforestation is crucial as they may augment as well as reduce the fragmentation of mangroves in Bhitarkanika. Our findings from this study and previous work suggest enhancing the monitoring efforts duly considering the fragmentation (Bryan-Brown et al. 2020; Kadaverugu et al. 2021). In this context, it is imperative to understand that lack of interactive policies that support the involvement of local communities in decision-making by respecting their role and livelihood concerns might jeopardize the ecosystem health in the region. The presence of poverty-ridden marginalized communities and lack of access to basic amenities like food and livelihood are mega hidden drivers of loss of ecosystems which need to be well understood. Hence, research on understanding diverse policy options that addresses and enhances policy effectiveness by taking stock of key enabling and constraining conditions can help to improve the policy efficiency, decision-making process, and effective enforcement of existing policies. In this regard, importance of capacity building using novel approaches, tools, and techniques should be used but that should not be limited to local communities but involve all important stakeholder groups including forest department, administrators, GOs, NGOs, CBOs, etc. While the country is serious about conserving blue carbon stocks of mangroves by developing participatory approaches, their involvement can help in collecting large-scale data and climate-sensitive restoration planning (Dhyani and Dhyani 2016; Dhyani et al. 2020, 2021). Community participation in REDD+ and PES (Payment for Ecosystem Services) has been a globally successful approach for bringing economic benefits to marginalized communities and addressing livelihood concerns for increasing blue carbon stocks. Degradation of mangroves by locals can be halted and checked by involving them as important stakeholders for carbon offsets and conservation payments by restoration and conservation of mangrove patches. The utilization of robust mathematical models in projecting the future of mangrove habitats through a scenario-based modeling approach will enhance policy decisions. This being a new research opportunity will also attract diverse researchers from multidisciplinary fields to engage in the field of mangrove conversation and promote the evidence-based assessment of ecosystem services by including sociocultural drivers. The involvement of ecologists along with the forest department in appropriate mangrove restoration areas becomes crucial to reduce the misuse of resources and enhance the success rates.

6.6 Conclusion

Loss of biophysical characters of any ecosystem is a critical indicator of loss of ecosystem health, liveliness, as well as pressure. The present chapter establishes that mangroves in Bhitarkanika and Mahanadi delta are vulnerable to ongoing changes and multiple drivers that are already affecting the ecological, financial, and social demands fulfilled by mangroves and will be furthermore affected in the future. Ongoing changes affecting the biomass and carbon stock of the region may have a lasting impact on regional ecosystem resilience. Biomass extraction for various purposes from various drivers indicates the biotic pressure areas because of harvesting of particular mangrove species and needs to be integrated into the disturbance regime map to prioritize conservation and restoration. Five important drivers of mangrove loss in the region are unsustainable economic growth, the exponential rise in population, rapid land-use changes, extreme climate events, and insufficient enforcement of policies. Our study stresses that Bhitarkanika and Mahanadi delta requires a comprehensive strategic approach that targets the reduction of impacts of mega drivers on the mangroves. Recognition and inclusion of traditional and indigenous rights in planning for conservation and management of mangroves are highlighted to reduce conflicts and enhancing local involvement in mangrove restoration. The local administration has a very important role in the enforcement of policy decisions, trust building for mangrove conservation and restoration by facilitating livelihood diversification opportunities, and reducing drudgery in local communities. Mangrove conservation and the restoration itself are an effective adaptive strategy that can act as a natural barrier to provide a wide range of ecosystem benefits, local livelihood opportunities for human well-being. Hence, involving local communities in carbon offset or conservation payments schemes can enhance both ecosystem and social integrity.

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Part II
Assessing Mangrove Ecosystem Services

Chapter 7
Advancement in Measurement and Estimation Methods of Blue Carbon Studies

Anirban Akhand, Abhra Chanda, and Rajarshi Dasgupta

Abstract Blue carbon and its storage for a long time in the coasts and estuaries are one of the most important natural ways to combat and mitigate ongoing threats of climate change. Hence, measurement and estimation of blue carbon storage and burial became extremely crucial for researchers throughout the globe. In the last few decades, many cut-of-the-age technologies have been developed for the estimation of blue carbon study. Mangroves, seagrasses, and salt marshes ecosystems have been unanimously accepted as blue carbon ecosystems. The principal compartments of blue carbon storage are aboveground biomass, belowground biomass, nonliving detritus, and sediment. Both destructive and nondestructive approaches have been considered as the conventional method of measuring and estimating blue carbon. Stable isotope and radioisotope techniques have widely been used in the study of blue carbon burial rates and source identification. Recent nondestructive methods have also been developed like remote sensing techniques. This chapter focuses on a comprehensive review of the conventional methods of blue carbon measurement and estimation along with recent advancements. This chapter also dealt with the future direction of the blue carbon measurement and estimation methodology.

Keywords Mangrove · Seagrass · Salt marsh · Detritus · Macroalgae · Dissolved organic carbon · Particulate organic carbon · Dissolved inorganic carbon · $p\text{CO}_2$(water) · Soil organic carbon

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A. Akhand (✉)
Coastal and Estuarine Environment Research Group, Port and Airport Research Institute, Yokosuka, Kanagawa, Japan

Department of Ocean Science, Hong Kong University of Science and Technology, Kowloon, Hong Kong, SAR, China

A. Chanda
School of Oceanographic Studies, Jadavpur University, Kolkata, West Bengal, India

R. Dasgupta
Institute for Global Environmental Strategies, Hayama, Kanagawa, Japan

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7.1 Introduction

The ongoing climate change has rattled the global scientific community. Scientists and policy managers all over the world are desperately looking for nature-based solutions to reduce carbon emissions and combat the evil of climate change. Blue carbon ecosystems in this regard have shown promising potential (Taillardat et al. 2018). The carbon sequestration potential of marine ecosystems has been long known to the scientific communities (Henson et al. 2017; Gattuso et al. 2018). However, the topic gained impetus ever since the term blue carbon was coined by Nellemann and Corcoran (2009). Blue carbon collectively refers to the carbon repository in the marine living setup, especially in the coastal vegetated ecosystems (Pendleton et al. 2012). Several pieces of research in the last few decades unequivocally indicated that coastal ecosystems like mangroves, seagrasses, and salt marshes are capable of storing disproportionately high quantities of carbon and much higher than any conventional carbon-rich terrestrial forested ecosystems (Alongi 2020). The vegetated coastal fringes are one of the dynamic regions of this planet and exhibit one of the most complicated biogeochemical dynamics (Luo et al. 2019; Neubauer and Megonigal 2021). The vegetation cover in these regions has developed a strong autotrophic potential (Collier et al. 2017) and can effectively act as filters to trap carbon generated from sources situated upstream or inland within the continents (Oreska et al. 2018; Hupp et al. 2019). Realization of the carbon sequestration potential of the blue carbon ecosystems triggered the necessity for their conservation and restoration, and at the same time, their enhancement to absorb significant quantities of CO_2 from the atmosphere.

One of the first and priority steps toward effective conservation and management of the blue carbon habitats is to generate an idea of the total blue carbon strength of a particular ecosystem and the pathways that lead to the input and exit of carbon from such ecosystems. Carbon exists in the form of different chemical species within the blue carbon ecosystems. The biomass of the autotrophic marine organisms, the underlying pedosphere, and the adjacent water column shelters carbon in various forms (Ridge et al. 2017; Krauss et al. 2018; Ricart et al. 2020). Thus, measuring the carbon content and monitoring their dynamics, both spatially and temporally, are of immense importance concerning the conservation of these crucial habitats. The measurement and analytical protocols involved in this domain have witnessed substantial changes in the past few decades. Several newer research questions are coming up with each passing day, and to answer them, novel approaches have become an urgent necessity. This chapter, in this regard, has tried to collate and discuss the present-day methodologies adopted in studying the blue carbon ecosystems. Early career researchers working in the blue carbon arena would find this chapter helpful, as all the crucial aspects are discussed under one umbrella.

7.2 Organic Carbon in the Biomass

7.2.1 Mangrove

Mangrove ecosystems thrive along the coastal intertidal stretches of the tropic and subtropics. These floral communities often grow in challenging terrains that are difficult to access. The aboveground compartment of this forest is comparatively simpler than many other terrestrial forested ecosystems. However, quantifying the carbon stored in the live biomass remains a tedious task even in the present date. Allometric estimation of aboveground biomass has been performed on several mangrove forests (Clough and Scott 1989; Clough et al. 1997). Several authors carried out region-specific measurements on the mangrove stands, like the height of the tree, diameter at breast height (DBH), and girth of the tree trunk (Fig. 7.1). They also measured the carbon content per unit volume of the tree by standard carbon estimation through a CHN analyzer. In most occasions, a linear or exponential relationship between these easily measurable parameters and carbon content per unit area of the forest could be figured out. Such estimation techniques vary across the type of forest and the unique characteristics of the particular forest type under the lens.

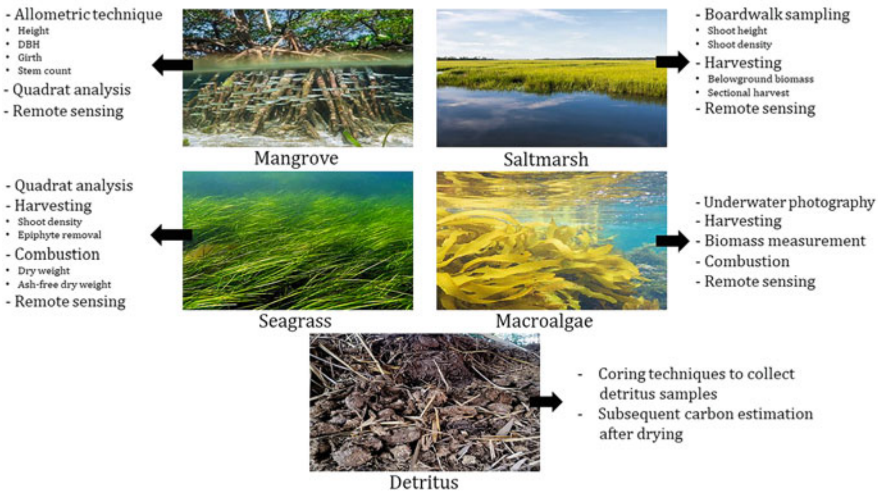

Fig. 7.1 A glimpse of the present-day techniques implemented to measure the carbon content locked in the biomass of the blue carbon ecosystems

7.2.2 Seagrass

Seagrass is one of the most important ecosystems in the long-term storage of blue carbon, and it can store up to 19.9 Pg organic carbon (Fourqurean et al. 2012). Hence, biomass estimation of seagrass is an important aspect for blue carbon study. Quadrat system is often used to count shoot density before biomass estimation of seagrass. Randomly placed quadrats are used for different species of seagrass' biomass estimation. The whole plant digging is used for efficient extraction of whole plant biomass as described in Duarte et al. (1998). To remove the epiphytes samples, seagrass is rinsed with distilled water and treated with dilute hydrochloride acid. The dry weight of the seagrass samples can be determined by drying the samples with 60 °C until the constant weight will be fixed. On the other hand, the ash-free dry weight of the samples can be achieved by combusting the dried samples in a muffle furnace at 550 °C. The reported above- and belowground biomass was comparable with a mean (± standard error) of 223.9 ± 17.5 and 237.4 ± 28 g dry weight m^{-2}, respectively. Hence, a general tendency for a balanced distribution of biomass between leaves and rhizomes to roots was reported as 1.11 ± 0.08 (Duarte and Chiscano 1999).

7.2.3 Saltmarshes

Studies on the biomass of saltmarshes are relatively lesser in number than the study of mangroves and seagrass. Monospecific stands of *Spartina alterniflora* were harvested for biomass estimation with 0.25 m^2 quadrat. The samples were collected from a series of boardwalks constructed for the ease of sampling and to minimize the damage of saltmarshes (Darby and Turner 2008). Thursby et al. (2002) proposed a novel nondestructive method for measuring the aboveground biomass of *Spartina alterniflora* and *Phragmites australis*. This nondestructive method uses the average height of the five tallest shoots and the total density of shoots over 10 cm tall. However, these estimates vary among intraspecific and interspecific saltmarshes. Data collection using this method takes a few minutes per replicate; however, calculated values for biomass are comparable with destructive measurements on harvested samples. Tripathee and Schäfer (2015) measured above- and belowground biomass, root and rhizome characteristics, leaf area index, and carbon to nitrogen ratio of various tissues of four species in New Jersey during pick growing season. They harvested aboveground biomass in 10-cm height increments, whereas for every 10 cm, biomass was separated into different components: fluorescence, green leaves, dead leaves, leaf sheath, and stem to measure the dry weight. Along with above-ground samples, they harvested belowground biomass by digging up to 55 cm below the soil surface. The harvested blocks were partitioned into 0–25, 25–40, and 40–55 cm depth from the soil surface for each sampling point. They randomly selected three average-sized plants and measured the diameter of the rhizome of every root at every node of the plant using a digital caliper from the uppermost belowground sampling block (25 cm^3). Root diameter was measured around the midsection of the root to account for slight variations in diameter along the root, whereas root surface area to volume ratio was estimated with the assumption that roots were approximately cylindrical.

7.2.4 Macroalgae

Whether macroalgae should be considered under blue carbon ecology is a still debated issue. Macroalgae stores a huge amount of carbon in their biomass; however, as macroalgae grow in the hard substratum, it hinders macroalgae to be considered as a long-term carbon sink. For this hard substratum, unlike other blue carbon ecosystems like mangroves, seagrasses, and salt marshes, macroalgae do not build large organic carbon-rich soil; rather macroalgae acts as a "donor" of organic carbon to the "receiver" blue carbon sites (Hill et al. 2015). On contrary, Krause-Jensen and Duarte (2016) reported that macroalgae growing in soft sediments have a global carbon burial rate of 6.2 Tg C $year^{-1}$. Setyawidati et al. (2018) used in situ techniques along with remote sensing to estimate percent cover, biomass, distribution, and potential habitat mapping of the three genera of macroalgae: *Padina*, *Sargassum*, and *Turbinaria*. The study was conducted during the low tide when macroalgae were air-exposed. The depth of the study site was recorded using a handheld depth sounder. Handwritten field notes survey and underwater pictures were taken as support to the digital data collected on a GPS data logger. Finally, the biomass of macroalgae was estimated following Mattio et al. (2008). Mattio et al. (2008) studied the diversity, biomass, and distribution pattern of *Sargassum* beds in South West lagoon of New Caledonia. They used a combination of remote sensing and in situ approach for estimating macroalgal biomass. Destructive sampling was carried out to identify floristic content from four random quadrats each with 0.25 m^2 was collected, sorted out species-wise, oven-dried at 60 °C for 48 h, and weighed to measure mean biomass per species and per station.

7.2.5 Organic Carbon in the Detritus

Tanaya et al. (2018) developed a novel box corer to retrieve intact cores which can preserve the structures of both sediments (including coarse sediments and dead plant structures) and living seagrasses. They measured seagrass density, total organic carbon mass, living seagrass organic carbon biomass, sedimentary organic carbon mass, and the stable carbon isotope ratio ($\delta^{13}C$) of sedimentary organic carbon and its potential organic carbon sources at *Thalassia hemprichii* dominated back reef and *Enhalus acoroides* dominated estuarine sites in the tropical Indo-Pacific region. They depicted that the trapping of organic matter in the water column and direct supply of belowground seagrass detritus is a major mechanism of sedimentary organic carbon accumulation in the seagrass meadows.

7.3 Forms of Blue Carbon in Water

The major blue carbon ecosystems stored carbon in the form of organic carbon in above- and belowground biomass, and in the underlying soil. However, the blue carbon lies in the water column, surrounding blue carbon ecosystems in the form of particulate organic carbon, dissolved organic carbon, and dissolved inorganic carbon. There is a knowledge gap in determining complex inorganic and organic biogeochemical processes which occur within the water column and determining CO_2 sequestration (Macreadie et al. 2019).

7.3.1 Particulate Organic Carbon (POC)

POC is considered a crucial parameter in the lotic carbon biogeochemistry adjoining the blue carbon habitats, like mangroves, seagrasses, and salt marshes. The water column adjacent to these blue carbon ecosystems often remains loaded with suspended particulate matter which, in turn, consists of substantial carbon in the particulate form. This parameter is of immense significance for those who are studying the inter-ecosystem pathways of carbon movement (Saavedra-Hortua et al. 2020). POC also undergoes interchange between the several blue carbon habitats when they are in the continuum. Thus, allocating the source of POC is fundamental in understanding the blue carbon dynamics in the water column and the sediment beds. POC undergoing burial is often measured by deploying sediment traps. POC in the water column is usually filtered followed by acidification to remove the inorganic counterparts of carbon (Table 7.1). Finally, an elemental analyzer (preferably a TOC or CHN analyzer) is used to measure the carbon content (Ray and Weigt 2018; Chen et al. 2020).

7.3.2 Dissolved Organic Carbon (DOC)

DOC comprises a plethora of organic compounds, and their concentration varies significantly spatiotemporally in the blue carbon habitats. Dittmar et al. (2006) advocated that mangroves act as a key source of DOC toward the oceans. Root exudates and pore-water exchange are usually the main pathways that lead to autochthonous DOC in the adjacent water columns of blue carbon habitats (Li et al. 2021). Pieces of research indicated that only a small fraction of the marine DOCs is highly recalcitrant and the remnants can participate in the microbial

Table 7.1 The present-day measurement protocols and instruments involved to monitor various forms of carbon in the aquatic column and the pedosphere of the blue carbon habitats

Parameters	Protocol/sample preservation	Instrument
Particulate organic carbon (POC)	– Sediment trap method (for quantifying burial) – Gravimetric filtration (for quantifying load in the water column) – Acid treatment to eliminate the inorganic carbon	– Mass spectrometer – Elemental Analyzer
Dissolved organic carbon (DOC)	– Filtration and subsequent reduction in pH by adding HCl/H_3PO_4	– TOC Analyzer (high-temperature catalytic oxidation)
Dissolved inorganic carbon (DIC)	– Unfiltered water treated with poison like $HgCl_2$ to prevent biological consumption – Estimation through CO2SYS software with the help of other data like pH, salinity, water temperature, total alkalinity, and nutrient concentrations	– Coulometer – Automated titrator (Gran plot titration; closed path mode)
pCO_2(water)	– In situ measurements directly with a sensor – Estimation through CO2SYS software with the help of other data like pH, salinity, water temperature, total alkalinity, and nutrient concentrations	– NDIR sensor fitted with equilibrator
Air–water CO_2 efflux	– Bulk formula method – Floating chamber method – Eddy Covariance method	– Floating chambers fitted with NDIR sensors – Sonic anemometers and NDIR sensors
Soil organic carbon (SOC)	– Coring technique to measure depth-wise SOC variation – Modified Walkley Black method	– TOC Analyzer – CHN Analyzer
Soil CO_2 efflux	– Closed chamber method	– NDIR Sensor – Soil temperature and moisture probes

consumption process (Hansell 2013; Lian et al. 2021). A substantial part of the labile DOC can mineralize into DIC (Ohtsuka et al. 2020; Volta et al. 2020) and actively participate in the CO_2 equilibrium dynamics. Thus, due to the reasons mentioned this far, DOC measurement has also become an essential component of blue carbon biogeochemistry. DOC is a very fragile parameter and requires meticulous sampling to get proper data. Filtration through cellulose acetate membrane followed by reduction of pH with HCl/H_3PO_4 to <2, and storage in dark and cold are some of the prerequisites. In the laboratory, DOC concentrations are measured by high-temperature catalytic oxidation with a TOC analyzer.

7.3.3 Dissolved Inorganic Carbon (DIC)

DIC forms the backbone of the carbonate chemistry in all the lentic and lotic ecosystems of the world. It is one of the critical parameters that is measured to monitor several crucial processes like gaseous exchange of CO_2, autotrophic activity, and so forth. The term DIC refers collectively to a group of chemicals that include the carbonate ion, bicarbonate ion, unstable carbonic acid, and aqueous CO_2. The constituents of DIC maintain a typical pH-dependent equilibrium (Oron et al. 2020). Under lesser pH, bicarbonate to pCO$_2$(water) conversion is more likely and vice versa. Thus, DIC variability plays a critical role in the air-water CO_2 exchange as well (Van Dam et al. 2018; Xu et al. 2019). DIC is measured by collecting samples in good-quality glass bottles and is usually poisoned with $HgCl_2$ to stop all sorts of biological activities involving DIC. It is measured by using either a coulometer or closed chamber auto-titration. Estimating DIC from other carbonate chemistry parameters like pH, total alkalinity, or pCO$_2$(water) is also practiced by many with the help of CO2SYS software (Xu et al. 2017). However, such estimations are associated with considerable uncertainties that need to be taken into account in any scholarly research involving DIC (Orr et al. 2018).

7.4 Carbon Sequestration in the Water Column

Submerged aquatic vegetations like seagrasses are generally net sinks for atmospheric CO_2. CO_2 absorption through the water column by the submerged aquatic vegetation can be considered as one of the major carbon sequestration pathways in the blue carbon ecosystem (Tokoro et al. 2014). There are three different methods through which carbon sequestration in the water column surrounding the blue carbon ecosystem has been measured, namely, the bulk formula method, floating chamber method, and eddy covariance method.

Several researchers implement the bulk formula method to characterize the air-water CO_2 exchange rates. The difference between the partial pressure or fugacity of CO_2 in the air [pCO$_2$(air)/fCO$_2$(air)] and the water surface [pCO$_2$(water)/fCO$_2$(water)] determines the direction of CO_2 movement across the air-water interface. When pCO$_2$(water) $>$ pCO$_2$(air), CO_2 is being emitted from the water surface, and under the reverse scenario, the water surface acts as a sink for CO_2. Besides this gradient, the factors that principally govern the rate of exchange are the wind speed, water current, salinity, and temperature of the water surface. Researchers usually compute a constant named the gas transfer velocity (k) based on empirical relationships between the CO_2 fluxes and the wind speed above the surface of the water (Wanninkhof 1992; Raymond and Cole 2001; Tokoro et al. 2014). When these studies are carried out in nearshore coastal seas or deep estuaries, wind speed-based gas transfer velocities are preferred. However, in shallow water bodies, the water current plays a crucial role in regulating the fluxes, and this parameter gains importance under such cases vis-à-vis wind speed. This method is relatively easy and cheap and goes well for long-term monitoring too. However, significant uncertainties lie in the fact that the relationships used to compute the gas transfer velocities are generated from observations carried out in different parts of the world. Hence, quantification of *k* on the study site is the best-advised approach, especially in the nearshore waters where wind speed and water current both play a critical role in regulating the fluxes; however, such techniques require sophisticated instruments manifold assembly (Raymond and Cole 2001; Tokoro et al. 2008, 2014; Ho et al. 2016). Direct quantification is often carried with the help of tracer gases that can be quantified in air and water, and hence empirical relationships can be formulated.

As an alternative to the bulk formula method, several researchers implement the floating chamber method. Tokoro et al. (2014) used a rectangular box made up of polyvinyl chloride with polystyrene foam floats. The pCO_2(water) analyzers are usually connected to the chamber by a Teflon tube that continually monitors the pCO_2(water) inside the chamber. The enhancement or depletion of CO_2 concentration within the chamber enables one to compute the air–water CO_2 fluxes in the floating chamber method (Frankignoulle 1988; Borges et al. 2004). This method has some advantages over the bulk formula method, as it can directly measure the fluxes and does not rely on any external constants. Hence, the confidence level of the flux measurements is much higher than the bulk formula method. However, these chambers are often difficult to handle under rough conditions. Physically disturbed situations often lead to air bubble intrusion within the chamber that leads to erroneous results. Moreover, this method is not suitable for long-term monitoring and cannot give us information over a large area that the eddy covariance technique can furnish (Tokoro et al. 2014).

The eddy covariance method considers the minute vertical movement of the gas volumes in the atmosphere and the changes in atmospheric CO_2 concentrations to quantify the air-water CO_2 fluxes. The principle of this method is based on characterizing the high-frequency vertical eddy diffusion regulated by the meteorological conditions of the atmosphere. This technique overshadows the other existing methods largely because it is a direct flux measurement method, and it can be easily deployed for long-term monitoring, and it covers a substantially large area. However, the spatial measurement range depends on the height where the sensors are deployed. Usually, the more the height, the larger is the coverage of the fluxes. The atmospheric stability and roughness length are crucial parameters that contribute to defining the spatial coverage of the fluxes (Schuepp et al. 1990). Usually, the spatial range varies from hundreds of m^2 to tens of km^2. The eddy covariance method has been widely implemented to monitor air-water CO_2 fluxes in the open oceans and nearshore waters (McGillis et al. 2001; Kondo and Tsukamoto 2007; Zemmelink et al. 2009; Polsenaere et al. 2012).

7.5 Soil Organic Carbon (SOC) and Soil CO_2 Efflux (SCE)

One of the specialties of the blue carbon ecosystems is their unique ability to hold and sequester substantial quantities of carbon in the pedosphere beneath these habitats (Miyajima and Hamaguchi 2019; Kida and Fujitake 2020). The autochthonous litter production and trapping of upstream carbon lead to varying magnitudes of soil organic carbon pool in the mangrove, seagrass, and salt marsh habitats. Depth profiling of carbon is necessary to understand the rate of change in carbon storage over time and also the total content (Gao et al. 2019; Chen et al. 2020). Deforestation or habitat degradation takes a heavy toll on the SOC content of these ecosystems (Arias-Ortiz et al. 2021). Thus, measuring SOC in blue carbon habitats has received substantial attention from the scientific community. Usually coring up to 1 m depth is considered customary to have an idea of the SOC pool. Dissecting the cores at chosen depths allows us to figure out the depth-wise variation in SOC. The modified Walkley-Black titration method is used by many; however, in the present day, it is largely getting replaced by the use of advanced TOC/CHN analyzers.

The substratum of the topsoil is usually rich in microbes and experience favorable oxic conditions that enable the soils to respire CO_2 back to the atmosphere. In the case of seagrasses and salt marshes, the anoxic substratum facilitates long-term sequestration of carbon. However, most of the mangrove soils are found to be emitters of CO_2 toward the atmosphere when remaining exposed (Ouyang et al. 2017). SCE rates allow us to infer the present status of carbon oxidation in these habitats. Measurement of SCE is usually carried out by closed chamber methods where the increase in CO_2 concentration is automatically monitored at specified time intervals to compute the efflux rates (Cameron et al. 2021). Soil temperature and moisture are two essential regulators of CO_2 efflux from mangrove soils (Capooci and Vargas 2022). Nowadays, coupled instrument manifold assemblies are available that simultaneously measure the SCE, soil temperature, and moisture that allow the scientific communities to model the relationships with high confidence levels.

7.6 Determination of the Source of Blue Carbon

Stable isotopic analyses have lately gained importance mainly to characterize the sources of carbon in the conventional blue carbon ecosystems like the salt marsh, seagrass, and mangrove. The natural stable isotopic ratio of common elements like ^{13}C, ^{15}N, and ^{34}S has been put to use to detect and compute the source of blue carbon in any particular reservoir. Studies indicate that these ecosystems often store carbon that is produced by the system itself and sometimes they trap and sequester carbon produced somewhere else. The differentiation of the allochthonous and autochthonous organic carbon sources is impossible without stable isotopic analyses. Latest advancements in this field can also quantify the relative contributions to long-term carbon burial within the blue carbon habitats. The stable isotopic techniques are usually cost-effective, and the protocols involved in sample preparation and subsequent analysis are easy to follow. Several researchers all over the world have successfully validated the outcomes from this type of analysis (Bianchi et al. 2016). However, going deep down the subject, one can realize that this type of analysis has significant shortfalls and limitations too. The organic world of the present day is composed of diverse materials that further complicate the issue of segregating the blue carbon sources, especially when varied sources have similar stable isotopic signatures. Similarly, the same source under different conditions might exhibit varying isotopic values that lead to ambiguities in explaining the outcomes, and it is hard to resolve such issues (Kramer et al. 2017; Canuel and Hardison 2016). This is why the global scientific community is advocating the analysis of trademark compounds within specific taxa along with the bulk analysis of stable isotopes to fine-tune the outcomes and enhance the confidence levels. In this regard, several organic compounds naturally found in the organic forms such as lignins, tannins, humins, and several lipids, alkanes, and amino acids are used as biomarkers to differentiate the carbon inputs from multiple sources in the blue carbon habitats (Bianchi et al. 2016; Upadhayay et al. 2017). Latest advancements have enabled the scientific community to study compound-specific stable isotopes. This technique facilitates the use of radiocarbon techniques to additionally comment on the age of the deposited carbon in a particular blue carbon compartment (Canuel and Hardison 2016). Geraldi et al. (2019) indicated the future possibility of implementing hydrogen and oxygen stable isotopes to characterize the carbon sources in the blue carbon ecosystems; however, their potential in this regard remains to be explored. Their utility is quite proven and tested in the domain of food-web-related studies. However, several researchers raised concerns on understanding the isotopic changes that might or might not take place during the decomposition of organic matter, as these changes can significantly modify the species-specific signatures (Kramer et al. 2017). It is undeniable that the stable isotopic approaches to a large extent met the shortfalls of the studies that exclusively focused on the natural abundance of various carbon types in specific compartments and could not comment on their source due to major overlaps. However, Oakes and Eyre (2014) mentioned that the applicability of these practices is so far tested to be good for short-term burial. Further studies are required to develop these techniques into a newer level to comment on the long-term changes in the burial rate. Lately, various scholars pushed forward the concept of environmental DNA to characterize the species composition in coastal ecosystems; however, the fruitfulness of this approach to quantify the carbon sources in the taxonomic level in the marine sediments remains to be tested (Geraldi et al. 2019). Contradicting results have surfaced from the eDNA and conventional stable isotopic studies. For example, Reef et al. (2017) observed that seagrass DNA encompassed close to 90% of the DNA repositories in the underlying seagrass bed sediments, and the remaining came from a mixed source of mangroves, freshwater marshes, and salt marshes. The contribution from these other sources varied significantly spatially. However, the mixing models using bulk stable isotopic analyses indicated a substantially lower contribution of seagrass to the carbon buildup in the seagrass bed sediments. At the same time, the confidence level of characterizing the carbon sources from other sources was poor as this method could not properly differentiate between the stable isotopic signatures of the varied possible sources that could potentially contribute to the carbon load in the seagrass bed sediments.

7.7 Lateral Flux of Blue Carbon

Lateral carbon fluxes from the blue carbon ecosystems to the deep sea and their long-term deposition have been seeking much attention from the scientific community recently. Maher et al. (2018) showed that the export of dissolved inorganic carbon (DIC) and alkalinity is approximately 1.7 times higher than burial as a long-term carbon sink in a subtropical mangrove system. This long-term CO_2 sink should be incorporated into the blue carbon paradigm when assessing the role of these habitats in sequestering carbon and mitigating climate change (Maher et al. 2018). Similarly, total alkalinity export to the open ocean from the blue carbon ecosystem is another aspect of the blue carbon repository (Sippo et al. 2016; Saderne et al. 2021). Different approaches have been taken to estimate lateral transport of carbon species from the blue carbon to ecosystems to the coastal ocean; among those, the biogeochemical mass modeling approach is often used (Ray et al. 2018; Akhand et al. 2021). Santos et al. (2021) emphasized the renaissance of Odum's outwelling hypothesis in "Blue Carbon" science. They advocated that lateral fluxes of carbon from blue carbon habitats toward the ocean can serve as a long-term sink, and the magnitude of carbon thus stored in the deeper abyss of the oceans might supersede the carbon that remains buried in the blue carbon substratum. Santos et al. (2021) pointed out that the general understanding of this issue is still in its infancy and with more data in near future, this aspect might become an inseparable part of blue carbon science.

7.8 Conclusion

With each passing day, the need for correctly quantifying the carbon stock in vegetated ecosystems of this planet is becoming dire, given the present scenario of climate change. Carbon locked in the biomass of the marine ecosystems is often difficult to measure owing to the difficulty in physically accessing them. Moreover, destructive methods permanently damage a part of the ecosystem. Though such an approach causes insignificant harm, it is always advised not to disturb the ecosystem while sampling. Thus, remotely sensed data are becoming more and more popular. However, extracting something meaningful from remote data also requires a fair amount of ground-truthing. Aquatic and sediment carbon measurements have become much advanced, and the confidence level of the data has enhanced significantly over the past few decades. Automation of the sensors and measurement of critical parameters on the field itself are some of the areas, which are under the lenses. Several global, regional, and local level policy-making decisions on marine habitat conservation are formulated based on the carbon stock of such ecosystems. Thus, the quantification of carbon stock and its regular temporal monitoring require sufficient attention from the scientific community.

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Chapter 8
Change Mapping of Aboveground Carbon Stocks and Ecosystem Services in the Mangrove Forest of Andaman Islands: Implications for Conservation and Ecosystem-Based Adaptation

Anukul Nath, Chitiz Joshi, Nehru Prabakaran, Sonali Ghosh, and Gautam Talukdar

Abstract Mangroves are globally recognized for their ecological, social, economic, and cultural significance. In recent years, data and assessment on carbon storage in tropical forests including mangroves have significantly improved. However, site-specific evidence as in the case of tropical islands and low-lying coastal zones where climate change effects are likely to be severe is lacking. This paper evaluates the change of carbon stock and its spatial variation in the mangrove ecosystems of Andaman Islands in India. The study highlights the mangrove cover change (2005–2019) and systematically reviews the variation in aboveground biomass of mangrove ecosystems in Southeast Asia. Our results showed that the mangrove cover significantly decreased from 2005 to 2010, largely due to the Indian Ocean tsunami and geomorphic changes associated with tectonic processes in the islands. The dense mangrove cover had declined by 92 km^2 between the years of 2005 and 2010 and then increased by 37 km^2 between the years of 2010 and 2019. The average aboveground vegetation carbon stock of mangroves was found to be $86.41_{Mean} \pm 59.82_{SD}$ t C ha^{-1}. In regard to ecosystem service, we estimated that the monetary value of AGB carbon stock is US$424.62 million. Our map delivers a valued tool for assessing carbon stocks and highlighting priority areas for conservation, EbA Ecosystem Based Adaptation, and restoration interventions. The present study also addresses the knowledge gap present in the ecosystem service dimensions of a major mangrove system in India, which can contribute to reliable and informed decision-making in mangrove management.

A. Nath · C. Joshi · N. Prabakaran · G. Talukdar (✉)
Wildlife Institute of India, Dehradun, India

S. Ghosh
Ministry of Environment Forest and Climate Change, New Delhi, India

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Keywords Aboveground biomass · Mangrove cover change · Ecosystem service evaluation · Tectonic uplift · Tsunami · Mangrove management · Ecosystem based adaptation (EbA)

8.1 Introduction

Mangroves are highly productive ecosystems located at the inference between sea and land. They play a vital part in the biogeochemical cycles of the coastal environment (Jennerjahn and Ittekkot 2002; Feller et al. 2003). Mangroves are globally recognized for their ecological, social, economic, and cultural significance. Mangroves offer a myriad of ecosystem services including habitat for a number of coastal fauna; are source of fishes, crabs, oysters, and non-timber forest products; act as a barrier against coastal erosion, cyclones, storms, and tsunamis; and have high carbon storage vegetation (Alongi 2014; Spalding et al. 2014). The ecosystem services provided by mangroves with an estimated economic value of more than US$900,000 per km^2 annually (UNEP-WCMC 2006) are indicative of their importance. The recent past has witnessed an exponential spurt in research on mangroves and their associated ecosystem (Lee et al. 2014). However, mangroves are disappearing globally at an alarming annual rate of 0.16–0.39%, primarily due to anthropogenic pressures (Hamilton and Casey 2016), and nearly 46% of mangroves were lost globally within a span of few decades (Romañach et al. 2018).

The increase in greenhouse gas emissions and the resulting economic loss induced by climate change have led to a growing interest in minimizing the atmospheric carbon levels (Parry et al. 2007). Vegetation cover across the globe can play a crucial role in mitigating the climate change effects as they naturally sequester carbon for their growth and development. Mangroves are especially recognized as an important element in the global measures to mitigate climate change. Recent studies have highlighted that the carbon sequestration potential of mangroves per unit area is the highest among any forest ecosystem in the world (Alongi 2014; Donato et al. 2011; McLeod et al. 2011). Therefore, the carbon storage and sequestration add additional impetus for the mangrove conservation. This appeal is even more significant since climate change is intensifying (Parry et al. 2007), and international agreements are being signed to decrease and offset greenhouse gas emissions.

Mangrove forests contribute to a mere 0.7% of tropical forested area globally but provide a disproportionate amount of ecosystem services. Despite providing myriad ecosystem services, mangroves are highly threatened due to sea level rise and accumulative pressures from human population growth across its distributional ranges. The increased scientific knowledge on mangroves in the recent decades has contributed to the policy level changes toward mangrove conservation in few countries (Dahdouh-Guebas et al. 2021). However, though mangrove carbon stocks were recently estimated at global/regional and local scales (Alongi and Dixon 2000; Hutchison et al. 2014; Harishma et al. 2020), till date, these have not been fully incorporated into policy perspectives for the management of larger coastal or island landscapes.

In South Asia, India has the second largest mangrove coverage spanning a total area of 4975 km^2 along its vast stretch of coastline (8118 km), which has rich coastal biodiversity and supports the livelihood of millions of people. The mangrove cover is widespread on the East Coast of India because of its distinctive geomorphological settings (Ragavan et al. 2019). In the eastern part, mangroves in the Andaman Islands—that account for 12.3% (614 km^2) of the total mangrove cover in India (FSI 2019)—are recognized as the most pristine due to their high species richness and luxuriant growth (Dagar et al. 1991). The canopy heights of mangrove forest in the Andaman Islands often exceed from 20 to 30 m, hence rivaling the biomass of the tropical evergreen forests. However, like many other island ecosystems, the mangroves in the Andaman Islands are also vulnerable to disturbances and have experienced an increased frequency of natural disasters (e.g., storms, cyclones, earthquakes, tsunami) and anthropogenic land-use change in the recent past (Yuvaraj et al. 2014).

The Kyoto Protocol 1997 was mounted on the principle that carbon dioxide from the air can be sequestered in biomass and soil and applied to mitigate climate change. More specifically, blue carbon sinks that include coastal habitats like salt marshes, seagrass, and mangrove forests are ranked in the order of carbon sinks. These habitats are the most carbon-rich forests in the tropic (Duarte et al. 2005). Thus, the mangrove ecosystem is presently being radical as a vital component of the climate change strategies such as blue carbon and REDD+. Reducing emissions from deforestation and forest degradation creates a monetary value for the carbon stocked in the ecosystem by offering incentives for developing countries to decrease emissions from forested lands and capitalize on low-carbon paths to sustainable development. REDD+ goes further than merely deforestation and forest degradation and comprises the role of conservation, sustainable management of different forest ecosystems, and enhancement of carbon stocks. The social cost of carbon (SCC) represents the economic cost linked with climate damage (or benefit) resulting from the emission of an additional ton of CO_2 (Ricke et al. 2018).

Several studies in the recent past have highlighted the mangrove species diversity, density, biomass, and the impact of disturbances on the mangroves of Andaman (Mall et al. 1991; Goutham-Bharathi et al. 2014; Kiruba-Sankar et al. 2018). Yet, carbon storage and other ecosystem services provided by the mangrove forest in these Islands are poorly documented (Chand et al. 2013). In general, the inventory of carbon stocks in mangrove forests of India is scanty (Pandey and Pandey 2013; Sahu et al. 2016; Suresh et al. 2017), and very few studies have attempted to determine the monetary value of the ecosystem services provided by mangroves. It is noteworthy that the increased frequency of natural disasters and developmental pressures in the Andaman Islands can adversely affect the future of its mangrove forests and the associated ecosystem services. Therefore, understanding the vegetation dynamics and land-use changes in mangroves is vital for quantifying carbon stocks and carbon sequestration and mapping the vulnerability of ecosystem services. These are important to develop and implement local and national policies linked to climate change mitigation and mangrove conservation (Harrison et al. 2014). The remoteness of the Andaman Islands and the scarcity of ground data can be a major impediment to assessing the ecosystem services and carbon stocks. The advancement in ecosystem service modeling that integrates relevant ecological processes into the classification of spatial and temporal distinction can negate the abovementioned impediments (Nelson et al. 2010). In the present study, the monetary values of carbon stock and its spatial variation in the mangrove ecosystems of Andaman Islands in India were evaluated using remotely sensed data and GIS applications. Additionally, the variation in the aboveground biomass of mangrove ecosystems in Southeast Asia has also been reviewed to highlight the importance of island ecosystems as in the case of Andaman Islands.

8.2 Study Area

The Andaman archipelago that comprised of more than 300 islands is situated between 10° to 14°N and 92° to 94°E (Fig. 8.1). These islands are divided into north, middle, and south Andaman. The islands witness both southwest and north-east monsoons, the earlier occurring from May to October and the latter in November and December. The mean annual rainfall is 3180 mm, and the average number of rainy days is 127 in a year. The temperature varies between 23 °C and 37 °C. Forest cover in the Andaman Islands has an area of 5336.61 km^2, which is 83.28% of its total geographical area (FSI 2019). The Andaman Islands are part of

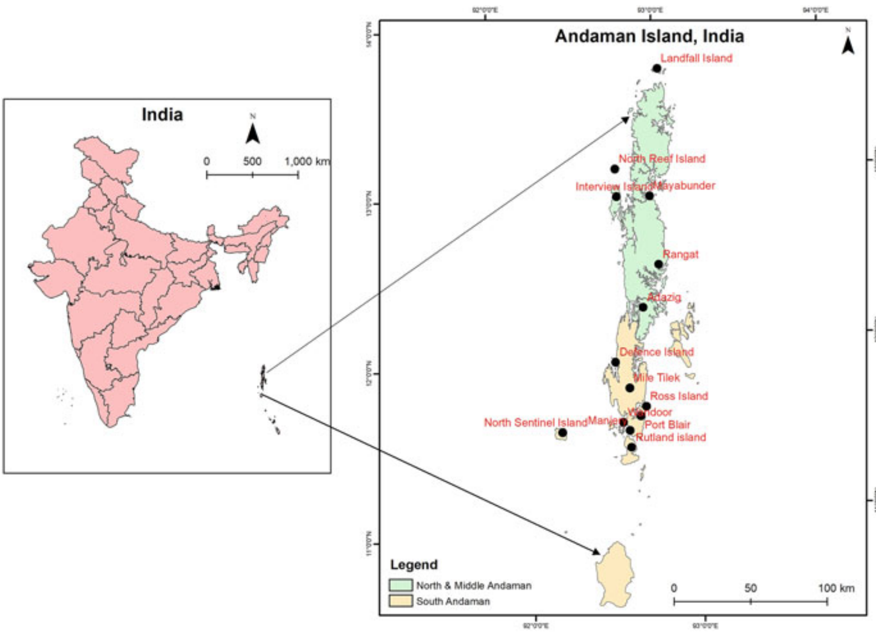

Fig. 8.1 Map showing the study area: Andaman Islands group

the Indo-Burma hotspot. Several studies have highlighted the mangrove floristics of the Andaman Islands (Roy et al. 2009; Ragavan et al. 2019; Ragavan et al. 2015). The Andaman Islands consist of 38 true mangrove species, which is ~50% of the true mangrove species in the world (Ragavan et al. 2019). The Shannon diversity index that ranges from 1.65 to 2.24 indicates the rich diversity of mangroves in the Islands (Kiruba-Sankar et al. 2018). The total mangrove tree density and stand basal area in Andaman Island were 1252–2200 ha^{-1} and 30.8–59.6 m^2 ha^{-1}, respectively (Kiruba-Sankar et al. 2018), and *Rhizophora apiculata* was found to be one of the most dominant species (Kiruba-Sankar et al. 2018).

8.3 Methodology

8.3.1 Delineation of Mangrove Cover

We used multi-temporal remote sensing satellite data to delineate the mangrove cover of the Andaman Islands. The mangrove cover map of Andaman is prepared for the three-time periods (2005, 2010, and 2019) to understand the spatial extent of the mangrove. The cloud-free satellite data of LANDSAT TM 5 (2005), LANDSAT TM5 (2010), and LANDSAT 8 (2019) was used to map changes in the spatial extent of mangroves (Table 8.1). The dataset is downloaded from the United States Geological Survey (USGS) Earth Explorer Programme website (https://earthexplorer.usgs.gov/).

The mangrove cover map of Andaman is classified at 1:50,000 scale. The satellite image was classified for mangroves based on visual interpretation key and differentiated from other coastal and terrestrial vegetation based on tone (bright red, greenish, pale red), texture, shape, location, and association (intertidal area/along the creeks and low-lying flats) following Nayak and Bahuguna (2001) (see Fig. 8.2). The detailed interpretation key used for the classification of mangrove vegetation using satellite data is given in Table 8.2.

Additionally, we used our field experiences along with the aid of high-resolution satellite data available in *Google Earth* during the visual interpretation. A Vector Map of the 2019 mangrove forest at the scale of 1:50,000 was prepared by interpreting two-time period satellite data of LANDSAT 8. Since the mapping scale was 1:50,000, the minimum mappable unit (MMU) was derived as 3 × 3 mm. The mangrove cover map for the year 2019 was taken as the base/master

Table 8.1 The details of cloud-free satellite data used in the study

Date of pass	Satellite	Sensor	Path/row	Resolution (m)
19/02/2019	LANDSAT 8	OLI/TIRS	134/51, 134/52, 134/53	30
02/11/2019	LANDSAT 8	OLI/TRS	134/51, 134/52, 134/53	30
26/02/2010	LANDSAT 5	TM	134/51, 134/52, 134/53	30
12/02/2005	LANDSAT 5	TM	134/51, 134/52, 134/53	30

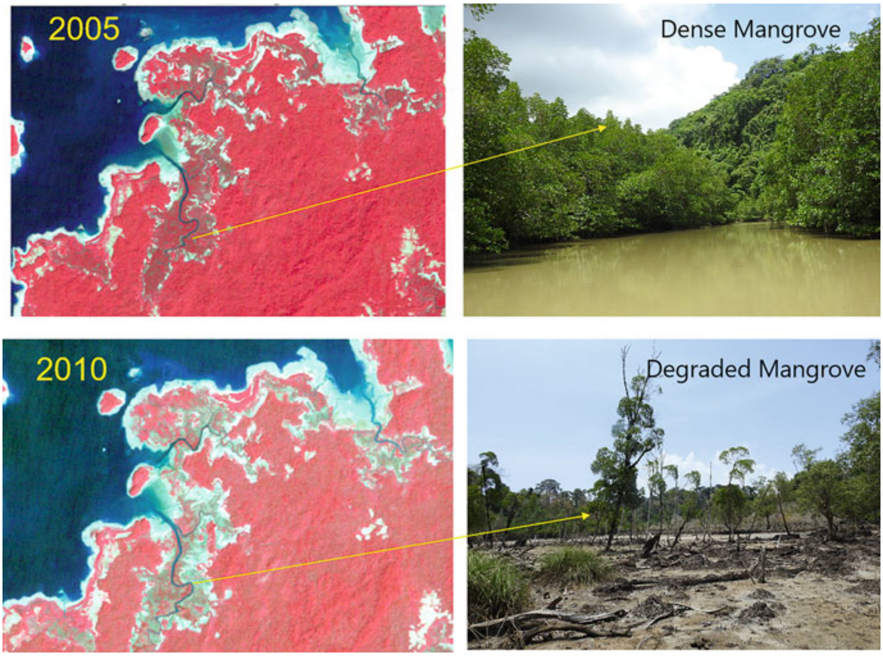

Fig. 8.2 Identification of different classes (dense and degraded) of mangroves using tone, color, and the texture of satellite image in the Andaman Islands

Table 8.2 Interpretation key for the identification of different mangrove classes of the Andaman Islands from satellite imagery

Mangrove classes	Tone	Shape	Texture	Pattern	Association
Dense mangrove	Bright red	Regular	Smooth	Noncontiguous	In the inter tidal area/along the creeks and low-lying flats
Degraded mangrove	Greenish, pale red	Irregular	Smooth	Noncontiguous	In the inter tidal area/along the creeks and low-lying flats

map for preparing the mangrove map of 2010 and 2005. A copy of this map was overlaid on the preceding year's (2010) satellite data of LANDSAT 5 TM, and changes were mapped. The two were registered as having uniform projection parameters. The map's mangrove class polygons overlaid over the same mangrove class onto the satellite data. The mangrove polygon on the map was edited to generate a new set of polygons depending upon the variability. Similarly, the 2010 mangrove map was overlaid over the satellite image of LANDSAT 5 TM (2005), and polygon was modified according to the satellite data to generate the mangrove cover map of 2005.

8.3.2 Accuracy Assessment

Accuracy assessment of mangrove change in Andaman Island for the year 2019 was performed using an error matrix. Standard methodology was adopted for accuracy assessment which is based on error/confusion matrix (Congalton 1991; Lillesand et al. 2004). The mangrove change map of the Andaman Islands has three classes (dense mangrove, degraded mangrove, and others) for which each class was assigned 50 points. Ground truthing was done using high-resolution satellite image of Google Earth. The overall accuracy, producer's accuracy, and user's accuracy were computed using a confusion matrix. The overall accuracy was calculated by dividing the total number of correctly classified pixels by the total number of reference pixels. The accuracy assessment for the years 2010 and 2005 was done only for change detection, since 2019 vector data is put over the satellite image of 2010 and only changes were mapped. Similarly, 2010 vector data was put over a satellite image of 2005, and changes were mapped.

8.3.3 Aboveground Biomass and Carbon Stock Calculation

The global dataset of aboveground biomass (AGB) for the mangrove ecosystem that was prepared based on the in situ field measurements and remotely sensed data by Simard et al. (2019) was used for the current study. Simard et al. (2019) used the GLAS lidar altimetry dataset collected globally from 2003 to 2009 to measure mangrove stands. Subsequently, spatially explicit AGB, derived from space borne sensors and in-situ measurements take into consideration of local-scale environmental and geophysical conditions (Simard et al. 2019). The resolution of the dataset is 30 × 30 m. For the present study, we have extracted the values of AGB from each pixel from the datasets as mentioned above and model (fourth-order polynomial: $AGB_{MANGROVE} = -13.21 + 14.22_{DEM} - 1.5180_{DEM} + 0.2779_{DEM} - 0.0072_{DEM}$) with the SRTM elevation dataset for the three different time periods (2005, 2010, and 2019) for the Andaman Islands. Initially, we have created a scatter plot with AGB of mangrove and elevation data and successively fit the models in increasing order and test the significance of regression coefficients at each step of model fitting. The total above biomass estimates for the Andaman Islands were generated by summing all corresponding pixels.

The carbon stock was calculated by multiplying the biomass values with the conversion factor 0.5 (IPCC 2006) based on the assumption that the biomass is made up of 50% carbon. The monetary values for carbon stock for three different periods were calculated following Ricke et al. (2018). The total annual carbon stock was converted to tons of carbon, and the social cost of carbon (US$86) was applied (Ricke et al. 2018). The social cost of carbon was used to represent the economic cost associated with climate damage (or benefit) resulting from the emission of an additional ton (t) of carbon dioxide.

Furthermore, we systematically searched the following keywords—aboveground biomass, AGB, mangrove carbon stock, and country names (southeast Asia) in *Google Scholar*—to retrieve the peer-reviewed articles for the comparative analyses of aboveground biomass in different mangrove ecosystems.

8.4 Results

8.4.1 Change in Mangrove Cover

Our results showed that the mangrove cover has significantly decreased from 2005 to 2010, and major loss was noticed in the northern part of the Andaman Islands. These changes in mangrove forests occurred after the December 2004 tsunami. Initially, the loss of classified degraded mangrove was marginal, and it was estimated at ~40 km^2 (in 2005). However, our classified map of 2010 showed extensive mangrove loss (decrease in dense mangrove and subsequent increase in degraded mangrove) in northern and southern parts of the Andaman Islands. In 2019, the aerial extent of dense mangrove vegetation showed a significant decrease of 92 km^2 from 2005 (686.21 km^2) to 2010 (593.69 km^2), followed by an increase of 37 km^2 from 2010 to 2019 (631.62 km^2) (Fig. 8.3). The degradation of mangroves started just after the tsunami, gradually showing a major increase in degraded mangrove from 2005 (39.93 km^2) to 2010 (137.78 km^2) and a minor decrease in 2019 (92.04 km^2). Presently, the mangrove forest cover showed marginal recovery in some parts of the islands (Figs. 8.4 and 8.5). The most affected areas were Hudson Bay, Duncan Bay, Jerotong Nala, Elizabeth Bay, Radhanagar Nala, Beele Bay, and Buchanan Bay, in which the mangrove cover has changed drastically in the northern Andaman (Fig. 8.5). In addition, mangrove of the south Andaman in and around Port Blair Tehsil and northern part of Little Andaman Tehsil has also degraded (Fig. 8.6). In 2019, the overall accuracy of our classified map was measured at 92.6%. Accuracy assessment for the years 2010 (86%) and 2005 (84%) was done only for change

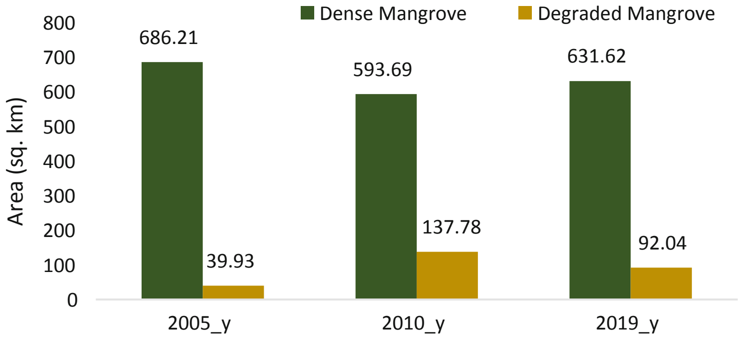

Fig. 8.3 Mangrove cover of Andaman Islands during 2005, 2010, and 2019

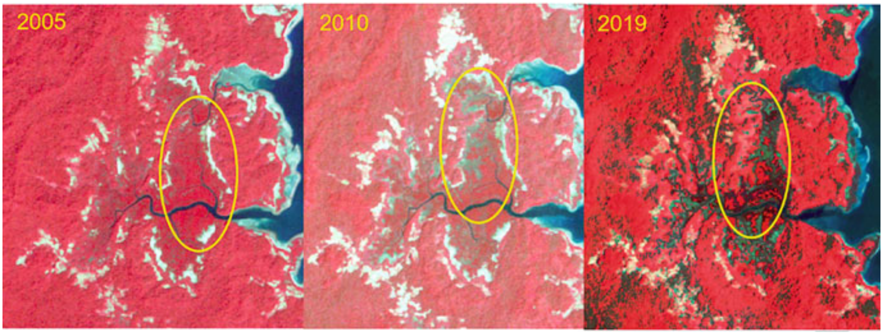

Fig. 8.4 Satellite image showing degradation of mangrove vegetation from 2005 to 2010 and slight recovery in 2019

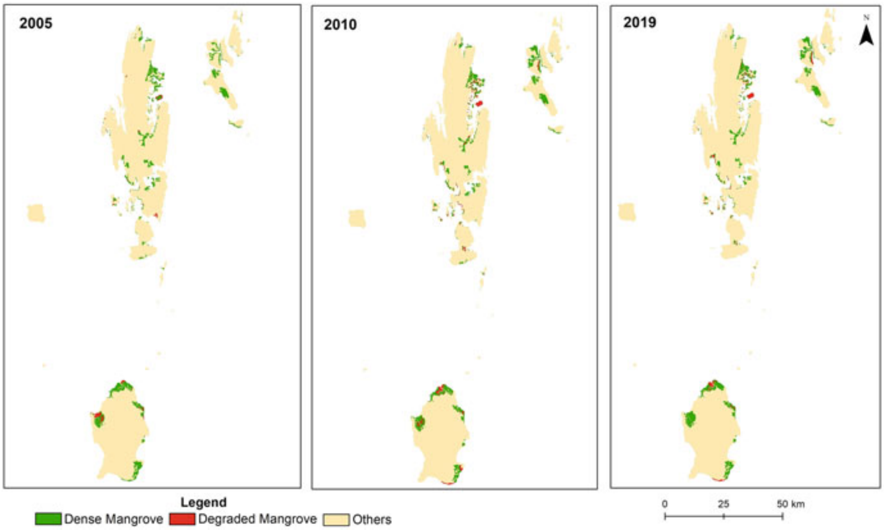

Fig. 8.5 Mangrove cover map of North and Middle Andaman (time periods: 2005, 2010, and 2019)

detection since 2019 vector data was put over the satellite image of 2010 and changes were mapped.

Estimation of AGB and Carbon Stock The mangrove aboveground biomass for three different periods has spatiotemporally varied (Fig. 8.7). As per the distribution of mangrove in 2019, the mean AGB stored in mangrove vegetation of Andaman Islands was $172.82_{Mean} \pm 119.65_{SD}$ t (or Mg) ha^{-1}, and the average vegetation carbon stock of mangroves was found to be $86.41_{Mean} \pm 59.82_{SD}$ t C ha^{-1}. The total carbon estimated for three different periods is as follows: 4,937,467.11 t (2019),

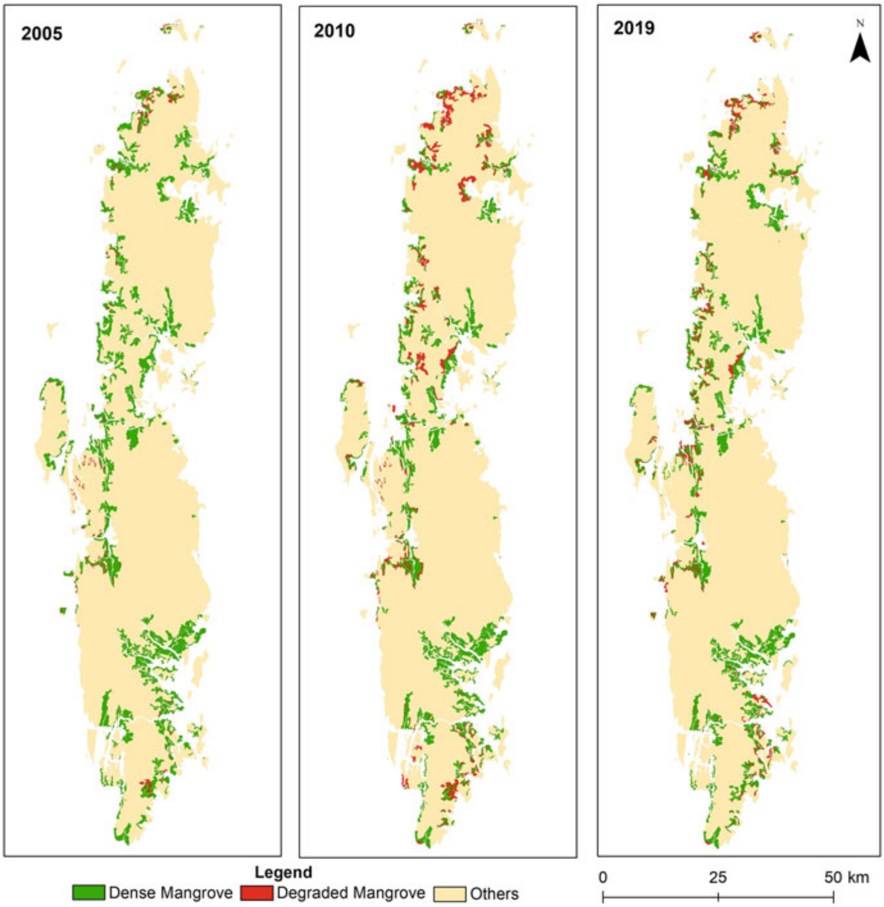

Fig. 8.6 Mangrove cover map of South Andaman (time periods: 2005, 2010, and 2019), India

4,765,890.90 t (2010), and 5,751,127.95 t (2005). Regarding the value of carbon storage, we estimated that US$ 424.62 million (2019) are stored in the AGB of the Andaman mangroves. The negative rate of change (2005–2019) in the monetary terms estimated was US$0.0832 million year^{-1}.

Comparison of AGB in Different Mangrove Ecosystems of Southeast Asia Our search on the AGB of mangrove ecosystems in Southeast Asia yielded 50 peer-reviewed articles that showed wide variation at local and regional levels (Table 8.3). Significant variation in AGB was reported among the different species and within the same species at different zones, for example, *Avicennia marina*: 52.3 ± 10.3 t ha^{-1} (Ayeyarwady Delta, Myanmar) and 21.14 t/ha (West Bengal, India). In Malaysia, the AGB varies from 98.4 t ha^{-1} to 460 t ha^{-1}, and Kuala Selangor National Park, Matang, and Kelantan Delta possess large AGB per hectare compared to other

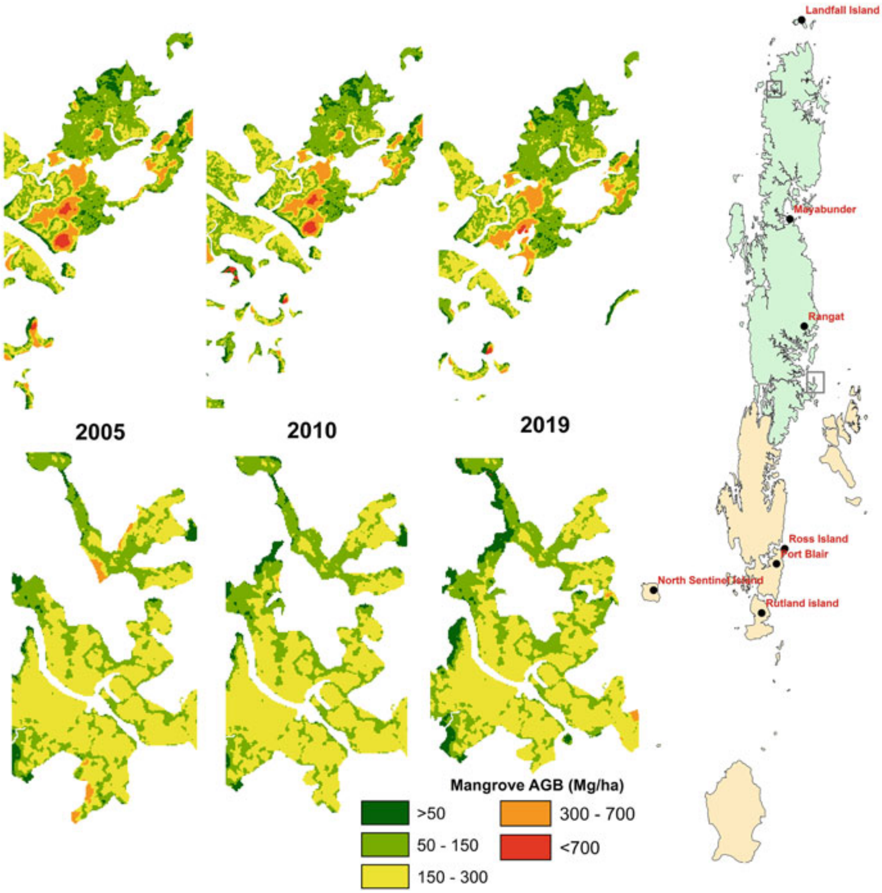

Fig. 8.7 Spatial variation of aboveground biomass in the mangrove ecosystem of Andaman Islands (periods: 2005, 2010, and 2019), India

mangrove ecosystems. Studies also reported the association of mangrove stand age and the AGB. In the Philippines, the AGB was reported to be significantly higher in the 40-year-old stand (823.7 t ha^{-1}) than the 15-year-old stand (463.4 t ha^{-1}). Additionally, the closed canopy mangrove forest has a higher AGB (158.4 ± 13.3 t ha^{-1}) than the open canopy (68.8 ± 8.9 t ha^{-1}) forest. Similar findings were also reported from Thailand about AGB—25-year-old forest: 344 t DW (dry weight)/ha, two 3-year-old forests, and one 5-year-old forest: 42 to 65 t DW/ha. In Indonesia, the mangrove species in the protected area (PA) have higher AGB than mangroves that stand in the unprotected area. The difference in biomass in the Coral Triangle ecoregion of Indonesia was reported for the three species of mangroves inside and outside protected area as follows: inside PA (*R. apiculata* 651.60 ± 54.68 t ha^{-1}, *R. mucronata*: 232.11 ± 34.27 t ha^{-1}, and *C. stagal*: 162.61 ± 22.89 t ha^{-1}) and

Table 8.3 Comparison of aboveground biomass (AGB) of mangrove ecosystem in Southeast Asia

Country	Area, site	Aboveground biomass	Source
Malaysia	Kuala Selangor National Park	305.46 t/ha	Zhila et al. 2014
	Matang Mangrove	*Rhizophora apiculata*-460.0 t/ha	Putz and Chan 1986
	Kota Marudu, Mangrove Forest, Maruda Bay	98.4 t/ha	Faridah-Hanum et al. 2012
	Langkawi Mangrove Forests	115.1 t/ha	Ozturk et al. 2017
	Sarawak Mangrove Forest	*Rhizophora apiculata:* 116.79 t/h	Chandra et al. 2011
	Kelantan delta, Eastern Malaysian Peninsular	*Avicennia alba*: 297.81 t/ha	Muhammad-Nor et al. 2019
	Sungai Haji Dorani	122.78 t/ha	Zhila et al. 2014
	Sabah Mangrove, Borneo island	196.88 Mg/ha	Wong et al. 2020
Philippines	Bahile mangrove forest, Palawan	561.2 t/ha	Abino et al. 2014a
	Botoc mangrove forest, Samar	401.07 t/ha	Abino et al. 2014b
	Banacon Mangrove forest, Bohol	15-year-old stand: 463.4 t/ha; 20-year-old stand: 332.2 t/ha; 40-year-old stand: 823.7 t/ha	Camacho et al. 2011
	Honda Bay Mangroves	Closed canopy: 158.4 ± 13.3 Mg/ha; Open canopy: 68.8 ± 8.9 Mg/ha	Castillo et al. 2018
Myanmar	Ayeyarwady Delta	*Avicennia officinalis*: 46.8 ± 11.6 Mg/ha; *Avicennia marina*: 52.3 ± 10.3 Mg/ha; *Sonneratia apetala*- 101.0 ± 17.1 Mg/ha	Thant et al. 2012
Singapore	Northwest coast	163.72 MgC/ha	Friess et al. 2016
	Southern islands (Pulau Semakau)	36.57 MgC/ha	
	Northeastern coast (Pasir Ris)	105.42 MgC/ha	
	Pulau Ubin	226.90 MgC/ha	
India	Kerala	189.26 ± 97.80 t/ha	Vinod et al. 2019
	Kerala	117.11 ± 1.02 t/ha	Harishma et al. 2020
	West Bengal	Aboveground stem biomass: *Sonneratia apetala*-19.79 t/ha, *Excoecaria agallocha*: 5.83 t/h, *Avicennia alba*: 20.22 t/ha, *Avicennia marina*: 21.14 t/ha, and *Avicennia officinalis*: 6.70 t/ha	Saha et al. 2019

(continued)

Table 8.3 (continued)

Country	Area, site	Aboveground biomass	Source
	West Bengal	Aboveground biomass ranges from 8.9 t/ha to 50.9 t/ha. *A. alba* 34.5 t/ha and *A. marina* 26.5 t/ha	Joshi and Ghose 2014
	Odisha	The highest mean total biomass 777.20 Mg C/ha	Rasquinha and Mishra 2021
	West Bengal	Stem biomass: Western region: 22.10 t/ha for *E. agallocha* to 111.39 t/ha for *S. apetala*; Central region: 22.10 t/ha for *S. apetala*, 9.79 t/ha for *E. agallocha* and 16.45 t/ha for *A. alba*	Mitra et al. 2011
	Odisha	Aboveground biomass: 70 t/ha to 666 t/ha	Ghosh and Behera 2021
	Andaman Islands	Mangrove biomass (*Rhizophora* spp.): 8.52 t/ha (wood) Oralkatcha: 113.62 t/ha (wood) Nilambur: 33.08 t/ha (wood); Kadamtala: 14.22 t/ha (wood)	Singh et al. 1987
	Andaman Islands	Standing biomass of two natural stands: One dominated by *Rhizophora* spp.: 124 Mg/ha other have mixed association of species (*Bruguiera*, *Lumnitzera*, *Avicennia*, *Rhizophora*, *Sonneratia*, and *Xylocarpus*): 214 Mg/ha	Mall et al. 1991
Bangladesh	Dhangmari, Karamjol, and Ghagramari areas	154.8 ± 3.5 Mg/ha	Kamruzzaman et al. 2017
Thailand	Phuket	151 t/ha	Christensen 1978
	Sawi Bay	AGB: 25-year-old forest: 344 tDW/ha, two 3-year-old forests and one 5-year-old forest: 42 to 65 tDW/ha	Alongi and Dixon 2000
	Ranong Province	250 ± 53.4 Mg/ha	Jachowski et al. 2013
	Ranong Province	Estimated stand biomass: *Rhizophora* spp.: 364.308 t/ha; other species: 34.495 t/ha	Tamai et al. 1987
	Satun Province	*Ceriops tagal*: 53.35 t/ha (stem)	Komiyama et al. 2000
	Ranong Province	91.3 t/ha to 497.6 t/ha	Hirata et al. 2010
Timor-Leste		Mean Standing biomass: 237 tDW/ha	Alongi 2014

(continued)

Table 8.3 (continued)

Country	Area, site	Aboveground biomass	Source
Indonesia	Aceh Province (Banda Ache)	Total Biomass: 4317 g/tree (*Rhizophora apiculata*: 2198 g/tree *Rhizophora mucronata*: 2119 g/tree)	Dewiyanti et al. 2019
	Enggano Island, Bengkulu Sumatra	*R. apiculata*: 60.21 t/ha, *B. gymnorrhiza* 138 t/ha, *X. granatum* 20.82 t/ha, *S. alba* 38.02 t/ha)	Awn et al. 2016
	Ciletuh mangrove forest, West Java	31.78 t/ha	Kusmana et al. 2019
	Mimika district, Papua province	314.37 ± 172.62 Mg/ha	Aslan et al. 2016
	Sinjai District, South Sulawesi	261.41 ± 194.75 Mg/ha	Malik et al. 2020
	Mentawir Village, East Kalimantan	103.36 tons/ha	Kristiningrum et al. 2019
	Rawa Aopa Watumohai National Park of coral triangle ecoregion, Southeast Sulawesi	*R. stylosa*:454.45 to 722.92 ton/ha	Analuddin et al. 2020
	The Coral Triangle ecoregion, Southeast Sulawesi	ABG of *R. apiculata*, *R. mucronata* and C. *stagal* in protected areas: 651.60 ± 54.68 t/ha, 232.11 ± 34.27 t/ha, 162.61 ± 22.89 t/ha, respectively. AGB of *R. apiculata*, *R. mucronata*, and *C. stagal* in an unprotected areas: 139.30 ± 30.52 t/ha, 189.35 ± 38.17 t/ha, 38.98 ± 9.32 t/ha, respectively	Kangkuso et al. 2018
	Parang island, Karimunjawa Islands	Mangrove biomass: 10.91 ton	Hartoko et al. 2015
	Bama Resort, Baluran National Park, Java	ABG (399.7 ± 447.2 Mg/ha)	Asadi and Pambudi 2020
	Segara Anakan, Central Java, Indonesia	Aboveground biomass for 2001 and 2013, respectively, with mean 359 Mg/ ha and 547 Mg/ha	Sasmito et al. 2013
Vietnam	Hai Phong city	Aboveground biomass: 87.67 Mg/ha	Pham et al. 2018
	Nam Dinh, Thai Binh, and Hai Phong	The mean aboveground biomass of Nam Dinh, Thai Binh, and Hai Phong is 51.58 Mg/ha, 79.90 Mg/ha, and 72.31 Mg/ha, respectively	Pham et al. 2020a
	Mangrove forests of Hai Phong city	AGB for *Sonneratia caseolaris*: 2.75 and 161.51 Mg/ha and for *K. obovata* 27.6 to 209.20 Mg/ha	Pham et al. 2017

(continued)

Table 8.3 (continued)

Country	Area, site	Aboveground biomass	Source
	Can Gio	mean above ground biomass-97.54 Mg/ha	Pham et al. 2020b
	Thai Binh Province coastal area and Xuan Thuy National park	Average AGB is 34.7 ton/ha ranging from 8.6 ton/ha to 111.3 ton/ha	Nguyen et al. 2019
	Vinh Quang village, Tien Lang district of Hai Phong city	AGB for *Sonneratia caseolaris* ranged between 2.78 and 298.95 ± 1.99 Mg/ha, with an average of 55.80 ± 1.99 Mg/ha	Pham and Yoshino 2017
	Coastal areas of Thai Binh and Nam Dinh provinces in Northern Viet Nam	Mean AGB values ranges from <1 Mg/ha to 115.38 Mg/ha	Cuc and Nguyen 2021
World	Eastern and Southern Africa	Mean aboveground biomass: 136.4 t/ha	Hutchison et al. 2014
	Middle East	110.4 t/ha	
	South Asia	136.4 t/ha	
	Southeast Asia	230.9 t/ha	
	East Asia	107.2 t/ha	
	Australia and New Zealand	132.9 t/ha	
	Pacific Islands	233.3 t/ha	
	North and Central America and the Caribbean	145.3 t/ha	
	South America	185.7 t/ha	
	West Africa	177.8 t/ha	
	Central Africa	184.8 t/ha	
	Global	184.8 t/ha	

outside PA (*R. apiculata* 139.30 ± 30.52 t ha^{-1}, *R. mucronata*: 189.35 ± 38.17 t ha^{-1}, and *C. stagal*: 38.98 ± 9.32 t ha^{-1}). The variation in AGB due to species composition and different mangrove ecosystems was reported in most of the ecoregions of Southeast Asia.

8.5 Discussion

Our results depicted that the mangrove cover and the carbon stock have significantly decreased in the northern and southern parts of the Andaman Islands after the tsunami. The total area under dense mangroves in 2005 was around 10.70% of the total geographical area of the Andaman, which decreased to 9.26% in 2010 and then showed a marginal increase of 9.85% in 2019. The degraded mangrove forest cover was higher in 2010 compared to 2005, and a steady slow recovery was observed in recent years. Earlier studies have also reported that the major changes in mangrove forests were associated with the December 2004 tsunami (Dharanirajan et al. 2007;

Majumdar et al. 2019; Ramakrishnan et al. 2020). After the tsunami, reduction in the tidal inflow into the mudflat and the following geomorphological changes linked with the conversion of certain hydrological settings could have resulted to the large-scale mangrove destruction (Dharanirajan et al. 2007; Ramakrishnan et al. 2020). The mangrove degradation in South Andaman is attributed to the high frequency of seawater inundation due to the land drowning/subsidence of up to 1.1 m (Dharanirajan et al. 2007). Similar to our findings, a prior study has also identified mangrove-bearing areas (Bay of Port Monat, Shore Point Creek, Colinpur, Dundas Point, Tirur, and Imlidera Point) in South Andaman those submerged after the tsunami (Dharanirajan et al. 2007). On the other hand, the landmass of North Andaman was uplifted by up to 1.35 m causing reduced tidal water influx into mangrove zones resulting in the degradation of mangrove forests (Malik et al. 2020; Ramakrishnan et al. 2020). Just like with our observations on North Andaman, Ramakrishnan et al. (2020) reported the loss of 65 km^2 area (2003–2019) of mangrove forest. In addition, the island has shown a tilt toward the east (Meltzner et al. 2006) affecting the mangrove on the west coast of the island in areas around Elizabeth Bay, Shyamnagar, and Kishori Nagar regions of Diglipur Tehsil. We also observed that the mangrove degradation was a slow process and is a secondary consequence of earthquake or is associated with tsunami. The effect of the tsunami on the mangrove vegetation has been seen slowly after two to three years (Ramakrishnan et al. 2020). The mangrove cover showed a marginal decrease in the first few years since the mangrove forest in the intertidal zone could survive on the moisture, salinity, and other significant nutrients present in the soil even after ground uplift and partial subsidence (Dharanirajan et al. 2007; Ramakrishnan et al. 2020). As per our results, the area under degraded mangroves has increased more than threefold within 5 years (from 2005 to 2010). The recent increase of mangroves in several sites, including northern and southern Andaman, can be attributed to the combined effects of natural regeneration and restoration projects implemented by the forest department.

The degradation of mangrove forests directly impacted the aboveground biomass of the study site. From 2005 to 2019, we estimated around 14% loss in total AGB of mangrove. The AGB of mangrove ecosystems in South Asia and Southeast Asia is reported to be 136.4 t ha^{-1} and 230.9 t ha^{-1}, respectively (Hutchison et al. 2014). The average AGB (172.82 t ha^{-1}) computed for the present study is comparable with studies carried out in Southeast Asia. Besides, Hutchison et al. (2014) measured the average global AGB of mangroves was 184.8 t ha^{-1}. Our search from different ecoregions of Southeast Asia showed several factors that could influence the AGB of mangrove forests—species composition, stand age, protection status, and degradation due to natural or anthropogenic causes (Woodroffe 1982; Singh et al. 1987; Camacho et al. 2011). Previous studies from Andaman have already reported the change in mangrove aboveground biomass associated with species composition and disturbance regime. Mall et al. (1991) reported AGB of two natural stands—one dominated by *Rhizophora* spp.: 124 t ha^{-1} and the other with mixed association of species (*Bruguiera*, *Lumnitzera*, *Avicennia*, *Rhizophora*, *Sonneratia*, and *Xylocarpus*): 214 t ha^{-1}. Subsequently, in a managed forest (undisturbed-old stand), the biomass was 239.4 t ha^{-1} in comparison with 69.4 t ha^{-1} in unmanaged (disturbed) mangrove forests of Andaman Islands (Singh and Odaki 2004). They have also mentioned that a significant amount of biomass production of managed forests of Andaman represents an older stand protected from human destruction. Therefore, the higher AGB of mangroves growing in the protected area indicated a suitable condition compared to an area outside with high anthropogenic pressure.

We could not verify our predicted aboveground biomass with the on-ground field sampling. However, our estimate on AGB falls within the estimate of a prior field study done in Andaman (Singh et al. 1987) and is comparable with the estimated AGB of South and Southeast Asia (Hutchison et al. 2014). Secondly, the detection and extent of mangrove change depends on the spatial scale; the higher the spatial level of detail, the larger the changes in the areal extent of mangrove cover which can be detected and recorded. Here, the chances of error in classification have increased manifold because of the different satellite imageries used in the study. Previous studies reported a loss of 80 km^2 mangrove in northern (65 km^2; Ramakrishnan et al. 2020) and southern Andaman (15 km^2; Dharanirajan et al. 2007). However, the study of Ramakrishnan et al. (2020) had not mentioned the degraded mangrove. A study carried out by Majumdar et al. (2019) from Middle Andaman reported a loss of dense mangrove by 64 km^2 (2000–2010), and a subsequent increase of 48 km^2 area was reported (2010–2018). Therefore, the total loss reported for dense mangrove pre (2000) and post (2018) tsunami measured was 15 km^2 (Majumdar et al. 2019). Forest Survey of India (FSI) reported an area of 54 km^2 to decrease in the mangrove area from 2004 to 2013 for the entire Andaman and Nicobar Islands and 13 km^2 only for the Andaman Islands. Our present estimate, including both dense and degraded mangroves and studies carried out in the past, suggests an underestimation of mangrove loss by FSI. However, the different approach adopted in the classification of mangrove and different time intervals makes it difficult to reach a precise conclusion.

The loss of mangrove vegetation after the tsunami has significantly impacted the ecosystem services, as shown in the rate of change in carbon valuation in the last 14 years. Besides, the substantial loss of mangrove vegetation has already indicated its effect on marine species, where fishermen have reported a significant reduction in the catch of fish, crabs, and shrimps (Ramakrishnan et al. 2020). Mangroves are tenfold superior to manmade defense systems in dealing with climate-associated disasters (Chand et al. 2013). Previous studies reported that the economic evaluation of Andaman mangroves was worked out to be more than INR. 125 million per year (Chand et al. 2013). The value of goods and services harvested per household per year was more than INR 61,000. Similarly, they have also revealed that the value of mangroves per hectare in the islands was more than INR 0.2 million (Chand et al. 2013). The monetary evaluation of ecosystem services is dynamic, and studies have taken into account different approaches. Besides, assigning a monetary value to an ecosystem service is heavily dependent on the precision of scientific measurements. We thus position ourselves cautiously with respect to the market mechanisms and the possibility of offsetting emissions. The estimated monetary value (US$ 424.62 million) derived in this study is much lower than other published figures as we have not incorporated major carbon stock for belowground biomass and soil carbon in the forested mangrove areas. Mangroves accumulate carbon in tree biomass, but then again, a considerable amount of this carbon is lost by way of various anthropogenic activities, namely , clear-cutting and human use, disintegration, and dissemination to adjacent ecosystems. However, over the long run, carbon is mainly stored belowground as soil carbon and, in time, under the right conditions, as peat. Therefore, in the future, studies should also consider soil carbon and belowground carbon stock for the Andaman Islands for a better estimate of valuation.

8.6 Policy Implications

Indian mangrove ecosystems are legally protected under the Indian Forest Act of 1927, several state forest acts, the Forest (Conservation) Act of 1980, the Wildlife (Protection) Act of 1972, the Coastal Regulation Zone (CRZ) Notification (2011) under the Environmental Protection Act of 1986, the Environmental Impact Assessment Notification (EIA) of 1994, and the Coastal Aquaculture Authority Act of 2005. At present, major area-based development is proposed under the SMART CITY project of Port Blair that is planned to be realized through retrofitting and redevelopment strategies with infrastructural investment of Rs. 770.15 crore (MUD 2016). Economic sustainability is ensured through intense tourism development in the chosen area along with skill development for tertiary sector employability. Retrofitting projects are to be implemented in order to improve the key metrics of livability and environmental sustainability (MUD 2016).

Based on the study results, it is highly recommended that areas with high mangrove carbon stocks are prioritized for conservation as part of EbA (ecosystem-based adaptation) approaches and being integrated under the SMART CITY project. EbA has been defined under the Convention of Biological Diversity as the “use of biodiversity and ecosystem services as part of an overall adaptation strategy to help people adapt to the adverse effects of climate change.” EbA aims to maintain and increase the resilience and reduce the vulnerability of people and the ecosystems they rely upon in facing adverse effects of climate change (SCBD 2019).

The modeling method used in the paper delivers a simple measure for AGB carbon stock, which can be replicated for other stocks and fluxes and for other ecosystem services of mangroves. Beyond carbon stock, mangroves provide a host of other ecosystem services, including coastal safety, water purification, fisheries, timber, and biodiversity (e.g., Sathirathai and Barbier 2001; Gunawardena and Rowan 2005). Thus, increased investments to secure individual ecosystem services are therefore likely to profit several other economic and social benefits. Likewise, enhancements in understanding the value and drivers of other ecosystem services can further strengthen efforts to manage and restore the mangrove ecosystem. The mapping of patterns of various ecosystem services has a great potential in strategizing conservation efforts.

It is suggested that planners and policymakers can choose from a wide range of interferences to adapt to climate change and reduce disaster risk in the exceedingly vulnerable island ecosystem. Such interventions can include "soft" options such as preservation and restoration of existing mangroves as opposed to "hard" options such as building infrastructure. Within this field, "green" options include those based on conserving, managing, or restoring ecosystems that deliver services critical to reducing risks and impacts, and "hybrid" choices include those that integrate ecosystem-based choices with other methodologies. Hybrid approaches could intake green infrastructure, ecological engineering, gray-green options, and building with nature solutions (SCBD 2019).

8.7 Conclusion

Mangroves form a dynamic habitat for varied marine and terrestrial organisms; therefore, degradation of mangroves would incur a significant and prolonged impact on the coastal ecosystems and hinder the socioeconomic upliftment of people living in the coastal zone. Therefore, certain necessary management strategies (e.g., mangrove plantation by Ministry of Environment and Forest, Government of India in the Andaman Islands) can help maintain a healthy mangrove ecosystem. Here, the mapping (AGB/carbon stock) of mangrove ecosystem service is essential and can support policies that would positively impact safeguarding natural resources and human well-being. Our current AGB map can be used for practical application since this map (Fig. 8.7) can efficiently communicate spatial information for practical utility. The current map can help landscape planning, environmental resource management, and (spatial) land-use optimization, prioritizing zones for long-term conservation. Therefore, ecosystem service maps are advantageous for raising awareness about ecosystem goods, environmental education, and delivering information on ecosystem service flows.

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Chapter 9
Depicting Mangrove's Potential as Blue Carbon Champion in Indonesia

Syarifah Aini Dalimunthe, Intan Adhi Perdana Putri, and Ari Purwanto Sarwo Prasojo

Abstract In June 2019, during the UNFCCC meeting, Indonesia pledged to reduce carbon emissions by adopting "blue carbon." The term refers to the role of the vegetated coastal ecosystem (mangroves, seagrass, brackish, and phytoplankton ecosystems) to mitigate anthropogenic CO_2 emission. Indonesia has the most extensive coverage of mangroves in the world. Its mangrove forest contains 3.14 billion metric tons of carbon. However, continuing and alarming destruction has consequences in obstructing the current carbon emission reduction and climate change mitigation effort. News media articles on ecosystem services are considered critical information for public opinion building processes because media provides and creates images and supports the initiative. This chapter aims to seek the answer to the following research questions: how is blue carbon covered in Indonesia's leading online media outlet and what does this coverage imply for the public opinion building process regarding the blue carbon initiative? In the past decade, news coverage on mangrove ecosystem services was successfully conveying tsunami risk reduction messages. This study will investigate online news media coverage to analyze mangrove's existing media representation as a "blue carbon champion"

S. A. Dalimunthe (✉)
Research Center for Population, National Research and Innovation Agency (BRIN), Jakarta, Indonesia

Graduate School of Environmental Studies, Nagoya University, Nagoya, Aichi, Japan
e-mail: syar012@brin.go.id

I. A. P. Putri
Research Center for Population, National Research and Innovation Agency (BRIN), Jakarta, Indonesia
e-mail: inta002@brin.go.id

A. P. S. Prasojo
Research Center for Population, National Research and Innovation Agency (BRIN), Jakarta, Indonesia

Department of Economics, Faculty of Economics and Business, Universitas Indonesia, Depok, Indonesia
e-mail: arip003@brin.go.id

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using qualitative content analysis. Online media coverage in the Indonesian language was collected from June 2019 to February 2021 under the term “karbon biru” (English: blue carbon) and “blue carbon.” The sample consists of articles from national online media outlets which scraped from Google News. The result is likely to show how news coverage on “blue carbon” represents a potential risk for the societal acceptance of blue carbon initiatives. As society is increasingly reliant upon the media to inform them, public opinion building processes regarding mangroves’ potential for a “blue carbon champion” required a novel discourse. Heavy coverage on mangroves as a carbon sink and frequent scientific jargon usage associated with blue carbon need to be reshaped.

Keywords Mangrove · Blue carbon · Content analysis · Public perception · Ecosystem services

9.1 Introduction

The role of blue carbon in climate change mitigation and adaptation has now reached international eminence. The blue carbon concept was introduced as a metaphor aimed at highlighting those coastal ecosystems, in addition to terrestrial forests (coined as green carbon), contributing significantly to organic carbon (C) sequestration. Blue carbon (BC) refers to organic carbon that is captured and stored by the oceans and coastal ecosystems, particularly by vegetated coastal ecosystems: seagrass meadows, tidal marshes, and mangrove forests. Blue carbon refers to mangrove forests, seagrass meadows, and tidal salt marshes—vegetated coastal ecosystems that represent significant carbon stocks and which are disappearing or becoming degraded as a result of continuing development pressures (Pendleton et al. 2012). The idea of blue carbon is attractive, indeed exciting to many in the conservation and policy actors. It appears to be a cost-effective strategy to achieve not only genuine reductions in greenhouse gas emissions but a host of co-benefits as well: providing habitat for valuable food species, filtering and treating runoff and chemical pollution from industry and agriculture and providing an effective defence against storms and extreme weather events (Nellemann and Corcoran 2009; Grimsditch et al. 2013). Given the mitigation and adaptation benefits that result from the protection or restoration of blue carbon resources and the limited public and private sector investment in projects to date, it is worth investigating the financial and economic aspects of project development. Blue carbon is an ideal case study in ecological economics and the political economy of climate change.

The multifaceted nature of the blue carbon concept has led to rich, varied, and cross-disciplinary debates and research that spans biophysical sciences, conservation, economics, policy, and law (Ahmed and Glaser 2016). Accordingly, effective communication about the reality and significance of blue carbon has been identified as a critical element of efforts to build broad engagement with government initiatives of blue carbon and its potential solution as well as challenges (Bernstein and Hoffmann 2019). Given the magnitude of its impact on every country in the world, numerous academic studies have researched the media's portrayal and its framing of climate change mitigation (Vu et al. 2019). Previous studies emphasize that national news outlets are important publicly visible spaces for government, corporations, think tanks, and social movements to engage in blue carbon debates (Broadbent et al. 2016). They are an influential and heterogeneous set of non-nation state actors that functions as key conduits to both formal and informal discourse within the spaces of cultural politics and geopolitics (Castree 2006; Dittmer 2005). This entity often embodies articulations of culture in society and significantly influences ongoing public understanding of climate change and policy (Wilson 1995). It has been demonstrated that most of the public rely on mass media for information, especially on scientific discourse (Boykoff and Rajan 2007).

Media is a combined agent of production, reproduction, and transformation of the meanings of social affairs, affecting the social construction of problems, through a complex mediating process between lay and expert understanding of scientific matters, such as climate change. According to the framing theory (Entman and Rojecki 1993), media shapes complex science into narratives (Smith 2005), playing a key role in framing scientific subjects, by selecting and emphasizing some viewpoints and suppressing others, through the influence of sociopolitical factors and political and industry interests (Anderson 2009; Entman and Rojecki 1993).

Despite the importance of this transnational issue, most research on media communication of blue carbon has been based in Western, economically developed, democratic countries, but there are void in nuances specific to developing countries that might represent the relationship between government, science, media, and society (Forsyth 2014).

Analyses of media coverage of blue carbon are valuable for understanding how key actors communicate issue "frames" to "render events and occurrences meaningful and thereby function to organize experience and guide action" (Benford and Snow 2000). Therefore, the main goal of this study is to investigate online news media coverage and existing media representation of mangroves as blue carbon champions using qualitative content analysis. Examining news framing on blue carbon will provide large information about how the relationship between rapidly changing environments and resource extraction is translated for media audiences.

9.2 Research Goals

This chapter aims to seek the answer to the two following research questions. First, how is blue carbon covered in Indonesia's leading online media outlet? The second question is what does this coverage imply for the public opinion building process regarding the blue carbon initiative?

9.3 Data and Methods

This study investigates online news media coverage to analyze mangrove's existing media representation as a "blue carbon champion" using qualitative content analysis, namely, discourse network analysis (DNA). A number of online media coverage in the Indonesian language was collected from June 2019 to February 2021 under the term "karbon biru" (English: blue carbon) and "blue carbon." The sample consists of articles from national online media outlets linked with the Google News platform. It's a news aggregator which collects or redistributes news articles or information from various sources into single websites (Isbell 2010; Lee and Chyi 2015). We use its sample because of three reasons. First, newspaper or news media articles are accessible and provide material information to assess national issues (Gamson 1992; Hallin and Mancini 2004 as cited by Broadbent et al. 2016), particularly for blue carbon. Second, its period time was used to increase the sample size, whereas June 2019 was used as the start period because Indonesia pledged to adopt blue carbon at the UNFCCC meeting (Coordinating Ministry for Maritime and Investing Affairs 2019). Third, Google News is the largest news aggregator that covered many countries and languages (Wang 2020) including Indonesian (Kemler 2015) and indexed many news publishers (Wang 2020). In addition, Google News applied strict guidelines for news to be listed, including originality and no misrepresentations to avoid redundancy and fake news (Searchmetrics n.d.).

The articles from Google News were obtained by a data mining approach using a python programming language (Van Rossum and Drake 2009). We use "GoogleNews" (Hu 2021) and "newspaper3k" (Ou-Yang 2018) library as tools for mining the articles. The first library was used to search Google News articles from python. The list of articles was determined using the .result() method for GoogleNews() function at the library after setting the period and article language and inputting the keyword in the .keyword() method. The article language for search is Indonesian or "id" (in ISO code). List of the article contained as a dictionary which nested in list data. Five important attributes from the list are title, media, date, and link of articles. The next step is downloading the article's text or content using the second library by setting the article link and language in Article() command and run the .download(), .parse, and .nlp() method, respectively. We recorded the mining result into a data frame that contains the date, media, title, summary, text, and link of the articles. This procedure was applied for all articles in the list which was determined in the previous step. Since we use two keywords, all of these procedures were applied for it and then append the data frame and remove the duplicated article. We adopted the python code from Dhingra (2020) for the implemented procedure. Code and other supplementary material are available at https://osf.io/d8fct/.

Article from the newspaper that contains direct statements of the actors related to "blue carbon" extracted using Discourse Network Analyzer (DNA). This software allows the user for qualitative coding from the text data such as newspaper, transcribed interviews, testimonies, and others (Fisher et al. 2013; Hilton et al. 2020; Leifeld 2013). DNA connects the qualitative analysis and social network analysis to visualization connection between the code variables through conversation data (Leifeld 2013). DNA developed by Philip Leifeld initially captures political debates among elite actors such as interest groups, legislators, government agencies, and other stakeholders. DNA can code the direct statement from elites covering four variables: actor, organization/institution, concept, and agreement or disagreement.

The result of DNA can be in the form of congruence or conflict networks from the actors or the concepts and also can be affiliation network of actor and network and longitudinal network (Leifeld et al. 2019). Figure 9.1 defines how the actor (red nodes/a1...*n*) and the concepts (purple nodes/c1...*n*) that link by the dashed line point out the edges called affiliation network. The number of dashed lines from every node from the actors connected to a particular concept is called statements. For example, actor number two (a2) makes three statements of three concepts (c1, c2, c3). Conversely, concepts number 3 (c3) are states from four actors (a2, a3, a4, a5).

DNA for "blue carbon" discourse in this paper is from several actors who make statements captured on the online media. The actors distinguish into three groups: government (blue round nodes), researcher and academics (yellow round nodes), and NGOs and INGOs (purple round nodes). A statement is a text section where an actor expresses his/her understanding or knowledge of the blue carbon issue. We do not look at how the debate on the blue carbon issues (agreement and disagreement), more to find the congruence networks on their perspective. So that in this paper, the direct text statement contains an actor and a concept: one-mode and two-mode approaches.

The qualitative coding procedure in this paper includes two steps. In the first step, every actor's statement is coded into the concept of the information, or the actors utter on the news article related to blue carbon discourse. The discourse of the blue carbon in the first step is distinguished based on each carbon resource such as mangroves, seagrass, or other ecosystems and the activities or program or commitment related to blue carbon. For example, a statement from researchers in the online newspaper is "As well as mangroves, Aan mentions that the ability to absorb carbon in the seagrass also occurs simultaneously in vegetation and substrate. In every hectare of seagrass, from the results of the Indonesian Institute of Sciences (LIPI) research, the ability to absorb carbon is known to reach 6.59 tons per year" which codes into the "Indonesian seagrass can absorb the number of carbons" concept.

The second step is screening all the first concepts that are being made, and then the concepts recode into 12 concept topics.

We discover 102 newspaper articles from Google News mining. The amount for "karbon biru" and "blue carbon" keywords are 60 and 42 articles, respectively. After checking duplicated articles from two keywords, we get 70 newspaper articles. Following the collection, screening and data cleaning activities found 31 newspaper articles to be part of data analysis. Within the articles, 134 statements and 80 concepts from 24 actors/organizations were codded for further analysis. At the end of data processing, we recoded into 12 topics. Then the final statement was reduced to 120 statements.

In general, the number of statements shown on news coverage related to blue carbon is fluctuate. June and July most likely show a spike in the number of

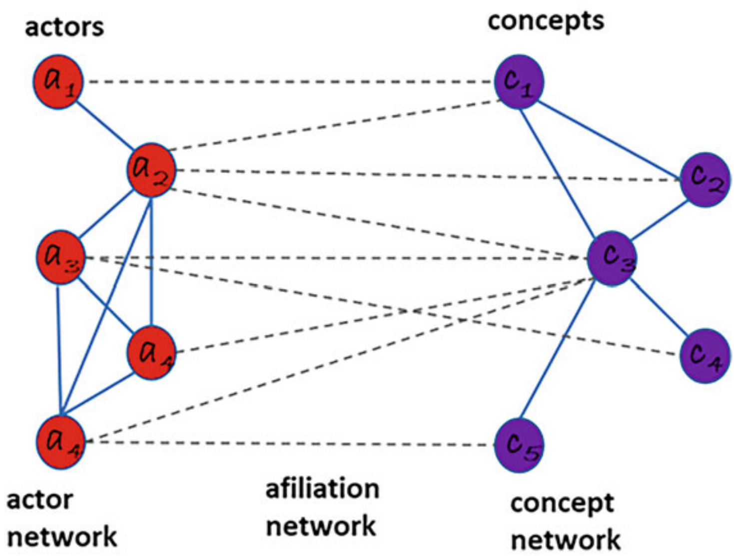

Fig. 9.1 Illustration of affiliation network between actors and concepts. (Source: Leifeld et al. (2019))

coverages. June 2019 is marked by world environment day. Following in the next year, the statement rises in the same period (June–July 2020) heavily influenced by two main events. They are world environment day and the Bonn climate change conference (Fig. 9.2). In other months throughout the years, the number of published statements is low, and the lowest was in September 2019 (Fig. 9.2).

9.4 Results and Discussion

9.4.1 Blue Carbon Adoption in Indonesia

A report was published in 2009 by United Nations Environment Programs (UNEP) titled Blue Carbon: A Rapid Response Assessment. The publication was an important milestone for three reasons: (1) It completed the process of global carbon accounting begun by the IPCC with the atmosphere and then terrestrial biomes (most notably forest) (Nellemann and Corcoran 2009); (2) highlighted the importance of the marine and coastal areas due to its carbon sink capacity and numerous ecological services; and (3) it created vital policy recommendations, including establishing a global blue carbon fund for the protection and management of coastal and marine ecosystems and ocean carbon sequestration. Later, the International Union for Conservation of Nature (IUCN) released a detailed assessment to document the C management potential of salt marshes, mangrove forests, seagrass

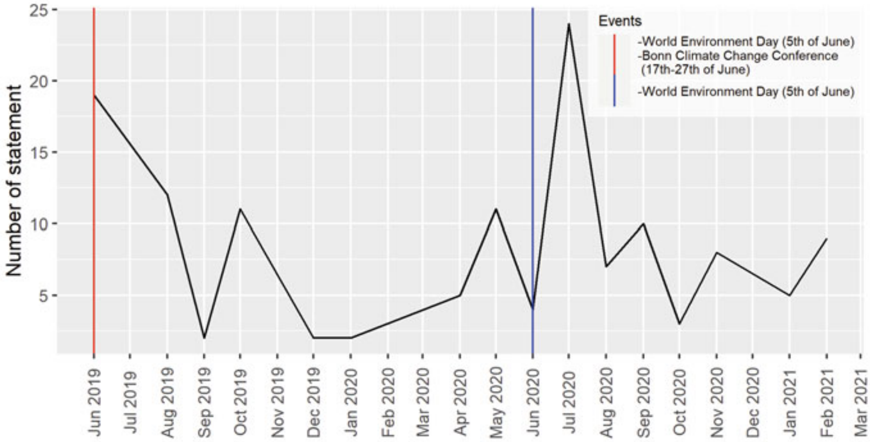

Fig. 9.2 Number of statement by month based on 120 statements

meadows, kelp forests, and coral reefs. The report found that these coastal habitats are quantitatively and qualitatively crucial for numerous reasons, including a high potential for C management (Herr et al. 2012). The 2012 report pointed out that: (1) sediments and soils in these ecosystems, while small in geographical range, sequester proportionally more C than terrestrial ecosystems due to lower potential for emissions of greenhouse gases (CH_4, CO_2); (2) there is a critical need for comprehensive C inventories from these habitats to properly assess their role in absorbing C emissions; (3) anthropogenic greenhouse gas emissions are being underestimated because such emissions from these coastal habitats are not being accounted for in national and international inventories, meaning their C savings from sequestration do not count towards meeting climate change commitments; and (4) these habitats continue to be destroyed and need to be protected and restored.

The rapid response assessment by Nellemann and Corcoran (2009) gave the policymaker and expert a very broad definition of blue carbon, starting with the following statement: Out of all the biological carbon (or green carbon) captured in the world, over half (55%) is captured by marine living organisms—not on land—hence it is called blue carbon. A follow-up study describes that blue carbon refers to mangrove forests, seagrass meadows, and tidal salt marshes—vegetated coastal ecosystems that represent significant carbon stocks and which are disappearing or becoming degraded as a result of continuing development pressures (Pendleton et al. 2012).

Quantitatively, mangrove carbon stocks have been measured in more than 50 countries in Africa, Southeast Asia, South and East Asia, Central and North America, the Caribbean, South America, the Middle East, Australia, New Zealand, and some Pacific Islands. As for South East Asia, the total estimates of organic carbon stocks (Mg C_{org} ha^{-1}) in mangrove aboveground ($AGBC_{org}$) and below-ground root biomass ($BGBC_{org}$) and soils (SC_{org}) to a depth of 1 m are fully available except for Cambodia as data is not available (Table 9.1).

Table 9.1 Estimates of organic carbon stocks (Mg C_{org} ha^{-1}) in mangrove aboveground ($AGBC_{org}$) and belowground root biomass ($BGBC_{org}$) and soils (SC_{org}) to a depth of 1 m (Source: Alongi 2020)

Country	$AGBC_{org}$	$BGBC_{org}$	SC_{org}	Total C_{org} stock
Cambodia	ND	ND	ND	657.4
Indonesia	142.0	335.9	420.1	794.9
Malaysia	119.7	5.9	763.0	894.4
Myanmar	20.7	18.4	167.0	206.1
Philippines	161.4	63.1	450.2	549.0
Singapore	105.0	39.9	307.3	452.3
Thailand	68.0	108.7	604.7	754.1
Vietnam	120.0	21.8	768.0	968.7

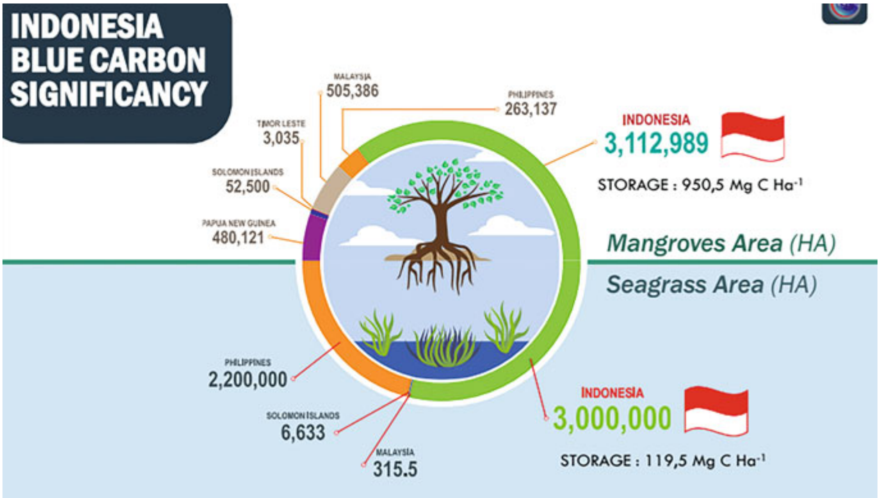

Fig. 9.3 Indonesia blue carbon significance. (Source: BAPPENAS 2021)

The conservation of mangrove carbon stocks has been promoted in global climate negotiations due to their potential contribution to mitigating GHG emissions. In response, the number of mangrove blue carbon assessments has increased rapidly over the past decade. However, continuing and alarming, Indonesia's mangrove destruction has consequences in obstructing the current carbon emission reduction and climate change mitigation effort. Mangrove's condition in Indonesia is deteriorating hastily due to loose licensing regulations for entrepreneurs in municipalities and provinces. Convoluted regulations contributed in creating conflict, and therefore mismanagement of mangroves is likely to take place (Fig. 9.3). As a response to the situation, in June 2019, during the UNFCCC meeting, Indonesia pledged to reduce carbon emissions by adopting blue carbon to mitigate anthropogenic CO_2 emissions. Climate change mitigation is likely to be more significant and effective at the national scale especially in countries losing mangroves rapidly, such as in Indonesia (Alongi 2020; Alongi et al. 2016; Taillardat et al. 2018).

The idea of blue carbon is attractive and indeed exciting. The conservation and policy actors found blue carbon appears to be a prime strategy because it appears to be a cost-effective approach to achieve not only genuine reductions in greenhouse gas emissions but a host of 'co-benefits as well: providing habitat for valuable food species, filtering and treating run-off and chemical pollution from industry and agriculture and providing an effective defence against storms and extreme weather events (Adriana Gracia et al. 2017; Narayan et al. 2016).

9.4.2 Actors and Messengers of Blue Carbon Initiative

Figure 9.4 derives from the DNA of the full set of articles and shows the discourse network of organizations that link, in agreement, to key issue categories related to the blue carbon. News source organizations are one mode of network data, represented by square nodes. Issue categories are the second mode of network data, represented by three colored nodes. Node size is weighted to reflect the centrality of the node within the network (i.e., how well connected the node is to others). Ties between nodes indicate the issue category is connected to the organizational actor, while tie thickness is weighted for the number of coding references linking the organization and theme (Fig. 9.5).

Fig. 9.4 Affiliate networks group of actors (government, researcher/academics, NGOs, and private) and an initial concepts

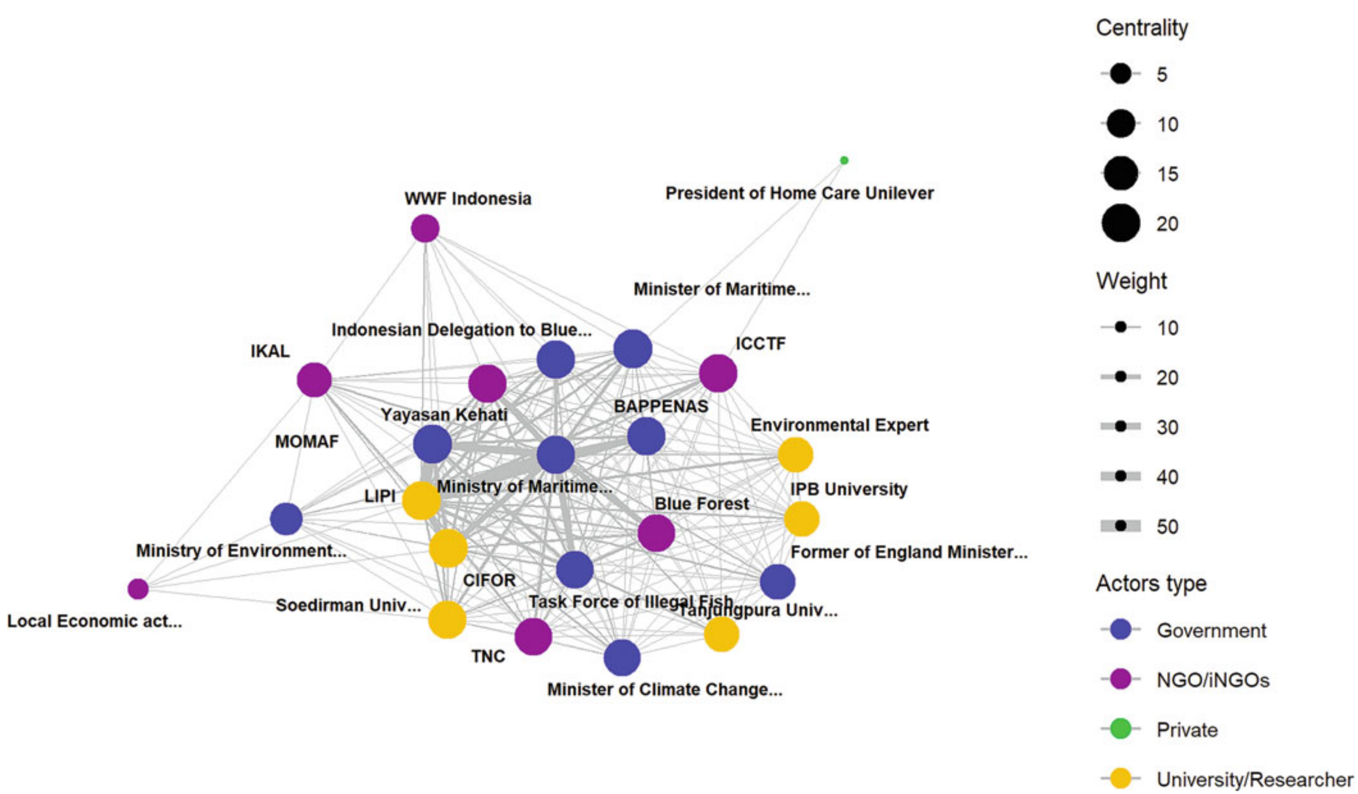

Fig. 9.5 Actors network. Node's color represents the actor's type. The edge weight between two nodes represents the number of times they co-support. The node's size is based on degree centrality measure, and it shows the number of connected edges or ties at each node

Various actor backgrounds appeared in media coverage of the blue carbon issue in Indonesia. The background organization of individuals includes expert, local champion, environmental observer, minister, think tanks, private sectors, international organization, national government, and even foreign government. The initial codes of a concept show that the 134 statements from the actors produce 80 concepts related to the topics related to blue carbon. Twenty-two concepts in this early stage connect between actors. Among them, there are 16 concepts related to the mangrove ecosystem, in which 22 actors discussed in 47 statements (Fig. 9.4).

The blue carbon discourse in Indonesia as portrayed in newspapers mainly discussed four groups of actors. They are the government, non-government organizations (NGO/INGO), private sector, and the university or research institute. In government group, the national planning agency (BAPPENAS), ministry of fisheries, and marine affairs (MOMAF) are the key actors. They are working closely with national NGOs such as Kehati as well as international NGOs, namely, Blue Forest and The Nature Conservancy (TNC). The private sector contributed to the debate, Unilever ambition of a "clean future" drive the company to revisit its carbon footprint. Meanwhile, the university and research institute join forces in providing scientific evidence about the causes and consequences of blue carbon into public debate. This organization ranges from national to a local level. This group provides a unique involvement of the subnational organization in the discourse. Indonesian Institute of Sciences (LIPI) and Bogor Institute of Agriculture (IPB) are the key actors. While at the subnational level, Jendral Sudirman University and the Tanjungpura University of Kalimantan provide their concerns too. The last institution is a think tank to environmental debate that is closely related to non-Java Island audiences. Reforestation of forests and mangroves is the focus of Kalimantan-based institutions as the natives generally live within the forests so they focus on providing policy evidence on the importance of the protection of these resources.

9.4.3 The Blue Carbon Discourse in the Public Arena

The dominant environmental discourses that could potentially construct how climate change-related issues are conceptualized have been highlighted by Dryzek (2012). He highlights three problem-solving discourses: (1) administrative rationalism, (2) democratic pragmatism, and (3) economic rationalism. The discourse of administrative rationalism puts faith in the ability of technocratic experts to solve environmental problems; the discourse of democratic pragmatism emphasizes the role of participatory and democratic policy processes in addressing environmental problems, while the discourse of economic rationalism favors the use of free-market economics as a means of efficiently and effectively addressing environmental problems.

We collapsed the results into 12 statements, each of which represents a different sphere of how blue carbon is stated by four groups of actors (see the top left legend of Fig. 9.6). Most organizations agreed that blue carbon is a powerful proxy for

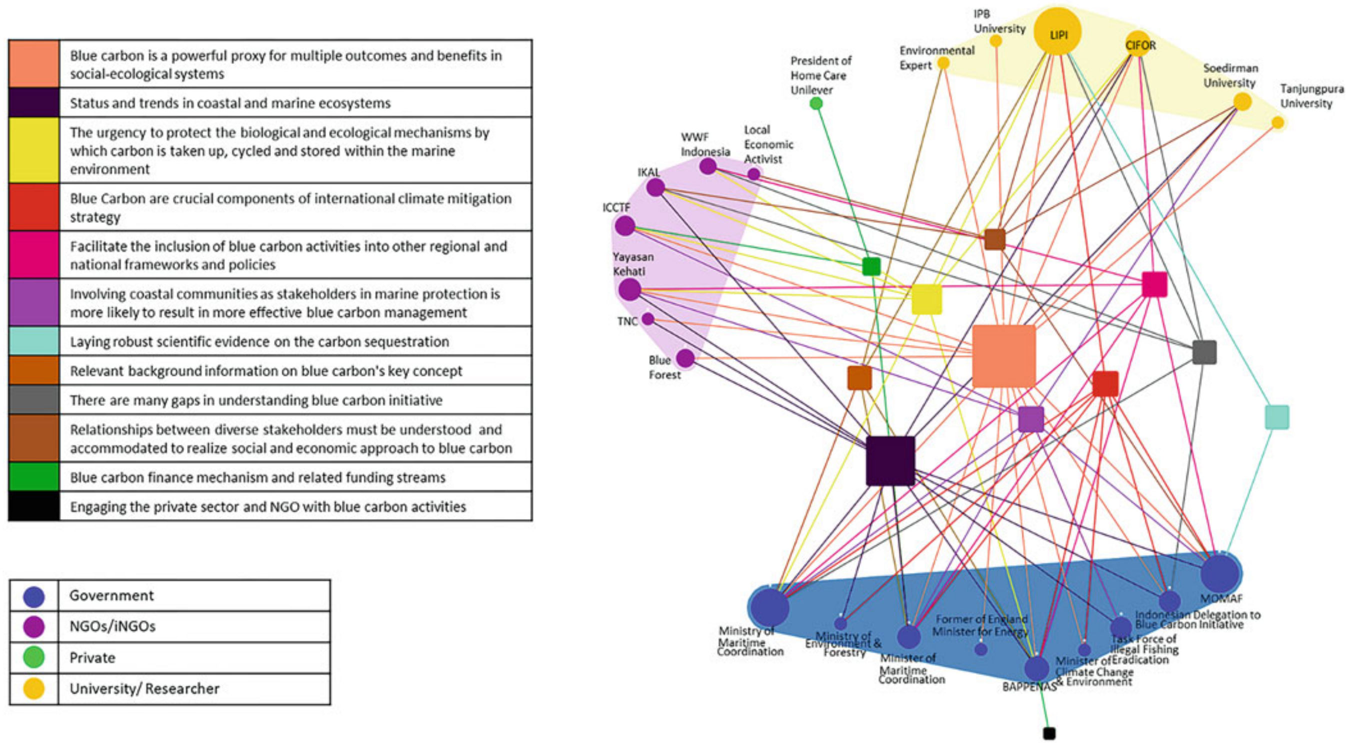

Fig. 9.6 Indonesian media discourse about blue carbon. The circle and rectangle shapes in the network graph represent the actor and statement concept, respectively, while the size of the shape represents the number of statements. The color legends for the concept is arranged by the number of statements

multiple outcomes and benefits in social-ecological systems. The thematic and linguistic frames that were most used by actor's through Indonesian news media to frame mangrove as blue carbon champion support our proposition that the issue would be constructed using ideas in line with ecological modernization theory. Our findings show that actors primarily contextualize the issue of blue carbon using the policymaking thematic frame and the economic interest thematic frame and that they primarily used the mitigation rhetorical frame to conceptualize how society ought to respond.

The second-largest theme to deliver the urgency of blue carbon is informing the status and trend of mangroves. The paucity of articles using the other thematic frames illustrates the lack of theoretical diversity in how the issue is classified and categorized by Indonesian media. Following the themes is the discourse of how blue carbon is a crucial component of climate change mitigation strategy. The dominance of the use of the mitigation frame is in line with the utilitarian logic of ecological modernization, that is, with the belief that society need only anticipates and prevents the worst effects of climate change rather than react to and cure them.

The incentives and funding mechanism as stated in Dryzek (2012) third point displayed in this study. The blue carbon finance mechanism and related funding statement as a group into the green color offer potential economic opportunities arising from blue carbon initiatives. The majority of actors of government, business actors, and NGOs made positive statements. There was no significant resistance to proposals arguing that economic incentives could be used to induce mangrove utilization as blue carbon practices. This statement can be understood as an attempt to provide a conduit to the dichotomy between economic growth on the one side and environmental protection on the other. This was expressed by promoting the idea that new jobs could be created in the emerging blue carbon and mangrove preservation and that existing coastal community livelihood could become more profitable if they were to take the opportunity to embrace sustainable human-environment interaction.

One critical finding in this study, the lack of blue carbon contrarians in the Indonesian media, is indicative of the fact that a high level of consensus existed about the anthropogenic drivers of climate change among those with institutional and economic power.

9.5 Conclusion

The data included in this study can be used to improve the understanding of how blue carbon is covered by online media in a developing country. On blue carbon coverage, the study found that the debate focuses on the trend and status of coastal and marine ecosystems particularly mangrove coverage in Indonesia. Data also showed that a significant body of news was especially related to outcome and multiple benefits of socio-ecological systems with scientific evidence coming from national and subnational scientific bodies. The second significant finding identifies that to influence the public's behavioral patterns in supporting the blue carbon initiative, economic benefit and budget scheme are pronounced. This was led by government and NGO actors.

This study has its limitations in terms of sample size and representativeness and is an initial approximation for research on blue carbon news coverage in Indonesia. This research area can continue to be advanced, above all by incorporating an analysis of qualitative discourses in the search for a more in-depth approach to the problems surrounding blue carbon in the printed media, as an instrument to raise social awareness and the first step toward acting. Future research may also incorporate a comparative analysis to detect any significant difference in the way blue carbon is discussed in the post-pandemic environment.

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Chapter 10
Eco-Engineering and Mangrove Restoration Methods to Stabilize Earthen Embankments and Establishing Bio-Shield Against Natural Disasters: A Case Study from Sundarban Ramsar Wetland, India

Aliya Naz and Abhiroop Chowdhury

Abstract Natural disasters such as cyclones, typhoons, storm surges, or tsunami are responsible for the destruction of land, livelihood and displacement of local populace. Sundarbans, the world's largest contiguous mangrove forest, located in the Ganges-Meghna-Brahmaputra delta, is the only barrier against these disasters. Eco-engineering with salt-loving mangrove plants can successfully establish a bio-shield against natural disasters and stabilize the earthen banks. It can also restore the four principles of ecosystem services—provisioning services, regulating services, supporting services, and cultural services. Restoration techniques promote the establishment of wave attenuating, rapidly growing, salinity- and flooding-tolerant *Avicennia marina* near the low tide level. The second layer of plantation can be established with true mangrove family (Rhizophoraceae) members *Bruguiera* spp. and *Ceriops* spp. that can consolidate sediment, survive flooding, and are salinity-tolerant. The third layer can constitute of stilt root possessing *Rhizophora mucronata* that has a potential to reduce flooding impact and can stabilize a comparatively larger volume of sediment due to extensive root structure. The fourth and final plantation layer can be established with resilient tree species with the potential to reduce wind force such as *Sonneretia* sp. and *Excoecaria* sp. near to the high tide level. Restoration must not be done with exotic or invasive species to minimize ecosystem damage. Community participation must be ensured to successfully establish

A. Naz
Tagore Society for Rural Development, Kolkata, West Bengal, India

Jindal School of Liberal Arts and Humanities, O.P. Jindal Global University, Sonipat, Haryana, India

A. Chowdhury (✉)
Tagore Society for Rural Development, Kolkata, West Bengal, India

Jindal School of Environment and Sustainability, O.P. Jindal Global University, Sonipat, Haryana, India

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mangrove bio-shield at Indian Sundarbans and reduce grazing pressure post plantation phase. A case study has revealed a successful restoration attempt at Satjelia Island of Indian Sundarbans with protection service during recent cyclones.

Keywords Super cyclone · Mangrove · Community participation · Plantation methods · Salinity tolerance · Sediment consolidation · Ecosystem services · Risk reduction

10.1 Introduction

Mangrove ecosystems are unique, as they are situated between the ocean and the land and act as a barrier between the two (Chowdhury et al. 2016a). This shields people living on the coasts from storm surges and other natural hazards like tsunamis and cyclones.

Mangroves are a group of salt-tolerant trees or shrubs that grow in water, with their roots emerging from the water (Chowdhury et al. 2016a; Ghosh 2019). Mangrove ecosystems provide important ecosystem services for flood protection in coastal areas and also provide economic benefit to the region. The growth and type of mangrove forests depend on hydrological connectivity and topographical features (Alongi 2002). Hydrological connectivity consists of the quality, quantity, and timing of freshwater and sediment inflow. This is responsible for deciding the height of the mangroves. Tidal conditions, coastal landscapes, and marshes decide the growth and biodiversity of mangrove ecosystems. Therefore, mangroves can adapt to rising sea levels and changing land use because of their ability to adapt to environmental stresses (Chowdhury et al. 2016a; Chowdhury and Maiti 2016). Mangroves are connected and form an integrated system linking the coast and the ocean. Though they thrive in saline conditions, the deltas where mangroves are found also depend on freshwater supply. Deltas have been shrinking in areas where freshwater is scarce, leading to the loss of mangrove forests. These ecosystems are being threatened by unsustainable human activities for development.

Indonesia has the highest mangrove cover scattered around islands, whereas Ganges-Brahmaputra-Meghna (GBM) delta houses the world's largest contiguous mangroves, covering around 10,000 square kilometers. Sixty percent of this forest is in Bangladesh, whereas the rest is in the state of West Bengal, India (Chowdhury et al. 2016a). This unique mangrove forest is referred to as Sundarban, which is also the home of enigmatic mangrove dwelling tigers. The etymology of the word "Sundarban" is from a true mangrove species (*Heritiera fomes*) dominant across the region and locally referred to as "Sundari." Another interpretation refers to the beauty of these myriads of mangrove forested islands separated by wide rivers, which has been the main reason for the coinage of the name "Sundarbans" which can be translated as "beautiful forest" as per the local Bengali language. According to available literature, the GBM delta is under high disaster vulnerability risk (Das et al. 2021). During the eighteenth century, the whole of the lower delta as far as the city of Kolkata was under mangrove cover. But since 1903, with the establishment of

"Gosaba cooperative society" by Sir Daniel Hamilton, colonization of Sundarbans started by clearing the native mangrove cover. Since independence from British colonization, policy makers are taking steps to conserve this unique habitat. Recently in February 2019, Indian Sundarban has been designated as the 27th Ramsar Wetland Conservation site which is also the largest wetland of the nation covering 4230 km^2. Currently, 54 out of 102 islands of Indian Sundarbans are under human habitation with minimum mangrove cover. Being a newly formed delta, erosion-deposition dynamics in the region is unpredictable. During high tide, most of the habituated land surface lies below the water level. To counter this issue and arrest flooding, earthen dams have been constructed along the east-west and north-south embankments. Recent storm surges/cyclones have conclusively proven the fragility of these temporary bunds. And every instance of disaster results in extensive flooding across the region due to breaching of this earthen structure. Vegetative methods such as restoring the mangrove cover along the disaster-vulnerable embankments may be the only sustainable, nature-friendly, and effective solution to protect the 4.6 million people residing in the Indian Sundarbans from disaster impacts.

Climate change has increased the occurrence and intensity of cyclones on tropical coasts. Indian Sundarban was hit by different cyclones in the last 12 years named Aila (2009), Bulbul (2019), Amphan (2020), and Yaas (2021). The tidal surge, strong wind, and huge floods during cyclone hit weaken the earthen dams, which is a great challenge for the local people. Damage in earthen dams allows the saline water to enter agricultural land which ruins the crops and agricultural soil fertility (Winterwerp et al. 2020). Thus to protect earthen/concrete embankments, mangrove plantations can work as a bio-shield (Chowdhury et al. 2019; Chinchmalatpure and Thakor 2020). Mangroves are natural barriers against cyclone surge and high-speed wind and thus help hold back the strong tidal blows. Mangroves stabilize the earth and prevent landslides (Dasgupta et al. 2019). Mangroves are very sensitive, and the survival rate of planted mangroves is comparatively lower than other tropical flora (Chowdhury et al. 2019). This book chapter provides the eco-engineered methodologies to be applied during the plantation of mangroves to restore ecological services as well as to protect the lives and livelihood in tropical mangrove ecosystems.

10.2 Ecosystem Services Provided by Mangroves

Goods and services provided by nature that supports the life and livelihood of human are known as ecosystem services (Vo et al. 2012). Ecosystem services are majorly classified into four types—provisioning services, regulating services, supporting services, and cultural services. The ecosystem services provided by mangroves are depicted in Fig. 10.1.

Mangrove ecosystem helps the local population in their livelihood and survival by different ways (Locatelli et al. 2014). The alkaline environment in mangrove sediments acts as a pollution sink (Natesan et al. 2014). Large quantities of carbon are stored in the soil and roots in the mangrove ecosystem. Therefore, mangrove ecosystems are large blue carbon sinks, which compensate for the greenhouse gases

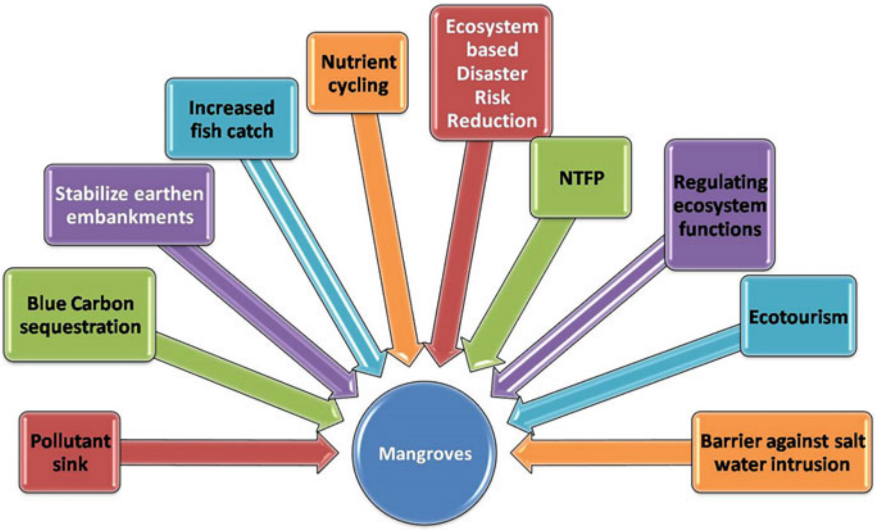

Fig. 10.1 The ecosystem services rendered by mangroves at Indian Sundarbans. NTFP: non-timber forest product

released by human activities (Bouillon et al. 2008; Chowdhury et al. 2019). Mangroves assimilate waste, cleanse flowing water, and perform the recycling of nutrients (Vo et al. 2012). Mangrove sediment acts as the main reservoir of macronutrients and micronutrients, and the mangrove played a major role in the recycling of nutrients (Ray et al. 2021). Mangrove forests support wildlife and diverse varieties of flora and fauna (Nagelkerken et al. 2008). Mangrove provides economic benefits to the local populace by providing resources such as firewood, food, fish, fiber, timber, and ethnomedicines (Chowdhury et al. 2021a). Mangroves enhance fisheries as mangroves are the habitat of fishes, crabs, and prawns (Sasekumar et al. 1992; Carrasquilla-Henao and Juanes 2017). Mangrove ecosystems protect coastal communities from floods, cyclones, storm surges, and tsunamis, acting as a natural barrier between the land and sea. The intricate root systems hold the soil together and prevent erosion (Spalding et al. 2014; McIvor et al. 2012; Jaisankar et al. 2018). The dense forests absorb wave energy, which helps the coast withstand sea level rise (Krauss et al. 2014; Enwright et al. 2016).

10.3 Rationale Behind Using Mangrove as Disaster Bio-Shield

Mangrove plantation and restoration in the mudflats act as an effective eco-engineering to minimize disaster damage. As these plants are sensitive to different levels of salinity and tidal flushing, multispecies mangrove plantations must keep this consideration in mind while planning any restoration efforts.

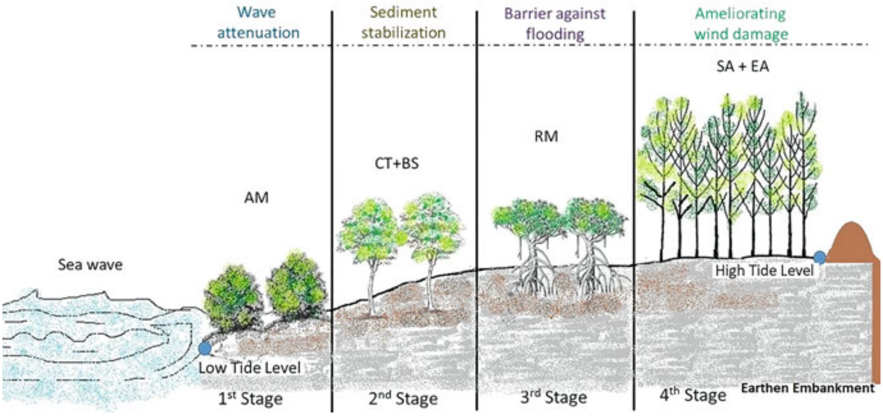

Fig. 10.2 The different plantation layers with specific roles in the eco-engineering model for creating effective mangrove bio-shield against natural disasters. The mudflat between low tide level (LTL) and high tide level (HTL) is divided into four stages with specific mangrove species with required disaster management roles. *AM Avicennia marina* (locally called Bani), *CT+BS Ceriops tagal* (locally called Mat Garan), *Bruguiera sexangula* (locally called Kankra) mixed-species plantation, *RM Rhizophora mucronata* (locally called Garjan), *SA+ EA Sonneratia casolaris* (locally called Chak Keora), and *Excoecaria agallocha* (locally called Gnewa) mixed-species plantation

The mangrove plant layers successfully tested against Amphan super cyclone (16–21 May 2020) and Yaas severe cyclone (23–28 May 2021) are depicted in Fig. 10.2. The principal consideration for any restoration ecologist while setting up an eco-engineering plan to use mangroves as ecosystem-based disaster risk reduction model revolves around the following consideration.

The first layer of mangroves nearest to the low tide level (LTL) must have resilience against wave damage and possess the ability to attenuate wave impact during any cyclone or storm surge. During any disaster incident, this is the first level that will receive the maximum impact from the waves. So the selected plant species must also possess natural adaptation to survive in prolonged flooding conditions (Table 10.1 and Fig. 10.2). So the species must be from a “true mangrove” variety that naturally possesses adaptations for surviving such vagaries and also have the potential to hinder wave force. That requires a high level of brunching near to the ground level as well as an extensive root network to minimize erosion damage. LTL level is frequently facing tidal flows hence making the sediments prone to erosion pressure. This condition gets worse during high winds and wave force during any disaster.

The second layer needs to be occupied by mangroves with natural salinity and flood tolerance as well as the ability to consolidate loose sediment and arrest erosion damage during a disaster. In the case of Sundarbans which have one of the highest mangrove biodiversity (34 true mangrove species) across the globe, candidate species can be selected among “true mangrove” species of Rhizophoraceae, which

Table 10.1 The botanical characteristics and potential of candidate mangrove species that can be considered for eco-engineering

Species	Family	Wave attenuation	Sediment consolidation	Wind breaks	Erosion reducing capacity	Resistance to damage	Flood tolerant	Regeneration potential after disturbance	Sensitive to cyclone induced damage	Remarks	Reference
Avicennia marina L.	Acanthaceae									Rapid growing, brunching from near the ground surface, salinity tolerant, extensive prop root system.	Chowdhury et al. 2018; Carlos et al. 2015; Hindell et al. 2004; Othman,1994 ,
Bruguiera sexangula (Lour.) Poir.	Rhizophoraceae									Shows unique viviparous germination	Hilmi 2018;Chowdhury et al. 2018
Ceriops tagal (Perr.) C.B.Rob.	Rhizophoraceae									Resilience to disaster increases if grown as a multispecies plantation along with *A. marina*	Okello et al. 2014; Komiyama et al. 2000; Huxham et al. 2010
Excoecaria agallocha L.	Euphorbiaceae									Possess extensive lenticels in the bark to compensate the oxygen deficiency in the soil, milky latex is present.	Mitra 2020; Chowdhury et al. 2018; Dasgupta et al. 2017; Mukherjee et al. 2014; Verhagen and Loi 2012
Heritiera fomes Banks	Malvaceae									Vulnerable to damage during cyclones. The intensity of damage due to wind increases	Halder,et al. 2021, Chowdhury et al. 2016;

(continued)

Table 10.1 (continued)

										with increasing girth of the tree.	
Rhizophora mucronata Poir.	Rhizophoraceae									Extensive stilt root system supporting the plant in loose sediment as well as act as breathing roots.	Hilmi 2018; Rasmeemasmuang et al. 2015
Sonneratia apetala Banks	Lythraceae									High brunches with more leaves that act as effective wind break. Invasive in China.	Yu-Jun et al. 2012; Ren et al. 2009
S. caseolaris (L.) Engl.	Lythraceae									High brunches with more leaves that act as effective wind break.	Thai 2012; Jian 2006
Xylocarpus granatum J.Koenig	Meliaceae									Timber yielding mangrove species with moderate salinity tolerance but sensitive to extensive flooding.	Chowdhury et al. 2018; Dasgupta et al. 2017; Duke 2015; Rahman et al. 2011

has a natural adaptation to survive saltwater inundation as well as salinity tolerance (Chaudhuri and Choudhury 1994; Chowdhury and Maiti 2016; Chowdhury et al. 2018). But the species can possess sensitivity to wave force because the wave forces will be reduced in the first layer.

The third plantation layer must ensure a reduction in flooding and the ability to the consolidate of sediment. Candidate species again can be selected that has salinity and flooding tolerance with an extensive root system even more than one layer and two species.

Fourth layer mangroves must have thick brunching, with considerable higher canopy height relative to the preceding three plantation layers. The main utility of this layer touching the high tide level (HTL) is the reduction of wind force during any cyclone/storm surge. But the candidate species must also possess an extensive root system to anchor the plant during heavy wind barrage and possess the resilience to wind damage.

10.3.1 First Restoration Layer: **Avicennia marina**

Locally called "Bani" in Indian Sundarbans, this species has the maximum capacity to tolerate high salinity as well as disaster-related damage. Works of Chowdhury et al. (2016a, b) have focused on the scenario that salinity rise in the central part of Indian Sundarbans can actually increase the dominance of this salinity-tolerant species over other salinity sensitive true mangroves such as *Heritiera fomes*, *Xylocarpus* spp., *Ceriops* sp., and *Sonneretia* sp.

Two types of plantation method work best for establishing *Avicennia marina* barrier in the seaward side of the mudflat.

a. Direct Seeing Method: In this method, the propagules of the plant are collected from the nearby rivers and directly seeded in the wet, soft, silt/clay-rich mudflat. It grows luxuriantly within 2–3 years time, and the thick bush acts as an effective wave attenuator.
b. Nursery-Grown Saplings: The propagule is grown in a separate nursery and then transplanted in the mudflat through the propagule dibbling method (Chowdhury et al. 2019). This method works best if the mudflat does not receive proper tidal flushing and is relatively dry. This method is more cost-intensive than the direct seeding method as argued by Chowdhury et al. 2018.

Scientific literature indicates that *A. marina* has the potential to attenuate wave damage and act as a windbreaker and is resilient to wind/flood damage (Table 10.1). Hence, the substantiation behind its establishment as the first layer of barrier in the disaster impacted mudflat. The typhoon Haiyan that hit the Philippines coast on 3 November 2013 revealed that the long-living genera of both *Avicennia* spp. and *Sonneretia* spp. were most resilient to disaster damage and proved to be the best candidates for restoration after any disaster (Villamayor et al. 2016). The seaward side of the mudflats is most prone to both wave and wind damage during any natural disaster, and in the case of Sundarbans, cyclones/storm surges are accompanied by saltwater influx from the Bay of Bengal. So the candidate species considered for restoring the seaward side of the mudflat must have a relatively high salinity tolerance as well as resilience to flooding.

10.3.2 Second Restoration Layer: Ceriops sp.-Bruguiera spp.

Ceriops tagal, *C.* decandra, *Bruguiera sexangula,* and *B. gymnorhiza* are members of "true mangrove" family of Rhizophoraceae. Members of this family are particularly adapted to grow and proliferate in the tidal, saline conditions of the tropical-subtropical coasts. They possess specific physiological, anatomical, and morphological adaptations to survive in the saline conditions and regular tidal flashings (Chowdhury et al. 2016a, b; Cochard et al. 2008).

The reason for planting these species after the *A. marina* layer is their sensitivity to wave pressure and relatively lower salinity fluctuations as evident from the studies of Liang et al. 2012; Krauss and Allen 2003; Chowdhury et al. 2016a, b.

The only plantation method that can be employed for planting the second layer species in the mudflat is the transplantation of nursery-grown saplings (Chowdhury et al. 2019).

10.3.3 Third Layer: Rhizophora mucronata

This Rhizophoraceae family member has an extensive stilt root system which is a unique characteristic of this true mangrove (Robert et al. 2015). This mangrove species has the ability to consolidate the sediment effectively due to its high root volume and proved to be effective in protecting the coastal shores during the 2004 tsunami (Cochard et al. 2008).

The plantation method used for *R. mucronata* is the transplantation of nursery-grown sapling after facilitating water flushing and sediment deposition by drain and trench method. Drains are excavated before the plantation of the saplings to facilitate regular water flow during tides as the location of the plantation is near the HTL. Saplings need periodical water flooding during their initial period of growth that is facilitated by this restoration technique, commonly used in the eastern part of Indian Sundarbans (Chowdhury et al. 2018, 2019)

10.3.4 Fourth Layer: Sonneretia sp. *and* Excoecaria sp.

This layer is closest to the HTL, hence tidal flushing will be minimum. On the positive consideration, this can facilitate salinity-flooding sensitive tree species to grow well. The main importance of this layer of plantation is to reduce the wind speed during a disaster situation. So the trees need to be well brunched with high leaf numbers and a strong root system to reduce wind speed as well as suffer minimum damage. *Sonneratia casolaris* of Lythraceae family along with Euphorbiaceae member *Excoecaria agallocha* is perfect candidate for this layer of plantation as evident from Table 10.1.

Other species such as *Heritiera fomes* (Malvaceae), *Xylocarpus granatum* (Meliaceae,) and *X. moluccensis* can also be chosen as this layer. But in that case, the salinity can become a limiting factor for the growth of these mangroves as all have different levels of salinity sensitivity. The only possible location for selecting these species can be in the north-eastern corner of Indian Sundarbans which has lower water and soil salinity than other parts of the Indian Sundarbans. Otherwise, for other areas, *Sonneratia casolaris* and *Excoecaria agallocha* can be a better choice.

The only plantation method that can be used for these mangroves is the transplantation of nursery-grown seedling through the pit digging method (Chowdhury et al. 2019). So pits need to be dug prior to transplantation to allow soft mud to deposit in them. The reason behind this is the hardness of the mud as it receives minimum tidal flushing being close to HTL.

10.3.5 Avoiding Introduction of Invasive or Exotic Species

The introduction of exotic species is always a hidden risk while drafting any restoration plan. The ideal thumb rule is to only use endemic species while planning for the establishment of mangrove bio-shield. Works of Ren et al. (2009) and Chen et al. (2013) indicated the invasiveness of *Sonneratia apetala* Buch-Ham (an exotic species) in the Qi'ao Mangrove Reserve, Hengmen estuary northeast of Zhuhai, Guangdong Province at China, and it has been competitively replacing *Aegiceras corniculatum* a native species of that region. The same species is native to Indian Sundarbans and observed to co-exist with *A. corniculatum* (Chowdhury et al. 2016a, b). Hence, one species may be a perfect candidate for eco-engineering at one part of the globe where it is part of the native floristic, while at a different location, it can act as an invasive species, destabilizing the community ecology of the wetland.

Feng et al. (2017) argued that exotic cordgrass *Spartina alterniflora* has severely invaded at Zhangjiang River estuary, Yunxiao County, Fujian Province, China. A similar invasive instance has been observed for Vertiver (*Chrysopogon zizanioides*) in China (Wang et al. 2016). Vertiber is not a native species of Sundarbans. Furthermore, salinity tolerance is observed in different species of Vertiber as per observations by Liu et al. (2016) and George et al. (2017), which makes this a potential species that can be considered during planning ecorestoration processes at Sundarbans. But there is a serious risk of invasion of this species if introduced in this region as it can easily replace grass (Poaceae) *Porteresia coarctata*, the pioneer species in the natural succession process.

Restoration should never introduce any exotic species in the fragile mangrove ecosystem as it can result in serious ecological catastrophe. The different regions across the globe have different native floral biodiversity. Native plants with similar ecological services can be selected as candidate species while planning any restoration work, and the introduction of any exotic species must be strictly avoided.

10.4 Community Participation in Mangrove Restoration

Community participation is vital for the success of any mangrove restoration initiatives and management. Researchers across the globe are advocating for active involvement of the third sector and local marginalized communities for any disaster management initiatives (DasGupta and Shaw 2013, 2014, 2017).

Chowdhury et al. (2016b) and Chowdhury et al. (2018) have focused on the success of mangrove restoration due to the involvement of the local community. One of the general problems responsible for the lower survival rate of mangrove plantations is the uncontrolled grazing by domesticated herbivores. During the initial months of plantation, mangrove saplings are fragile and more sensitive to any abiotic stress. It takes about a week to a couple of months for the species to successfully establish themselves in the mudflat. In this incubation period, plants are sensitive to any grazing stress. To ensure minimization of this risk, community-organized protection committees have proven useful. Forest Department, Government of West Bengal, India, has introduced Joint Forest Management' schemes with local communities all along Indian Sundarbans. Involving these groups or separate Self-Help Groups (SHG) for guarding the initial restoration site can minimize grazing damage. Hence, community participation is the most effective method for ensuring the better establishment of the mangroves. Employing local communities in the plantation process as labor is another way to ensure community participation in the restoration process.

10.5 Case Study

A success story of mangrove restoration can be observed in the island of Satjelia at Indian Sundarbans (Chowdhury et al. 2018). A hundred hectares of multispecies mangrove plantation has proven useful in protecting the nearby revenue village from excessive flooding during Amphan and Yaas cyclone. *Avicennia marina* (Acanthaceae), *Bruguiera sexangula* (Rhizophoraceae), *Ceriops tagal* (Rhizophoraceae), *Rhizophora mucronata* (Rhizophoraceae), and *Xylocarpus moluccensis* (Meliaceae) were planted along the stretch to ensure reforestation of the degraded mudflat (Fig. 10.3a–d).

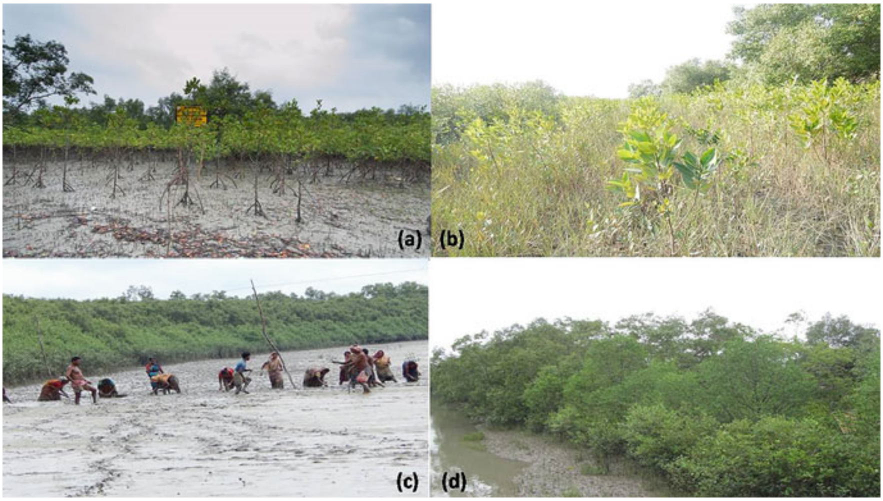

Fig. 10.3 The mixed-species mangrove bio-shield and plantation process at Satjelia island, Indian Sundarbans. (**a**) The Rhizophora mucronata patch set up using drain and trench plantation method; (**b**) the saplings of *B. sexangula* and *C. tagal* interspaced in the second stage; (**c**) community participation in the plantation activity where the local people taken active role in plantation and got payment as per the existing labor rates, a source of employment; and (**d**) the four layered mixed species mangrove bio-shield after 8 years of restoration drive with planted as well as naturally regenerated plants that has proved effective in ameliorating damage during Amphan and Yaas cyclone in 2020 and 2021, respectively

The *Rhizophora mucronata* patch of this plantation (Fig. 10.3a) resulted in an increment of above 80% organic carbon density in the mudflat between 2012 and 2016 (Chowdhury et al. 2018). *B. sexangula* and *C. tagal* are planted in the second layer guarded by *A. marina* in the LTL (Fig. 10.3b). Community has actively taken part in the plantation drive as well as protecting the habitat (Fig. 10.3c). The eco-restoration site clearly shows the layered mangrove species composition with A. marina in the LTL side followed by slow growing *B. sexangula* and *C. tagal* in second layer, *R. mucronata* in the third, and tall *S. caseolaris* trees with black stems in the last layer along with natural regeneration of other mangrove species during 2012–2020 (Fig. 10.3d). Recent research have proved that this mangrove patch has been effective in ameliorating disaster impact during the landfall of Amphan supercyclone in May, 2020 (Chowdhury et al. 2021b).

10.6 Conclusion

This work examines the ecosystem services that are provided—in flood control, coastal protection, and helping coastal ecosystems thrive. It delves into the importance of mangroves specifically in the Sundarbans region in India and Bangladesh. It also highlights the need for mangrove conservation by considering the disastrous events that recently took place across various countries and in the Sundarbans. It is concluded that eco-engineering with mangroves is effective to combat furies of natural disasters like cyclones and storm surges. But restoration methods and candidate species need to be selected according to the ecological services required for protection against disaster events. Different mangrove species have different adaptations that make them either extremely flood, wave impact tolerant or soil consolidator due to extensive root structure, or wind impact ameliorator due to high brunching as well as height. Salinity tolerance is a natural adaptation of true mangroves that proves useful for building bio-shield against cyclones in vulnerable tropical- subtropical coasts. Eco-engineers must understand the nature of the plants, their limitations as well as potential, and abundance in the local ecosystem to successfully plan a bio-shield plantation model.

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Chapter 11
Ecosystem Services of Urban Fringe Mangrove Forests: The Case of Tamsui River Estuary Mangrove Forest, Taiwan

Ming-Kuang Chung, Wan-Hui Huang, Li-Pei Peng, and Shizuka Hashimoto

Abstract Tamsui River Estuary mangrove forest is located adjacent to the Taipei Metropolitan area, where the river meets the ocean. The Greater Taipei area is Taiwan's largest metropolitan area with a population of over 7 million. Following successive designations of several mangrove forest reserves in the 1980s, the mangrove area of Tamsui River Estuary mangrove forest now exceeds 108 ha, making it Taiwan's one of the most important sites for environmental education and research. Mangroves are generally considered to perform critical ecological functions, such as water purification and tidal impact reduction. However, only a few studies have assessed the ecosystem services of mangroves at the Tamsui River Estuary. This study highlighted the mangroves and their relationship to the fringes of Taipei City to assess the ecosystem services provided by the catchment area. The study found that the mangroves have transformed from a wasteland into a mangrove ecosystem, which was familiar to, recognized and protected by citizens and institutions and providing additional cultural services to people. Mangroves are important patches that provide downstream ecosystem services affected by upstream land use changes within the watershed. The government undertook intensive regulatory measures to preserve the environmental quality of the watershed and improve ecosystem services. In this sense, urban mangroves are deeply influenced by urban resilience goals with judgments from multiple perspectives.

Keywords Ecosystem services · Land use · Urban fringe · Mangrove · Taiwan

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M.-K. Chung (✉)
Institute of Information Science, Academia Sinica, Taipei, Taiwan

W.-H. Huang
The Research Institute for Humanity and Nature, Kyoto, Japan

L.-P. Peng
Department of Bio-Industry Communication and Development, National Taiwan University, Taipei, Taiwan

S. Hashimoto
Department of Ecosystem Studies, The University of Tokyo, Tokyo, Japan

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11.1 Introduction

The capacity of a mangrove forest to provide ecosystem services is proportional to its area. The larger and more complete patches of mangrove forest can provide a higher level of ecosystem services (Alemu et al. 2021). Several studies have shown that urban expansion and concomitant changes in land use often lead to a decrease in mangrove coverage (Lugo et al. 2014). This is partly due to the increasing demand for developable land resulting from high rates of urbanization. The construction of housing, roads, and public facilities corresponds to increasing rates of mangrove deforestation (Ai et al. 2020). In rural areas outside cities, mangroves are deforested into aquaculture and agricultural lands to meet the increasing food demands of a growing urban population (Richards and Friess 2016). In addition, a massive increase in urban population and industrial activities leads to pollution caused by wastewater and heavy metals, altering the original nutrient profile of mangrove forests and profoundly affecting the animal community and biodiversity (Kruitwagen et al. 2006; Branoff 2017). Further fragmentation of mangroves also occurs because of coastal developments, such as harbors and roadways (Rogers 2004). Therefore, the disappearance of mangroves caused by urbanization is a complex challenge.

The content and value of mangrove ecosystem services are geographically variable (Shih et al. 2015). In some rural areas, mangroves can provide fish, firewood, and various plants for humans (Lee and Yeh 2009), whereas mangroves in urban areas can provide carbon storage, coastal protection, water filtration, and biodiversity for urban dwellers (Everard et al. 2014; Lee et al. 2014). Such services carry tremendous value for cities with high population density, becoming an important countermeasure for climate change mitigation and adaptation and providing opportunities for education, recreation, and cultural development (Duke et al. 2014). Land development occurring because of economic growth and urbanization poses challenges to the survival of urban mangroves, causing problems such as area loss, reduced density, and increased fragmentation (Branoff 2017). Additionally, large amounts of sewage and waste produced by urban activities indirectly cause changes and losses of mangrove ecosystem services, and in turn, this adversely affects the safety and well-being of urban residents (Gilman et al. 2008; Chen et al. 2018). Furthermore, mangrove forests have survived in some cities because of policy-based conservation, even expanding beyond their original size at some places.

Severe damage to mangroves from urbanization partly stems from underestimating the value of ecosystem services provided by mangroves, viewing them instead as a patch of wasteland (Valentine 1994). Conversely, mangroves are included in the existing regional planning of cities as land use sites. The economic, cultural, and political characteristics of a city influence management strategies and the quantity and quality of mangroves (Branoff 2017).

This study was performed with a belief that urban mangroves are embedded in the land use of existing cities and are vulnerable to the impact of the development of surrounding urban areas. Therefore, when evaluating their ecosystem service, it is necessary to approach from various aspects using various models while also paying attention to the impact of changes in surrounding land use on mangroves. This is critical in effectively obtaining overall benefits from mangroves and in establishing an operational and management model consistent with the current situation within the broader spheres of urban planning and conservation policy.

11.2 Study Area and Methods

11.2.1 Study Area

The mangroves in Taiwan are mainly concentrated in the estuary area of the west coast. On the western coast of Taiwan, a large amount of mud is deposited in the estuary area, forming a series of shoals and wide tidal zones; they are extremely suitable for the growth of mangroves. In recent years, under active conservation efforts by the government, mangrove areas have gradually increased (Wang et al. 2015). This study focused on mangrove habitats at the edge of a city and their interrelationships with urban development. The Tamsui River basin in northern Taiwan was selected as the study area in this chapter (Fig. 11.1). Figure 11.2 shows the concrete region included in this study, and additionally, the main tributary of the Keelung River was included to further study the impact of urban mangroves and surrounding land use on ecosystem services. Regarding Taiwan's urban

Fig. 11.1 The Tamsui River basin and related sub-catchments

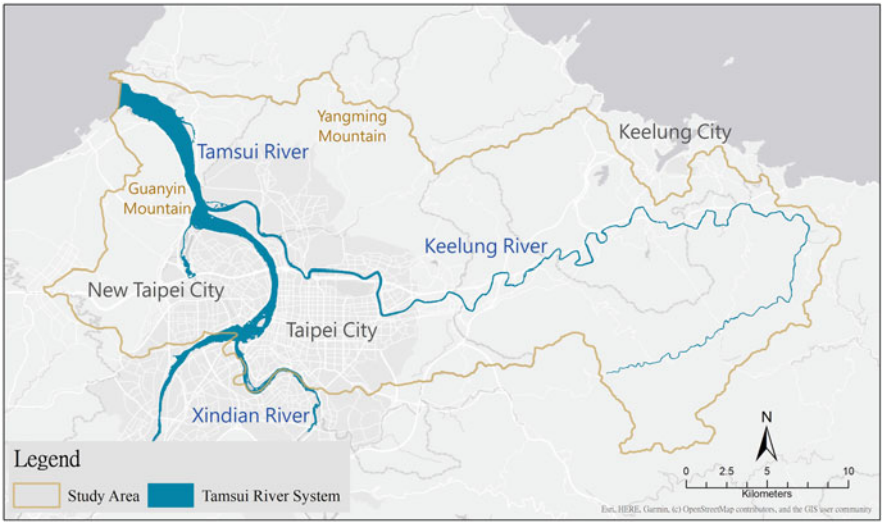

Fig. 11.2 Location of the study area

development, this region has the highest population density and significant urban expansion and is the most threatened region according to future climate change.

The length of the principal stream of Tamsui River is approximately 158.7 km with a basin area of approximately 2726 km^2, making it the third largest river basin in Taiwan (Fig. 11.1). The population of the Tamsui River basin area is nearly 8 million (more than 30% of the national population), along with highly developed industries and commerce. In fact, it is the political, economic, and cultural center of Taiwan. In addition, the ecological environment of the Tamsui River is diverse. The main tributary channel of more than 100 km is connected to high altitude mountains, hills, grassy plains, and tidal estuaries. Moreover, it is an important mangrove habitat in Taiwan (Water Resources Agency 2019). Mangroves in the Tamsui Estuary are mainly distributed in four areas: Wazi Wei, Zhu Wei, Guandu, and Shezidao (Fig. 11.3). The vegetation mainly includes a single mangrove species *Kandelia obovata*, which is the largest habitat of this species in the Northern Hemisphere (Sheue et al. 2003) and the northernmost boundary of distribution (Lee and Yeh 2009).

Since 1984, several conservation laws have been enacted, and various protected areas have been created to conserve the precious mangrove ecosystem. In recent years, under active conservation by the Taiwanese government, the mangrove area has been increasing annually. By 2010, the total area reached 107.9 ha (Wang et al. 2015) (Fig. 11.4). Additionally, the rich mangrove ecosystem has become an important region for environmental education for urban dwellers. The conservation authority has set up a “Mangrove Ecological Education Center” and pedestrian walkways so that citizens can get close to the mangrove ecosystem and understand its presence in the city and the value of ecosystem services provided by it.

Fig. 11.3 Distribution of mangroves in the Tamsui River basin

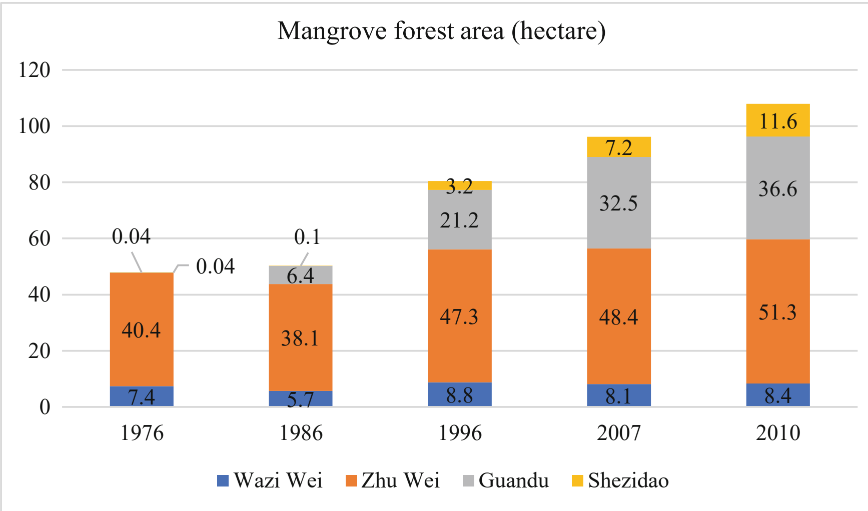

Fig. 11.4 Changes in mangrove area over the years in the Tamsui River basin. Original data source: Wang et al. (2015)

11.2.2 Research Methods

Mangrove ecosystem services are increasingly recognized as pivotal to building nature-based resistance to climate change and hydro-meteorological hazards in urban areas. Broadly, the three methods employed in this study were as follows: (1) land change analysis, (2) ecosystem services evaluation, and (3) hotspot/cold spot analysis for ecosystem services.

11.2.2.1 Analysis of Changes in Land Use

Since the 1990s, Taiwan has actively promoted the Land Use Survey Project hoping to use decennial data to understand trends in land use change and provide a foundation for informed land management and planning. Taiwan's land use survey divided land into nine primary categories: (1) agriculture, (2) forests, (3) transportation, (4) water conservation, (5) construction, (6) public, (7) recreation, (8) mineral salt, and (9) other uses. The land was further subdivided according to 102 classes as per detailed uses (National Land Surveying and Mapping Center 2020). Because mangrove forest information is not recorded in Taiwan's existing land use surveys, we attempted to integrate historical data on mangrove distribution in the Tamsui River with existing land use data. To enable subsequent assessment of ecosystem services, we aimed to reclassify the aforementioned nine land use categories according to their characteristics as follows: forest, water body, paddy, wasteland, grass, industry, traffic, residential land, other urban, and mangrove. These 10 revised categories were input to GIS to convert the data into 100 $\times$ 100 m land use units according to the principle of "maximum combined area."

Using the above sorting process, we obtained raster data for the years of 1994 and 2018. Meanwhile, we used the Map Algebra tool in GIS to compare the land use data from different years to further investigate the overall change in land use, aiming to obtain the land use change data of each unit. This was the basis for subsequent analysis.

11.2.2.2 Ecosystem Service Evaluation

Despite the proximity of the Tamsui River Estuary mangroves to the densely populated Taipei area, their ecosystem service value has been rarely studied. In this study, we integrated the historical distribution of mangroves in the Tamsui River Estuary with existing land use data to evaluate the value of ecosystem services through InVEST 3.8.0. The main assessment items were: (1) carbon storage (ton-C), (2) habitat quality, (3) nutrient (nitrogen) delivery ratio (NDR) (ton-N/year), and (4) sediment delivery ratio (SDR) (ton/hectare/year). The InVEST model performs the assessment of ecosystem service dynamics and sustainability and predicts changes in service functions through contextual analysis. Previous studies using this tool have confirmed the versatility of sustainable land use (Rogers 2004; Zhang et al. 2007; Goldstein et al. 2012; Leh et al. 2013; Delphin et al. 2016; Trisurat et al. 2016; Zarandian et al. 2017). Based on the above studies, this study aimed to: (1) measure "carbon storage," which relates the function of carbon dioxide to the impact of the study area; (2) determine "habitat quality" measure for biological habitat space and study the impact of changes in land use patterns (such as increase in built-up land and decrease in green space) on biodiversity in the study area; (3) calculate "nutrients" or the nutritional value of the soil based on the amount of potential nutrient (N) in the freshwater river stream and the way in which they are transported through natural vegetation; (4) calculate "sediment transport" that reflects the effects of disasters (such as typhoons, floods, and landslides). The situation around the Tamsui River basin was analyzed using these four types of regulating services by ecosystem, and in the context of hotspot analysis, the spatial distribution characteristics of ecosystem services were assessed.

11.2.2.3 Hotspot/Cold Spot Analysis for Ecosystem Services

After obtaining data on the status of ecosystem services in different years, we used GIS Map Algebra to calculate the quantitative changes in ecosystem services in these years. To use statistical methods that can test the spatial aggregation of these changes, we also used the Getis-Ord Gi model to examine the distribution of "hotspots" of ecosystem service change. We treated the difference in ecosystem services between 2018 and 1994 as a random variable "x" and divided the study area into land use units "i" so that the quantitative change corresponding to i can be expressed by "xi." Additionally, we took circular sampling with a fixed radius of 500 m, and other spatial units "j" within this circle were adjacent to the land use units of i. To indicate whether there is spatial aggregation in a particular geographic space, the formula uses a weighted matrix to express "wij." If j is inside the circle with center i and radius d, $wij = 1$; conversely, if j is outside the circle with center i and radius d, $wij = 0$. For spatial unit i, the degree of aggregation between it and all neighboring spatial units j can be expressed using the following formula:

$$Gi^* = \frac{\sum^{n}_{j=1} w_{ij}(d) x_j}{\sum_{j=1}^{n} x_j}$$

After the statistic Gi^* has been standardized, the Z-score of each land use unit was obtained and used to estimate its level of significance. After standardizing the spatial distribution of Gi^*, we can reveal the hotspots for changes in ecosystem services between 2018 and 1994. Based on the distribution of the hotspot, we also examined the changes in the status of land use to determine the land factors affecting their development.

11.3 Results and Discussion

11.3.1 The Changes in Land Use

The Tamsui River basin is the political and economic center of Taiwan, and changes in its land use reflect trends in population, economic development, and social change in the Taipei Metropolitan area. The total drainage area of the study area was approximately 65,721 ha. According to the land use data from 1994, the study area was divided into the following areas: forest 33,618 ha (51.15%), water bodies 3233 ha (4.92%), paddy 5839 ha (8.88%), mangrove 98 ha (4.92%), grass 1500 ha (2.28%), industry 1906 ha (2.9%), traffic 2375 ha (3.61%), residential land 11,163 ha (16.99%), other urban 2459 ha (3.74%), and wasteland approximately 3530 ha (5.37%). The relevant land use is shown in Fig. 11.5.

According to the land use data from 2018, the study area was divided into the following areas: forestry 37,080 ha (56.42%), water body 2698 ha (4.11%), paddy 3496 ha (5.32%), mangrove 104 ha (0.16%), grass 1997 ha (3.04%), industry 1696 ha (2.58%), traffic 3271 ha (4.98%), residential land 14,492 ha (22.05%), other urban 808 ha (1.23%), and waste approximately 79 ha (0.12%). The relevant land use is shown in Fig. 11.6.

When we further analyzed the land use changes in the basin during the 24-year period from 1994 to 2018, it was observed that forestland increased by 3462 ha (+10.3%), grassland increased by 497 ha (+33.13%), and water body decreased by 535 ha (−16.55%). Paddy land was heavily reduced by 2343 ha (−40.13%) due to urban development; similarly, other urban areas saw a steep reduction of 1651 ha (−67.14%). In contrast, land for traffic and residential land increased by

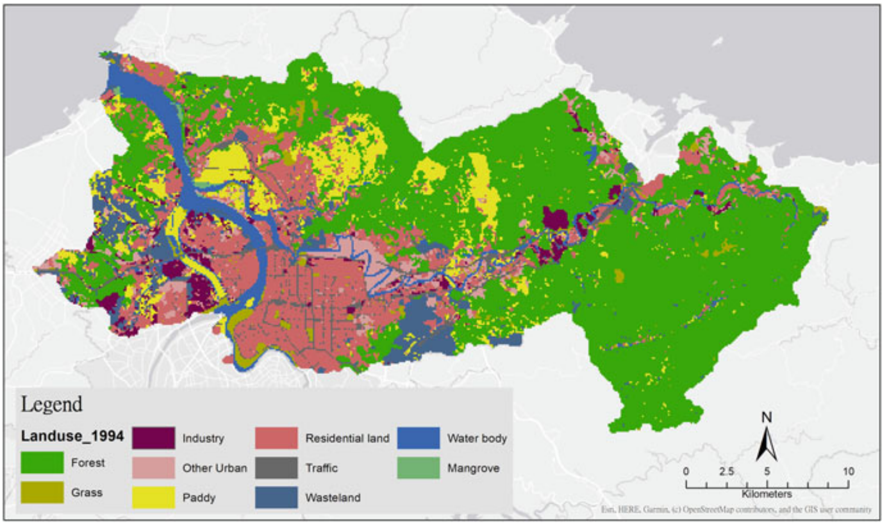

Fig. 11.5 Overview of land use in 1994

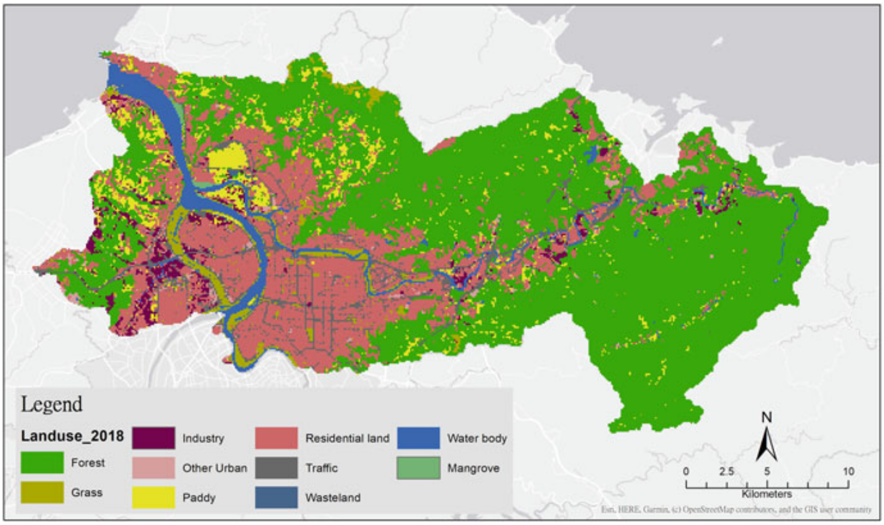

Fig. 11.6 Overview of land use in 2018

896 (positive growth rate of 37.73%) and 3329 ha (positive growth rate of 29.82%), respectively. Finally, the proportion of mangroves increased by approximately 6 ha, with a growth rate of approximately 6.12%, because of the establishment of protected areas and implementation of related conservation measures. Table 11.1 presents the changes in the relevant land use.

In general, the population of the Tamsui River basin increased from 6.2 million to 7.02 million between 1994 and 2018. The changes in land use during the urbanization process reflect the development trend of the Taipei metropolitan area. Although the residential land and other urban areas increased, total industrial land decreased and gradually migrated to the peripheral area. Under the strong control of the urban plan of the metropolitan area, the core area is based on residential land, whereas nearby paddy lands found in low mountain areas are gradually transformed into forests to aid water and land conservation and disaster prevention in the metropolitan area. In addition, under land use in 1994, there was a large area of undeveloped desert, which was gradually transformed into forests and emergent residential areas under the control of the urban plan. This further facilitated urban development. Since the Tamsui River system has always been prone to flooding, prevention of flooding disaster has become an important agenda for the Taipei City Government over the past 30 years. The Taiwanese government has introduced large-scale dike and diversion measures along the Tamsui River to effectively prevent floods caused by typhoons and heavy rains. We observed that a part of the Keelung River, a branch of the Tamsui River, was cut and reclaimed, and the remaining land generated after the reclamation also became a new residential land with a large number of residents and

Table 11.1 Land use changes during 1994–2018 (hectares)

		Year 2018										
		Forest	Grass	Industry	Other urban	Paddy	Residential land	Traffic	Wasteland	Water body	Mangrove	Total (1994)
Year 1994	Forest	30,521	322	156	222	1078	959	257	18	72	13	33,618
	Grass	538	476	9	22	66	225	111		53		1500
	Industry	268	15	702	82	41	631	142	11	14		1906
	Other urban	388	238	157	86	90	1167	290	4	39		2459
	Paddy	2528	331	234	147	1670	671	147	30	79	2	5839
	Residential land	789	98	170	64	172	9496	337	1	36		11,163
	Traffic	117	51	33	36	12	440	1667	1	18		2375
	Wasteland	1868	79	201	130	330	724	138	3	49	8	3530
	Water body	63	374	33	18	37	179	182	10	2326	11	3233
	Mangrove		13	1	1				1	12	70	98
	Total (2018)	37,080	1997	1696	808	3496	14,492	3271	79	2698	104	65,721

commercial activities moving in. These developments occurred alongside the development of the urban flood control plan[1] with tower walls and highways along the Tamsui River being built in large numbers, delimiting a clear and visible boundary between residential land and the body of water.

11.3.2 Changes in Ecosystem Services

After analyzing the data on land use changes in the study area, we used InVEST to assess the ecosystem services within the area. The following results were obtained from InVEST, revealing changes in the study area over the past 24 years. Carbon storage quantities increased from 7,908,912 to 8,530,404 ton/ha; habitat quality measures increased from 41,506 to 42,633, and nitrogen retention reduced from 5446 to 4464. The sediment delivery ratio model reduced from 12,575 (in 1994) to 1752 (in 2018). Figure 11.7 provides a detailed spatial distribution of ecosystem services (Fig. 11.7).

Overall, the ecosystem services in the study area, such as carbon storage and habitat quality, exhibited a slight increase indicating that the overall environmental quality gradually improved. Nitrogen retention and sediment delivery ratio tended to decrease. Among the ecosystem services, a clear change in carbon storage strongly correlated with the amount of forestland. The forests surrounding the Tamsui River basin have a high carbon storage capacity, and the increase in forest area affects the amount of carbon in the ecosystem. This is mainly because the urban plan attaches great importance to the conservation of catchment areas, which has caused many wasteland and paddy land to be converted into forests. The habitat quality range is determined by the degree of threat to the habitat. The value takes between 0 and 1, where 1 defines better habitat quality. This study defined agricultural, residential, and transportation lands as habitats that threaten the survival of organisms and assessed land use based on the presence of threat sources as high- or low-quality occupants. Generally speaking, habitat quality increased incrementally as the distance increased from the city center toward the outer forest. In other words, damage and disturbance from land use were less intensive and habitat quality was higher when we move further away from the urban area. The nutrient delivery ratio (NDR) assesses the correlation between land use and delivery of nutrients (N) particularly focusing on the transformation of agricultural land, which has heavily altered the

[1] Prior to 1980, there was virtually no artificial control of floods of the upper and middle reaches of the Tamsui River. The major erosion and deterioration phenomena caused by the river were driven by natural flows and storm surges. Since 1980, the flood control plan of the Tamsui River basin has been implemented in accordance with the content of the proposal for the flood control plan of Taipei District. The project was completed in 1999. Since then, the erosion and silting processes of the Tamsui River have been overall clearly limited by the twin dikes located on the either riverbank. In 2004, the "Yuanshanzi Flood Diversion Project" was completed in the upper reaches of the Keelung River, bringing a further state of completeness to the Tamsui River flood control system.

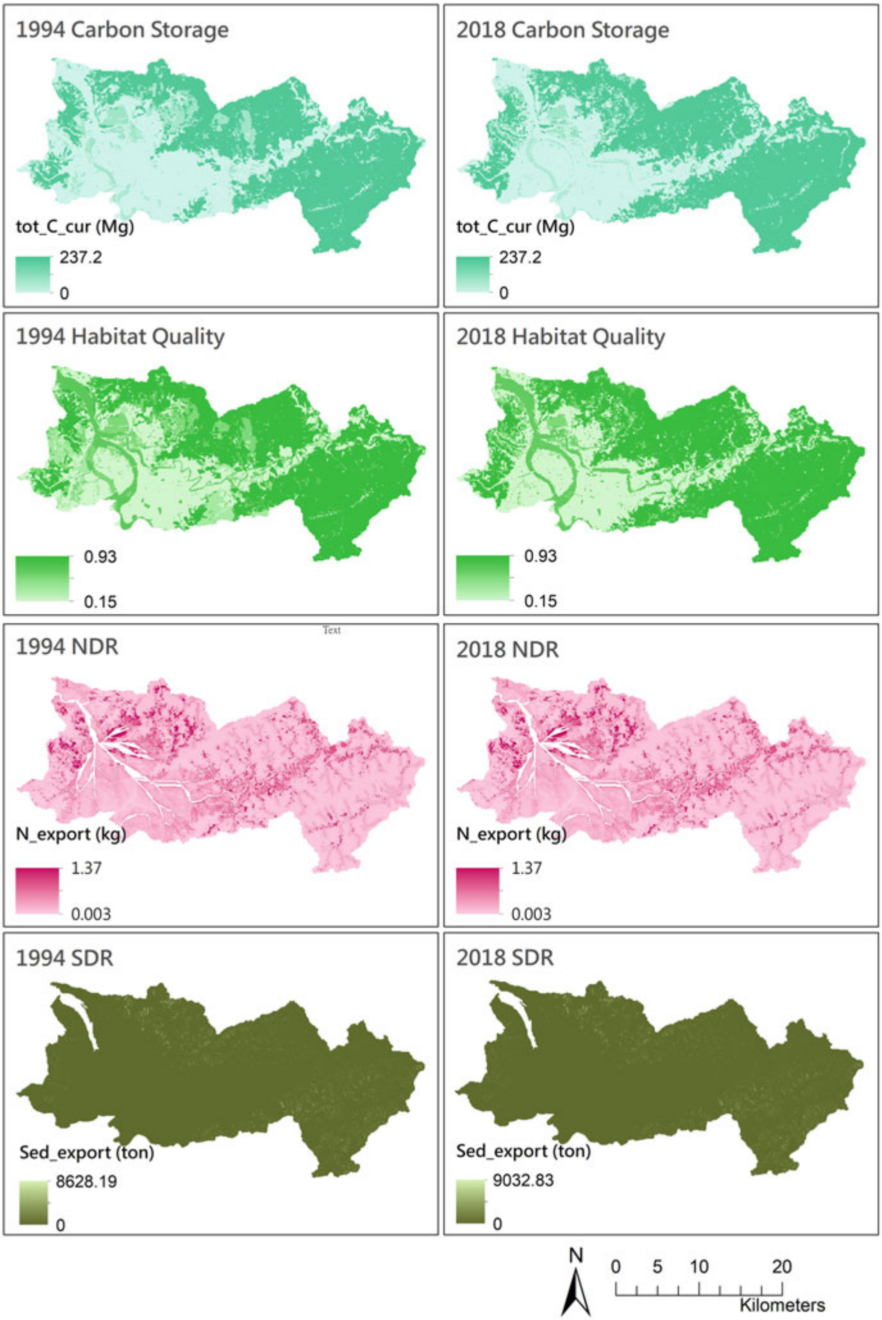

Fig. 11.7 The ecosystem services from 1994 to 2018

natural nutrient cycle. In addition, the impact of rainwater flows can carry urban pollutants into streams, rivers, and oceans. However, ecosystems can retain or degrade pollutants before they flow downstream through purification services. The highest value of nitrogen retention was 9032 kg/year, with its distribution mainly concentrated within agricultural land, wetlands, and grasslands on both sides of the riverbank. Additionally, this land use happens to be the last barrier before pollutants enter the river.

Sediment transport is calculated by the annual ratio between the soil and rock loss of each grid, and the calculation will also be influenced by the grid's digital elevation model. In the sediment delivery ratio (SDR) model, we calculated the annual soil loss of each grid and sediment transport rate to estimate the actual ratio of river soil loss. From the unit calculation results, the soil losses were the highest in the agricultural and desert areas (approximately 1.36 tons). Moreover, it was clearly observed that the area ratio of paddy and desert lands in 1994 was relatively high compared with that in 2018.

11.3.3 Changes in Ecosystem Service Hotspots

To further investigate the differences in ecosystem services between 1994 and 2018, we used the Map Algebra feature in GIS software to compare the values of these 2 years and calculated the "hotspot" based on their differences. This provided an understanding of the distribution trends of the overall variation. Furthermore, we examined the changes in land use in this area by considering the different thermal zones as a category to unravel the impact of changes in urban land use on ecosystem services. Overall, different hotspots for the four ecosystem services including carbon storage, habitat quality, NDR, and SDR are shown in Fig. 11.8.

The main hotspots for carbon storage were found in the Guanyin Mountains on the east side of the Tamsui estuary and in the shallow mountain range around the Tamsui River basin. The primary land use types in the hotspot were forest (73.2%), residential area (12.5%), and paddy (8.1%). Figure 11.9 shows the differences in land use between 1994 and 2018 at the hotspots. The most important elements in this land use change within these categories were: inherent forest (1793 ha), paddy land to forest (1704 ha), wasteland to forest (1658 ha), followed by inherent residential land (569 ha) and wasteland to residential land (195 ha).

The increase in the ecosystem service benefits of carbon storage was mainly because of the increase in forests within the study area. Because Taipei City is an important core city of Taiwan, the primary aim of land use control is to maintain the development of the city while maintaining the safety of the catchment area. Therefore, conservation of the environment is recognized as a critically important task within non-urban mountainous areas, and severe restrictions are imposed. Moreover, urbanization processes in Taipei lead to rural residents living in many surrounding areas to migrate to urban areas, abandoning shallow mountain agricultural land and allowing its transformation into forests. This in turn contributed to the increase in

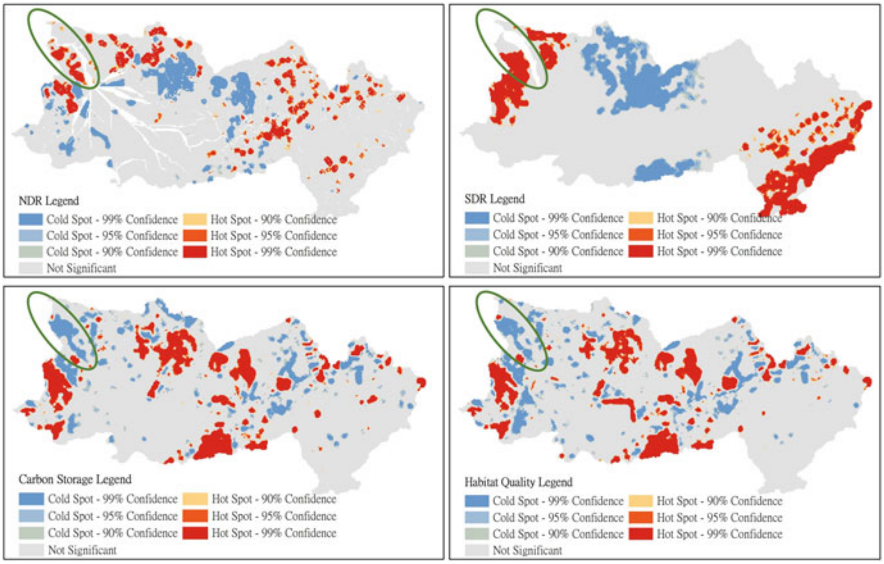

Fig. 11.8 Hotspots of the different ecosystem services between 1994 and 2018. (* Circled area is the mangrove distribution area)

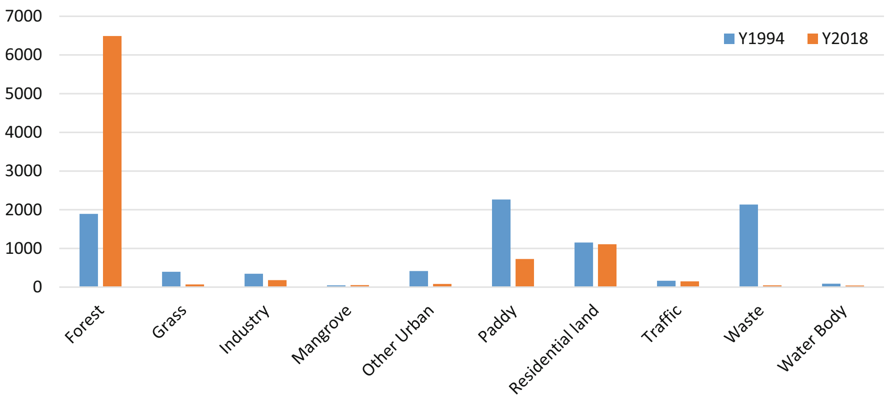

Fig. 11.9 Changes in land use in hotspots with differential carbon storage

carbon storage benefits. Two hotspot blocks were observed inside the mangrove area, and high carbon storage might have contributed directly to the distribution of mangrove forest.

The hotspots related to habitat quality occurred mainly in the Guanyin Mountains east of the Tamsui estuary, the shallow mountain ranges around the city, and the Keelung River valley. This included 68.7% of forests, 12.7% of residential areas, and 7.2% of paddy lands. Figure 11.10 shows the differences in land use between 1994 and 2018 at the hotspots. The most important elements in this land use change

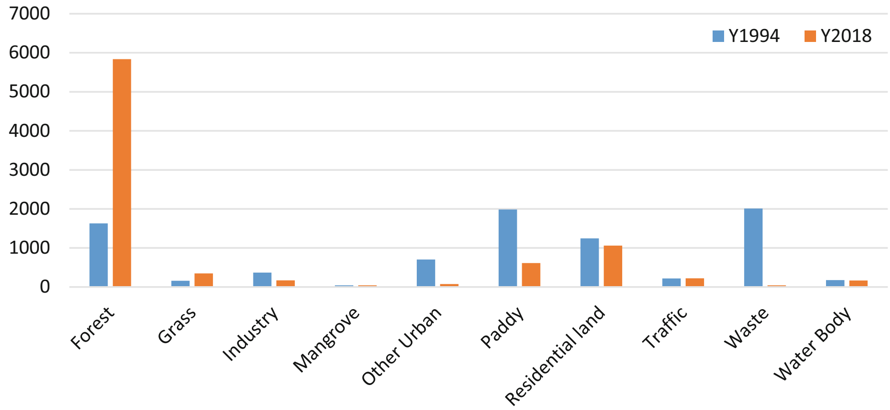

Fig. 11.10 Changes in land use in hotspots with differential habitat quality

were wasteland to forest (1603 ha), paddy to forest (1534 ha), inherent forest (1530 ha), inherent residential land (606 ha), residential land to forest (500 ha), and wasteland to residential land (128 ha).

Numerous factors influence the habitat quality. In addition to changes in land use, other threats include traffic land and settlements. The change trends of habitat quality and carbon accumulation in this study area were roughly the same, both of which increased gradually. The reason might be that the large areas of land under the control of urban and regional planning are gradually being converted into underutilized grasslands or forests. Interestingly, a hotspot for habitat quality change appeared in the city center. This was mainly caused by the flood control project that began in the 1980s and continues today. It has converted the land it reclaimed from the river into park land, providing a rare boost to habitat quality in the center of the city. Inside the mangrove area, two hotspots were observed because of mangrove forest distribution. This was similar to the results of carbon storage.

The NDR hotspots were Guanyin Mountain on the east side and Yangming Mountain on the west side of Tamsui estuary and the upper and middle valleys of the Keelung River, covering 47.2% of forests, 27.8% of residential land, and 17.8% of paddy land. Figure 11.11 shows the differences in land use between 1994 and 2018 at the hotspots. The most important elements in this land use transition were inherent forest (2713 ha), forest to paddy (687 ha), followed by inherent residential area (583 ha) and forest to residential area, with others sporadically distributed.

NDR focuses primarily on the amount of potential nutrients (N) in river basins and the way in which they are transported by natural vegetation. For the hotspots of NDR change identified in this study area, we observed that forests still play an important role, and residential and paddy areas play a secondary role. This trend is reflected not only in the forests of shallow mountains but also in the fields of the river valleys and emerging residential areas developed in response to the housing needs of urban immigrants. The reasons for this trend go beyond the aforementioned regulatory effects of urban and regional planning. They also include the overall impacts on

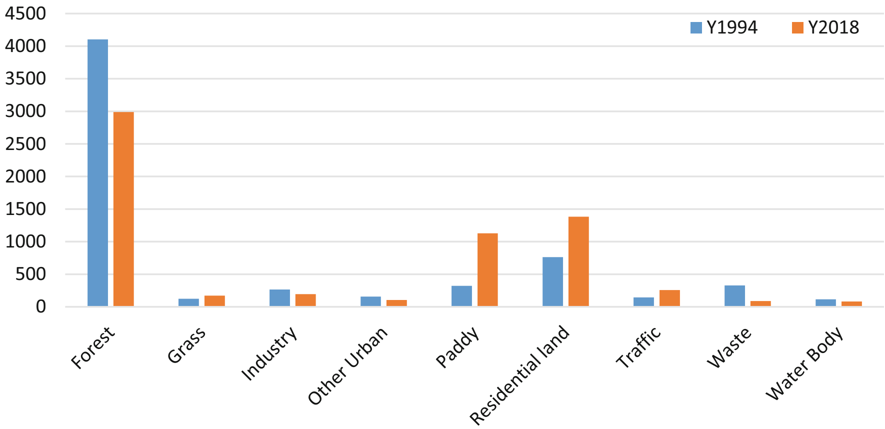

Fig. 11.11 Changes in land use in hotspots with differential NDR

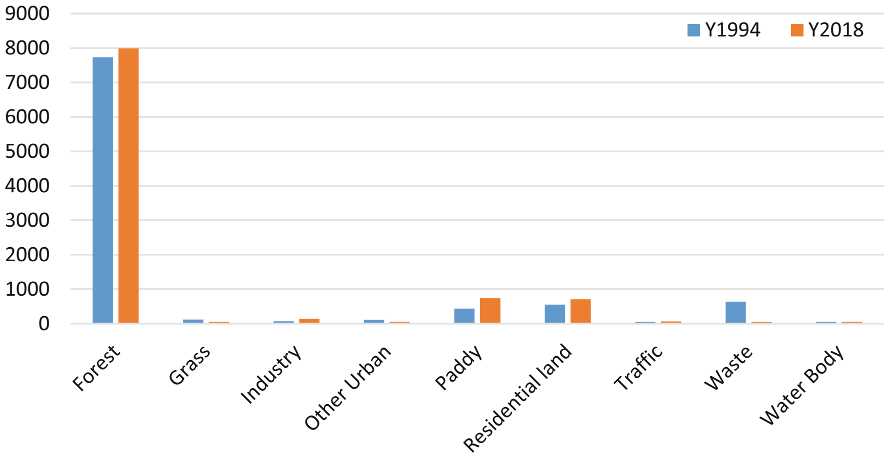

Fig. 11.12 Changes in land use in hotspots with differential SDR

ecosystem services resulting from land use changes caused by urban development (particularly, demand for housing).

Lastly, in the SDR area, the hotspots appeared mainly in the Guanyin Mountains and Yangming Mountains on the east side of the Tamsui estuary and the shallow mountains in the upper parts of the Keelung River, covering corresponded to approximately 83% forest, 7.6% paddy, and 7.3% residential land. Figure 11.12 shows the differences in land use between 1994 and 2018 at the hotspots. The most important elements in land use transition were: inherent forest (7181 ha), wasteland to forest (422 ha), forest to paddy (353 ha), followed by inherent paddy (209 ha) and paddy converted to forest (141 ha). SDR focuses on the measurement of sediment transport in the catchment area and uses it to understand the impact of rainfall, soil, and erosion on sediment retention. By comparing the changes in the land use area, we could observe that the total land and water retention system is guaranteed by the increase in mountain forests, and the distribution of hotspots also showed a similar trend.

Overall, the ecosystem services in the study area gradually improved over the period included in this study. The hotspots of change have been concentrated mainly in the suburbs of the city and the Keelung River valley, whereas the core area of the city showed virtually no significant change. The reason may be that the land use in the core area is stable and highly intensive, such as residential land and other urban areas. The hotspots in suburban hills on the outskirts of the city were observed because of the control of urban and regional plans and migration of farmers to the city. This leads to underutilization of agricultural land, which is gradually transformed into forests and thus improves ecosystem services. In addition, the city's powerful ability to control land is also present in terms of water management. After the ongoing water management projects from the 1980s to the present, large dikes and large public park spaces have been built in Taipei City along the riverbanks within the dikes. Additionally, urban green spaces created by water management have contributed to ecosystem services.

11.4 Conclusion

Mangrove forests in the Tamsui River Estuary are deeply affected by urbanization processes in the Taipei Metropolitan area. The Tamsui River basin is the political and economic center of Taiwan. To keep the capital city free from the threat of natural disasters, the Taiwanese government used high-intensity urban and regional planning to preserve land, water, and overall environmental quality in the upper and middle parts of the catchment. Such measures have been observed to improve ecosystem services in catchment areas. In this study, we examined the interactive relationship between mangroves and changes in urban land use within the watershed. We analyzed the overall changes in ecosystem services from the perspective of multiple types of ecosystem services. In particular, ecosystem services such as carbon storage, habitat quality, NDR, and SDR are quantitatively assessed in this study. An improvement in environmental quality could be seen across these four ecosystem services. In response to an increasing population, many new residential areas have been created around the core of the city; however, because the overall core residential area and land use are stable, they do not have a significant impact on ecosystem services. In contrast, the surrounding hills have gradually become a focal point for improving ecosystem services due to the control of urban planning.

Our analyses indicated that urban mangroves are deeply influenced by urban resilience goals, and their values must be judged from multiple perspectives. Follow-up studies should attempt to integrate land use during multiple time periods with future land planning scenarios to conduct simulation analyses of land use changes. Such research can productively improve the understanding of the potential impacts various land development policies will have on mangroves and the surrounding urban environment. Current ecosystem assessment methods calculate the impact factor primarily from land use. In case of mangrove forests in the Tamsui River estuary, the opportunities for environmental education and cultural services provided by mangrove forests have become increasingly important, indicating the need for a broader perspective than that which forms judgment from land use alone. In the future, when evaluating the cultural service value of urban mangroves, it is advisable to include divergent views of stakeholders and to link the characteristics of mangroves to urban society to more precisely measure the cultural value and extent of the influence of mangroves.

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Chapter 12
Diversity and Structural Characteristics of Mangrove Forests in the Southern District of Oriental Mindoro, Philippines

A. F. M. Raganas and D. B. Magcale-Macandog

Abstract Mangrove ecosystem is a highly dynamic environment due to the tidal and seasonal variations of its physical and chemical properties, influencing its diversity and community structure. Six mangrove ecosystems on the southern coast of Oriental Mindoro, Philippines, were studied, and their species composition, diversity, and structural community were determined using various diversity indices and vegetation analyses. Twenty-four mangrove species were recorded which was higher compared to the previous assessment conducted in 2014. The highest species richness was recorded in Roxas (16 species), while the lowest was recorded in Bongabong (nine species). Common mangrove species in the study sites are *Avicennia rumphiana*, *Excoecaria agallocha*, *Rhizophora apiculata*, *Rhizophora mucronata*, and *Sonneratia alba*. Interestingly, six species are considered new records in the southern district including *Acanthus ebracteatus*, *Acanthus volubilis*, *Acrostichum aureum*, *Acrostichum speciosum*, *Heritiera littoralis*, and *Scyphiphora hydrophyllacea*. Species diversity varied per mangrove site, with Roxas having the highest diversity and Gloria having the lowest. In terms of evenness, mangrove site in Bongabong has highly proportional species abundance distribution. The most diverse mangrove ecotypes can be found in the middle and landward zones, where growth conditions are favorable. The abundance of regenerating and small stem-sized mangrove trees classified the mangrove forest communities in Gloria, Bongabong, Roxas, and Bulalacao as early growth, whereas the mangrove community structures in Bansud and Mansalay were classified as old growth, characterized

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A. F. M. Raganas
Department of Biological Sciences and Environmental Studies, College of Science and Mathematics, University of the Philippines Mindanao, Mintal, Davao City, Philippines

WISER BioCon Lab, College of Science and Mathematics, University of the Philippines Mindanao, Mintal, Davao City, Philippines
e-mail: amraganas@up.edu.ph

D. B. Magcale-Macandog (✉)
Institute of Biological Sciences, College of Arts and Sciences, University of the Philippines Los Banos, Laguna, Philippines
e-mail: dmmacandog@up.edu.ph

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by large boles and tall mangrove trees. Occasional mangrove tree cutting and fishpond activities are both regarded as potential threats to the mangrove areas. Local environmental authorities should design their own mangrove conservation framework to guide them conserve and manage their local mangroves.

Keywords Diversity · Mangroves · Structural characteristics · Oriental Mindoro

12.1 Introduction

The Philippine archipelago is rich in mangrove forests along with its coastal areas and caters to around 50% of the known mangrove species worldwide (Primavera et al. 2004; Garcia et al. 2014; Buitre et al. 2019). Of the 70 mangrove species worldwide (Spalding et al. 2010; Abantao et al. 2015), around 39 species including the associates are found in the Philippines (Primavera et al. 2004; Sinfuego and Bout 2014). The majority of the common genera found in the country are *Rhizophora*, *Avicennia*, *Bruguiera*, and *Sonneratia* (Calumpong and Menez 1997). In 1920, the total mangrove coverage for the entire country was estimated at a total of around 400,000–500,000 hectares (ha) (Brown and Fischer 1918; Chapman 1976; Primavera 2000; Garcia et al. 2014). Despite the established protective legislation in the Philippines, mangrove ecosystems are still at risk, threatening their future abundance and distribution. Even though the mangrove ecosystem is a valuable bio-network, its diversity and expanse are increasingly being threatened (Xie et al. 2020). This ecosystem is continually experiencing decline due to the various types of anthropogenic activities including land conversion.

The mangrove ecosystem is considered one of the highly productive ecosystems in the marine environment. Its unique ecological functions and the variety of ecosystem services that it can provide to the environment and society are already known for many decades (Heumann 2011; Buitre et al. 2019). Protection of coastal areas and communities from tidal surges during typhoons (Soegiarto 2004) is one of the major services mangrove ecosystems provide. The crown and stem of mangrove trees serve as physical barriers, and their specialized root systems trap and hold sediments from the upland areas (Srikanth et al. 2016). The ecosystem also serves as a habitat for many aquatic and terrestrial organisms (Buitre et al. 2019). However, its resiliency has been threatened by anthropogenic activities (Adger 1997; Buitre et al. 2019). Increase population pressure along the coasts, poverty, lack of livelihood options (Macintosh and Ashton 2002; Chowdhury et al. 2019; Begam et al. 2020), reclamation of lands for aquaculture, salt-pond construction (Terchunian et al. 1986; Primavera 1995), and pollution (Lewis 1990) are among the anthropogenic forces that drive mangrove ecosystem's degradation (Pearce 2002; Garcia et al. 2014; Begam et al. 2020). The change in global climate as characterized by the increase in temperature, altered precipitation patterns, and sea-level rise has also been linked to the decline of mangrove coverage around the world (Buitre et al. 2019; Chowdhury et al. 2019; Begam et al. 2020).

Oriental Mindoro is a province located in the southwestern part of Luzon, facing south of the Verde Island Passage which is home to diverse marine organisms. Among its valuable biodiversity features is the mangrove ecosystem. However, for many decades the mangrove ecosystems in the province have experienced threats due to human activities. Vegetation survey of mangrove ecosystems in the province in 2014 recorded around 5–13 species per municipality (Cayabyab 2014). This study aimed (1) to assess the current status of the mangrove species composition in six mangrove areas in the southern district of the province and (2) to determine their diversity, similarity, and community structures. Additionally, this study also aimed to identify changes in the mangrove composition patterns in the southern district of the province. The identification of mangrove species, particularly in places where they have not yet been surveyed, is a critical piece of knowledge that this study can provide. The findings of this study will be useful as additional information concerning mangrove species composition, diversity, and structural characteristics of mangrove forests in Oriental Mindoro province. The results are expected to provide a scientific foundation for advocating effective sustainable management approaches on the mangrove ecosystems in the province.

12.2 Materials and Methods

12.2.1 The Study Sites

Oriental Mindoro is one of the two provinces of the Mindoro Island in southwestern Luzon. In 2010, the province has approximately 2392 ha of mangrove forests located in 13 coastal municipalities (Cayabyab 2014). The study sites were located in the southern district (from 12°53′N and 121°29′E to 12°19′N and 121°21′E) of the province, comprising of six municipalities—Gloria, Bansud, Bongabong, Roxas, Mansalay, and Bulalacao (Fig. 12.1). These municipalities cover approximately 661.02 ha of mangrove forests as of 2010 (Cayabyab 2014). The study sites were selected based on the size, characteristics, and unavailability of information of a particular mangrove area. The zonal ecotypes of each mangrove site were then identified such as the seaward, middle, landward, and riverine zones. The identification was based on the following features: seaward zone, situated at the intertidal zone where mangroves are daily submerged to seawater, and middle zone, situated at the transition zone between the seaward and the landward zones, at least 8–10 m away from the seaward zone. However, the distance is still determined by each mangrove area's geophysical formation. Landward is a zone inland from the boundary of the middle zone, and riverine as zone located along the river bank or estuarine.

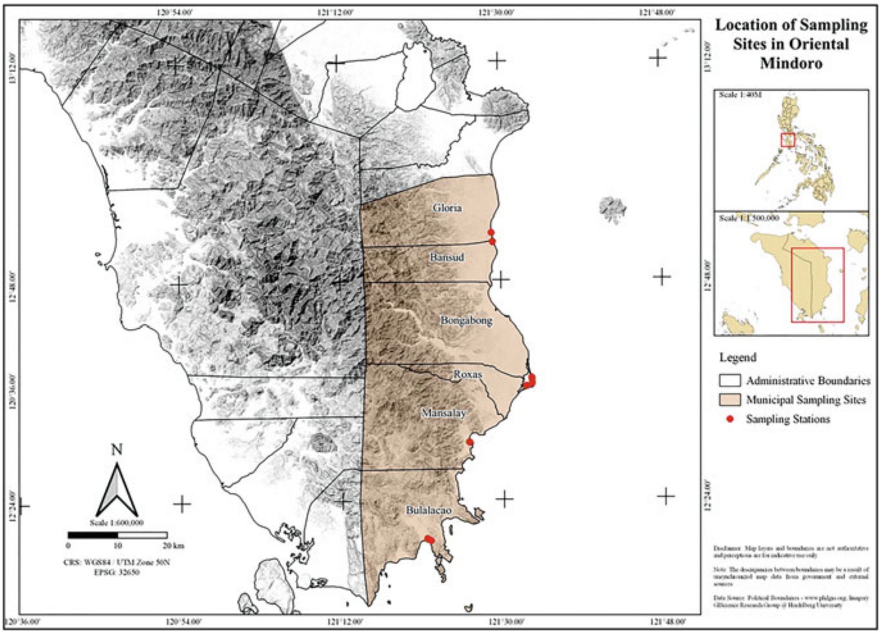


Fig. 12.1 Location of study sites in the southern district of Oriental Mindoro, Philippines. (Map generated QGIS v.3.3.10. made by J. W. Edaño)

12.2.2 Data Collection

A stratified random sampling (SRS) method was employed to determine the mangrove species composition in each mangrove site. Four 100-m transect lines were established at the seaward, middle, landward, and riverine zones of each mangrove site. Five plots measuring 10×10 m^2 were laid within each transect line with 20-m intervals using Gareth's method (1991), to determine species diversity and composition of the mangrove community. All the mangrove species including the associates within the plot were recorded and identified. Materials and equipment such as measuring tape were used to determine the distance and plot size on the ground. Geographic Positioning System (GPS) device was used in tagging and in getting the coordinates of all the plots in each zone per site. Notepad, ball pen, and pencil were used to record all the data.

Vegetation measurements which include species density, frequency, basal area, tree height, and diameter at breast height (diameter at 1.3 m above ground) were recorded to determine the community characteristics of each mangrove stand. Tree heights were measured in meters using Haga Altimeter, while stem diameter was measured in centimeters using a tape measure. A total of 117 plots for vegetation survey were established in all study sites. Mangrove species were directly identified on-site using the field guide for Philippine Mangroves by Primavera et al. (2004) and based on the knowledge of the local field guides. Species conservation status was also determined according to the Department of Environment and Natural Resources (DENR) Administrative Order 2017-11 (DAO 2017-11) and The IUCN Red List of Threatened Species version 2021-3 (http://www.iucnredlist.org). All the data were collected from October to November in 2018.

12.2.3 Diversity Analysis

Various diversity indices were used to determine and compare species diversity in six mangrove areas. Three of the common diversity indices were employed in the study, namely, species richness, species evenness, and species heterogeneity for characterizing the species diversity of a mangrove community using the standard methods outlined by Magurran (2004). Species richness (S) was obtained from counting the number of species encountered in each mangrove ecosystem. Whereas, species evenness was measured using Pielou's Index of Evenness (J) which measures the evenness wherein individuals are divided among the taxa present. Species evenness assumes a value between 0 and 1, with 0 being no evenness (one single species dominant) and 1 being complete evenness.

The species heterogeneity of each mangrove ecosystem was calculated using the Shannon-Wiener index (H') and Simpson's index of diversity ($1-D$). Shannon-Wiener diversity index takes into account the number of individuals as well as the number of taxa of a particular ecosystem. Values range from 0 for communities with only a single taxon (low diversity) to high values for communities with many taxa (high diversity). Meanwhile, Simpsons' Index of Diversity $1-D$ takes into account the number of species present as well as the evenness of each species in a particular ecosystem. It quantifies the biodiversity of a forest community with values ranging from 0 (considered no diversity) to 1 (considered high diversity).

12.2.4 Species Similarities

On the other hand, species similarities across mangrove areas based on the presence/absence data of all mangrove species encountered in all sampling points were analyzed using Bray-Curtis Similarity Index using Unweighted Paired Group (UPGMA) algorithm. The result was presented through a cluster dendrogram. All these statistical analyses were analyzed using PAST software version 4.02 (Hammer et al. 2001).

12.2.5 Mangrove Structural Characteristics

The ecological importance of each mangrove species was calculated by summing up their relative density, relative frequency, and relative dominance. The relative frequency was determined based on the number of times the species was recorded in a given number of repeatedly established sample plots per ecotype per mangrove site. Relative density was determined based on the number of individuals of a particular species encountered in a given number of sample plots per ecotype of each mangrove site. The relative dominance was determined using the basal area (m^2), which is the total circumference at the breast height level of all the stems of the individuals of a particular species encountered. However, for multi-trunk mangrove trees, the dbh of each tree trunk was measured separately (see formula below). The Species Importance Value (SIV) was then calculated to determine the mangrove species of a mangrove community with the highest importance value. It is the sum of the relative frequency, relative density, and relative basal area of all the species encountered. Results of vegetation analyses were expressed in percentage. All the measurements were calculated following the Curtis and McIntosh (1951) method.

For the basal area (m^2) of each species especially with multiple trunks, the DBH of the whole tree was obtained by calculating the square root of the sum of all squared trunk stems DBHs. The DBH of the whole tree was then determined using the foresters' constant formula:

$$\mathrm{BA} = 0.005454 \times \mathrm{DBH}$$

12.3 Results and Discussion

12.3.1 Mangrove Composition Across Mangrove Sites

The six mangrove sites in southern Oriental Mindoro cover approximately 661.02 ha as reported by Cayabyab (2014). Accordingly, the largest mangrove area cover was located in the municipality of Bongabong with approximately 344.67 has, while the smallest was located in Mansalay with approximately 20.34 has only. Three mangrove areas were newly assessed in this study specifically in the mangrove areas of Bongabong, Mansalay, and Bulalacao. A total of 24 mangrove species were recorded in all study sites (Table 12.1). Among the study sites, highest number of species was recorded in Roxas (16), followed by Gloria (13), Bansud (13), Bulalacao (12), Mansalay (11), and Bongabong (9), respectively. An increase of mangrove species record was observed in the southern district, from a total of 19 species in the previous study in 2014 to 24 species in the recent study. Most of the new recorded species was identified from the previously assessed mangrove areas in Gloria, Roxas, and Mansalay.

Table 12.1 Comparison of the recorded mangrove species across mangrove sites in southern Oriental Mindoro, from the previous (2014) and current (2018) assessments

Municipality	Mangrove species records	
	Previous record (Cayabyab 2014)	Recent record (2018)
Gloria	7	13
Bansud	13	13
Bongabong[a]	13	9
Roxas	11	16
Mansalay[a]	5	11
Bulalacao[a]	8	12
Total no. of species	19	24

[a]Newly assessed mangrove areas

Among the 24 mangrove species recorded in the recent study, six new record species were added to the list which include *Acanthus ebracteatus* Vahl, Symb.; *Acanthus volubilis* Wall.; *Acrostichum aureum* L.; *Acrostichum speciosum* Willd.; *Heritiera littoralis* Aiton; and *Scyphiphora hydrophyllacea* C.F.Gaertn. which are mostly mangrove associates except for the two latter species. Meanwhile, *Avicennia rumphiana* Hallier f., *Excoecaria agallocha* L., *Rhizophora apiculata* Blume, *Rhizophora mucronata* Lam., and *Sonneratia alba* Sm. are the most common mangrove species in all study sites. Large number of species was represented by Rhizophoraceae family. One vulnerable (*Avicennia rumphiana*), and two near threatened (*Aegiceras floridum* Roem. and Schult., and Ceriops *decandra* (Griff.) W.Theob.) species were recorded in the study sites, while the other species were considered least concern (Table 12.2).

In terms of species composition similarity (Fig. 12.2), the Bray-Curtis Similarity Index demonstrated that Bongabong and Bulalacao have the highest species similarities among the mangrove sites. Although other mangrove sites such as Bansud and Roxas also show high species similarities. Gloria's dissociation from the clustering could be traced to species *A. aureum*, which was only found at this mangrove site (Table 12.2). Overall, approximately 40% of the total mangrove species recorded were common in the southern district.

12.3.2 Species Diversity Across Mangrove Sites

Comparing the species richness of the mangrove vegetation across all sites, the study site in Roxas had the highest species richness (16), while Bongabong (9) had the lowest. In terms of species abundance, Mansalay (365) had the highest, while Bansud (309) had the lowest (Fig. 12.3).

With regard to species diversity (Fig. 12.4), Shannon-Weiner index (Fig. 12.4a) shows that the mangrove site in Roxas (2.229) had the highest diversity followed by Bansud (2.027), Bulalacao (2.011), Bongabong (2.008), Gloria (1.870), while Mansalay (1.810) had the lowest. This finding is supported by Simpson's $1-D$

Table 12.2 List of recorded mangrove species across six mangrove sites in southern Oriental Mindoro, Philippines

Family	Species	Study sites						Habit	Con Stat
		Gloria	Bansud	Bongabong	Roxas	Mansalay	Bulalacao		
Acanthaceae	*Acanthus ebracteatus* Vahl, Symb.	√[a]	√	–	–	√	–	Shrub	LC
	Acanthus volubilis Wall.	–	√[a]	–	–	–	–	Shrub	LC
	Avicennia marina (Forssk.) Vierh.	–	–	√	√	√	√	Tree	LC
	Avicennia rumphiana Hallier f.	√	√	√	√	–	√	Tree	VU
Arecaceae	*Nypa fruticans* Wurmb	√	√	–	√	–	–	Palm	LC
Combretaceae	*Lumnitzera littorea* (Jack) Voigt	–	–	√	–	–	–	Shrub	LC
	Lumnitzera racemosa Willd.	–	–	√	√	√	√	Shrub	LC
Euphorbiaceae	*Excoecaria agallocha* L.	√	√	–	√	√	√	Tree	LC
Lythraceae	*Sonneratia alba* Sm.	√	√	√	√	√	√	Tree	LC
Meliaceae	*Xylocarpus granatum* J.Koenig	√	–	–	√	–	√	Tree	LC
Myrtaceae	*Osbornia octodonta* F.Muell.	√	√	–	–	–	√	Shrub	LC
Primulaceae	*Aegiceras corniculatum* (L.) Blanco	√	√	–	√	–	√	Shrub	LC
	Aegiceras floridum Roem. and Schult.	–	–	–	–	√	–	Shrub	NT
Pteridaceae	*Acrostichum aureum* L.	√[a]	–	–	–	–	–	Shrub	LC
	Acrostichum speciosum Willd.	–	–	–	√[a]	–	–	Shrub	LC
Rhizophoraceae	*Bruguiera cylindrica* (L.) Blume	–	√	–	√	√	–	Tree	LC
	Bruguiera gymnorhiza (L.) Lam.	√	–	–	√	–	–	Tree	LC
	Bruguiera parviflora (Roxb.) Wight and Arn. ex Griff.	–	–	–	–	–	√	Tree	LC
	Ceriops decandra (Griff.) W.Theob.	√	√	√	√	–	–	Shrub	NT
	Ceriops tagal (Perr.) C.B.Rob.	–	√	–	√	√	√	Shrub	LC

	Rhizophora apiculata Blume	√	√	√	√	√	√	Tree	LC
	Rhizophora mucronata Lam.	√	–	√	√	√	√	Tree	LC
Rubiaceae	*Scyphiphora hydrophyllacea* C.F.Gaertn.	–	–	√	√[a]	–	–	Shrub	LC
Sterculiaceae	*Heritiera littoralis* Aiton	–	√	–	–	√[a]	–	Tree	LC

Check (√) means present, while (–) means absent. Species conservation status (ConStat): *VU* vulnerable, *NT* near threatened, *LC* least concern based from the IUCN Redlist of threatened species website and DAO 2017–11

[a]New species record in southern district

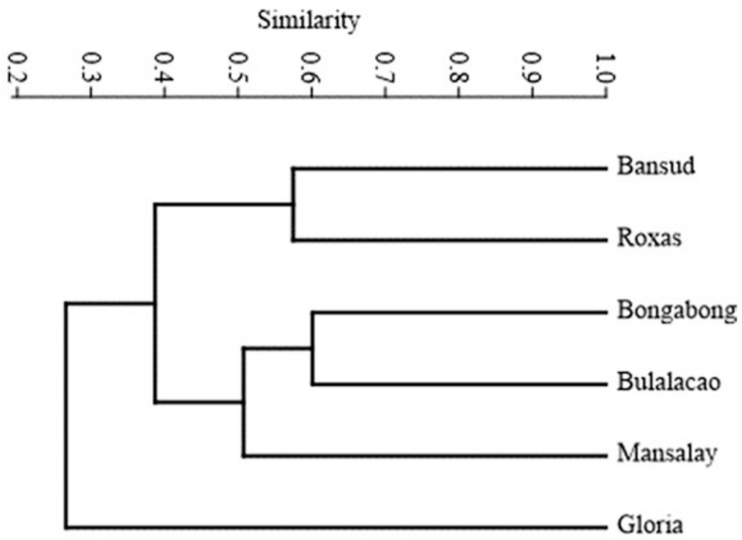
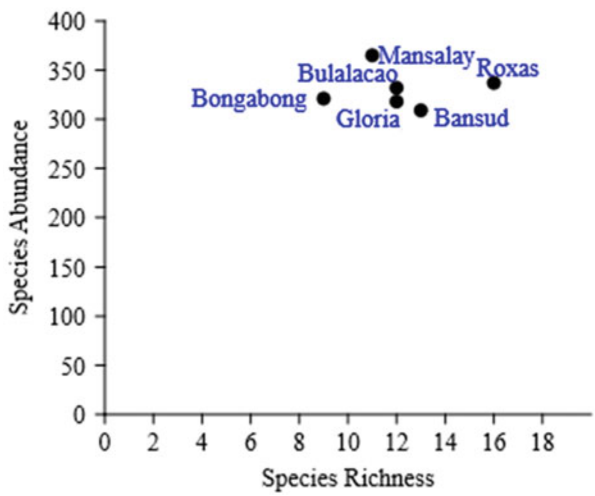


Fig. 12.2 Cluster dendrogram showing similarities of species composition across mangrove sites using Bray-Curtis Similarity Index

Fig. 12.3 Species richness and abundance across mangrove sites



Index (Fig. 12.4b) which also shows similar trend with Roxas (0.854) being the highest and Mansalay (0.775) being the lowest. Generally, the diversity index of the six mangrove areas falls within the range above 1 (Shannon-Weiner index) and above 0.5 (Simpson's index of diversity) which indicate that these mangrove areas have well-diversified forest communities (Margalef 1972; Singh 2020). Hence, the diversity of a particular ecosystem does not account only for the total number of species but also for the relative abundance of each species present.

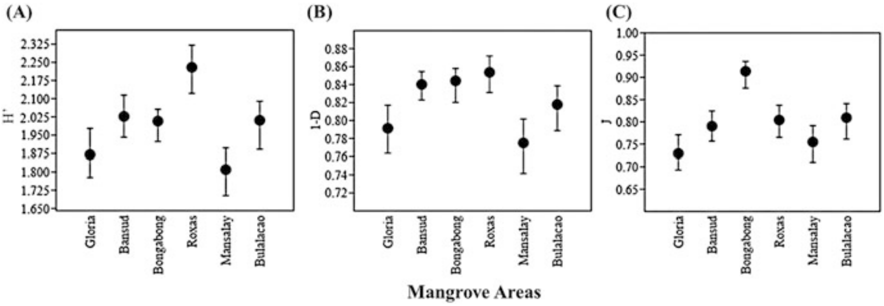


Fig. 12.4 Species diversity across six mangrove sites using (**a**) Shannon-Weiner Index (H′), (**b**) Simpson's Index of Diversity (1−D), and (**c**) Pielou's Index of Evenness (J)

On the other hand, Pielou's Index of species evenness (Fig. 12.4c) indicates the degree of structuring of community which was constrained between 0 and 1. The Pielou's evenness values closed to 1 indicates that most mangrove sites have low variation of species abundances within plant communities, meaning that all species occur in relatively similar proportion. According to the report of Singh (2020), with higher species richness and evenness in a mangrove community, the diversity is expected also to be higher. Among the study sites, the mangrove community in Gloria showed quite low evenness compared to the other sites, while Bongabong showed the highest species evenness. Based on these diversity results, the study assumed that the variation in species diversity in all mangrove sites may depend on the degree of disturbances that have occurred in each site. The type of substrate and exposure to high salinity through tidal inundation may contribute to the disproportion of species diversity.

12.4 Mangrove Structural Characteristics

Vegetation analysis is important in determining the species composition and structural characteristic of a mangrove community. Results of this study show that the mangrove stand of Gloria (Fig. 12.5) was characterized by the abundance and dominance of *R. mucronata* species, followed by *C. decandra* and *X. granatum*. The abundance and dominance of *R. mucronata* was greatly attributed to the rehabilitation program implemented by the local government (MENRO, pers.com). As observed during the vegetation survey, the highest species richness was recorded in the riverine zone of the mangrove forest but was highly dominated by *R. apiculata* species. The vegetation structure of the mangrove forest was considered an early growth stand as evidenced by the abundance of regenerating mangrove trees. On the other hand, the species with large boles as well as those with highest density greatly contributes to the importance value of a particular species. This correlates to the high

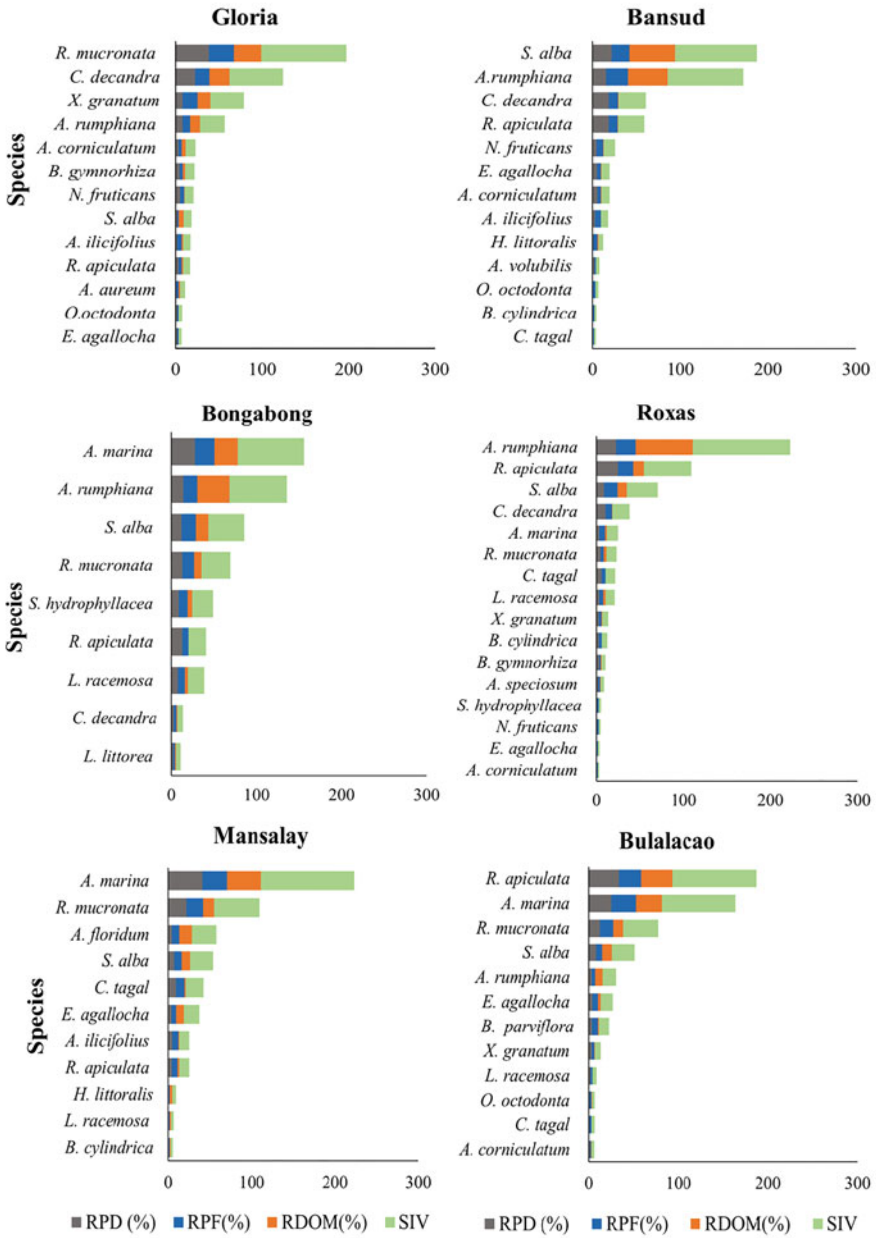


Fig. 12.5 Structural characteristics of the six mangrove stands showing the relative population density (RPD), relative population frequency (RPF), relative dominance (RDOM), and species importance value (SIV) of each mangrove species across mangrove sites

importance value observed among the species *R. mucronata*, *C. decandra,* and *X. granatum* in the entire mangrove stand.

In Bansud, the mangrove vegetation structure was considered old growth characterized by the large boles and tall heights of the mangrove trees. *Sonneratia alba* and *A. rumphiana* were the mangrove species with the largest basal area and thus considered to be the pre-dominant species in the mangrove stand. In contrary, those species having small-sized stem diameters or with very few number of individuals were having low dominance. Among the recorded species, *A. rumphiana* was observed to be the most abundant species. However, the species had lower dominance compared with *S. alba*. Moreover, these two species are considered to have highest importance value in the mangrove stand. Meanwhile, shrubs and other understory mangroves were among the species with low importance value, mainly attributed to their smaller basal area and low individual counts.

In Bongabong, the mangrove structure was characterized as early growth stand due to the abundance of regenerating trees. The mangrove area was previously exposed to a huge fishpond operation but was currently abandoned and rehabilitated with *R. mucronata* species. The seaward zone of the mangrove stand was observed to be dominated by the coconut (*Cocos nucifera*), pandan (*Pandanus* sp.), and aroma (*Acacia farnesiana*) species. Species *Avicennia marina* and *A. rumphiana* were among the most abundant and dominant species and thus considered to be the species with highest importance value in the mangrove stand.

Meanwhile in Roxas, the mangrove area is located adjacent to a huge coastal community. Large fishpond plots were observed within the mangrove stand. Most of the large-sized mangrove trees were only thriving along the edges of river systems within the mangrove stand. A large proportion of these fishpond areas were already abandoned and rehabilitated with *R. mucronata* species, especially in the landward zone. The mangrove area was generally characterized as an early growth stand due to the abundance of regenerating mangroves. The mangrove species found within the stand showed an immense disparity in terms of density and dominance. Some species with higher densities were having very low dominance due to their small stem sizes, similar to the observations from the other mangrove areas mentioned above. *Avicennia rumphiana* was the only species with large boles, thus showing high dominance and importance value in the entire mangrove stand. It is the only species that has remained untouched thriving along the edges of the river banks. The small stem diameter sizes of most of the mangrove species are a manifestation of the regenerating conditions of the mangrove forest. Hence, the entire mangrove stand is still recovering after its exposure from the impacts of fishpond activities in a long time.

In Mansalay, the mangrove structure was characterized as an old-growth stand with huge and tall mangrove trees. The mangrove stand is dominated by *A. marina* species from the seaward up to the landward zones thriving in a muddy substrate. The seaward zone with seagrass beds is planted with *R. mucronata* but has stunted growth due to unsuitable substrate for the species. The middle zone has the highest species richness, owing to the combination of species found in both seaward and landward zones. Similar to the observations in other mangrove areas, mangrove species in Mansalay also showed variations with regard to densities and dominance. The variations directly correlate to the differences in stem diameter sizes and densities. *Avicennia marina* is regarded as the species with highest importance value in the mangrove stand.

In Bulalacao, *R. apiculata* and *A. marina* are the species with the highest densities and dominance in the mangrove stand. The abundance of *R. apiculata* particularly in the riverine zone, was attributed to the high number of individual count in all plots but with smaller stem diameters, implying a lesser dominance over *A. marina*. In contrary, *A. marina* with a lower individual count has a larger stem diameter, contributing to its dominance in the riverine zone. In the entire mangrove stand, the species regarded highly important were *R. apiculata* and *A. marina*. However, as observed during survey, three species dominated the mangrove stand from the seaward to the landward zones, which are *A. marina*, *R. apiculata*, and *R. mucronata*. The former species was observed dominant in all zones co-dominated by *R. apiculata*. However, *R. mucronata* was observed abundant along the seaward zone which was attributed to the tree planting activities conducted in the zone. The vegetation structure of the entire mangrove stand was considered early growth as observed through the abundance of regenerating and small-sized mangrove trees.

12.5 Discussion

Mangrove species density, frequency, and basal area varied throughout the six mangrove sites studied. The variability appears to be linked to the degree of disturbances occurred in each mangrove site. Differences in species frequencies indicate the spatial distribution of the mangrove species in a mangrove stand. For instance, species frequently observed are those that are widely distributed, while those that are not are the species with sparse distribution. According to Strauch et al. (2012), the abundance and distribution of mangrove species are typically associated with abiotic factors such as nutrient availability, salinity level, soil composition, tidal inundation, and biotic processes such as species competition. This is somehow true with regard to the abundance and distribution patterns of mangrove species in the study sites. As observed, the species with high tolerance to salinity such as *A. marina*, *S. alba*, and *R. apiculata* can grow better in the highly saline substrate, whereas those species with low tolerance to salinity usually grow inland or distant from the sea. Because the inland environment is favorable for all mangrove species, it is likely that competition (interspecific and intraspecific) for resources will be high, resulting in a sparse distribution of species. Tidal currents, for example, may also influence mangrove distribution by dispersing propagules. Another factor is land barriers, which may prevent propagule movement, resulting in sporadic dispersal (Numbere 2018). We hypothesized that differences in the density, frequency, and dominance of different mangrove species in the study areas were influenced by competition between and among species, as well as natural disturbances (Verberk

2011). The structural characteristics of each mangrove ecosystem may also be influenced by their habitat preferences, as well as the size and age of each species.

Interestingly, an increase in the number of species records was observed in the recent assessment which may lead to various implications. First, that the mangrove areas in southern Oriental Mindoro are already recovering from past disturbances as manifested by the presence of newly recorded species. The open spaces brought about by the extensive fishpond activities may encourage recruitment of mangrove species allowing them to grow and establish in these mangrove areas. Accordingly, when a disturbance occurred in a particular site that resulted in the opening of the forest canopy, more light could reach the ground surface and facilitate the establishment of seedlings (Alemayehu and Chemuku 2017). Another cause for the disparity in the number of species recorded between previous and recent assessments could be related to differences in sampling plot locations within the mangrove stand. When comparing the species richness of past and recent assessments, Bongabong was found to have the most species in the previous but the least in the latter assessment (see Table 12.1). The mismatch is related to the varied locations of the sampling sites in the municipality, with the recently surveyed mangrove site having a high species richness. Furthermore, in the recent study, an increase in species record was noted in two municipalities, Mansalay and Bulalacao, from five and eight species, respectively, to 12 species. Again, the disparity might be due to the different locations of the sampling plots in these mangrove areas.

The species diversity in all mangrove sites falls within the H′ range value of 1.5–3.5 which is considered well-diversified mangrove areas (Margalef 1972; Singh 2020). Those with the lowest species diversity indicate stressed mangrove areas influenced by the natural and anthropogenic factors specifically soil salinity and fishpond industries (Kulkarni et al. 2010; Singh 2020). The mangrove diversity, dominance, and adaptability greatly depend on the ecological and environmental conditions of the area (Singh 2020). The size and extent of the mangrove area, such as in Roxas, which has the largest mangrove area in the southern district, contributes to its high species diversity. The small-scale mangrove area, on the other hand, has low diversity, as it only caters to a few mangrove species. Furthermore, the dominance of a certain species in a mangrove area may contribute to diversity differences among study sites. However, the types of disturbances and environmental conditions affecting the mangrove area still play a significant role. The increase in species records in the southern district could imply that mangrove ecosystems are already recuperating from previous disturbances.

Moreover, we observed that the high species richness was found in the middle and landward zones of each mangrove site. This finding is consistent with the results of Primavera et al. (2012), who reported that the mangrove ecosystem's diverse zones are in the middle and landward zones. This is because these ecotypes have ideal conditions for the growth of most mangrove species. Similarly, the physical formation and topography of each mangrove site may also contribute to the variations in the species diversity in each zone of a particular mangrove ecosystem.

The age and geographical location of the mangrove stand may also influence their structural characteristics (Singh 2020). Because the stands in Bansud and Mansalay were already old growth, the mangrove trees in those areas had the largest basal area as well. Other mangrove stands, on the other hand, feature a large number of small stem-sized mangrove trees, indicating that they are regenerating. Accordingly, the microclimate on the particular coastal environment as instigated by tidal and wave actions, the salinity level of soil and water, and the characteristic of mangrove substrate also have a significant effect on mangrove vegetation structure (Singh 2020). In addition, other factors such as biogeophysical, hydrology, climate, and soil chemistry may also have a strong influence on species composition, growth, and structure of the mangrove ecosystem. Hence, some mangrove species are highly dependent on the environment's condition and the coastal geography (Singh 2020). The density, height, and dbh of mangrove species may also be influenced by the mean annual rainfall in each particular mangrove stand where high rainfall increases species richness (Duke et al. 1998; Singh 2020). In the study areas, the average annual rainfall is estimated at 2285 mm (State of the Coasts of Oriental Mindoro 2015). The impacts of higher rainfall and runoff can decrease salinity, reduced exposure to sulfates, and increased sediments and nutrients available in coastal areas, which might cause an increase in diversity, growth rates, and productivity in a mangrove stand. Whereas lower rainfall would lead to an increase in soil salinity which may cause a decrease in productivity, growth, diversity, and seedling survival, thus altering the composition among mangrove areas (Eslami-Andargoli et al. 2009; Singh 2020). Furthermore, the establishment of mangroves is governed by site-specific conditions especially salinity, light, canopy gaps, and soil sediment characteristics (Clarke and Allaway 1993; Nguyen et al. 2020).

Among the mangrove species recorded in the study areas, *Avicennia* spp. and *Rhizophora* spp. are the species with wide ecological ranges. They can be found thriving in all zones of the mangrove stand, from seaward to landward, particularly in Bongabong, Mansalay, Roxas, and Bulalacao. On the other hand, all mangrove sites are considered natural stands, despite the fact that some portions of each stand were often rehabilitated with *R. mucronata* species. As further observed, the planted *R. mucronata* in Gloria, Bongabong, Roxas, and Bulalacao is already about 3–5 m in height, and some individuals are already producing propagules. However, the planted *R. mucronata* in the intertidal zone of Mansalay has stunted growth due to the unsuitable substrate for the species. Among study sites, the largest rehabilitated mangrove areas are in Bongabong, Roxas, Mansalay, and Bulalacao. Accordingly, even environmental stress and anthropogenic barriers may impact the mangrove environment, the distribution of species can remain stable if there is still enough habitat available for the mangrove species to grow (Xie et al. 2020). Also, mangroves are considered resilient to any forms of disturbances may it be natural or human-induced, but their recovery may still depend upon the rate of recurrence, intensity, extent, and length of disturbances (Nguyen et al. 2020). The changes in species composition and stand structure may also differ as influenced by the accretion and erosion factors in each mangrove site (Nguyen et al. 2020).

12.6 Conclusion

The recent study recorded 24 mangrove species in the Southern coastal areas of Oriental Mindoro. Further, this study assessed three mangrove areas in Bongabong, Mansalay, and Bulalacao for the first time. Interestingly, the study recorded additional six mangrove species in the southern district of Oriental Mindoro. The increase in species richness from 2014 to 2018 suggests that certain mangrove habitats in the province still have undocumented species. *Avicennia rumphiana*, *Excoecaria agallocha*, *Rhizophora apiculata*, *Rhizophora mucronata*, and *Sonneratia alba* are the five most common mangrove species found in the southern district. At present, the mangrove study sites are observed to be already recovering from previous disturbances brought about by the fishpond activities. The abandonment of the fishpond operations within the mangrove stands may highly contribute to the recovery of most mangrove ecosystems. Unfortunately, some anthropogenic threats still exist in these mangrove areas due to its open accessibility. The constant access of people and unsupervised fishpond operations can impose threats to these mangrove areas if remain unattended. Occasional cutting of mangrove trees and the increase in the number of residents near the mangrove stands are still going. If these disturbances are constantly occurring and cannot be minimized, the effect would lead to the reduction in the biodiversity in these mangrove areas. Therefore, the study recommends that the local environment authorities in the province should develop their own mangrove management and conservation framework. The understanding of the structural characteristics of each mangrove ecosystem is very useful for planning an effective mangrove management and conservation strategies. The development of mangrove management conceptual framework is highly recommended as it guides the local environment authorities in effectively protecting and sustaining their mangrove ecosystems. They should also regularly monitor the activities of the fishpond owners and strictly look on the provisions of the fisheries lease agreement (FLA) to minimize the impact of the activities mangrove stands. Lastly, they should observe the science-based protocols in rehabilitating the mangrove ecosystem such as the use of appropriate species in a suitable substrate.

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Chapter 13
Cultural Ecosystem Services of Mangroves: A Review of Models and Methods

Kanika Bimrah, Rajarshi Dasgupta, and Izuru Saizen

Abstract Mangrove forests are important for sustaining and enhancing ecosystem services that are beneficial for both local and regional communities as well as the global environment. Regardless of the significant research carried out on mangroves and the valuation of ecosystem services, the literature demonstrates a deficit in the valuation of cultural services. Most published studies focus on aspects of cultural services based on the ability to measure values with market prices, whereas the importance of cultural services in the lives of local communities gets sidelined. In this chapter, we have studied the interlinkages of cultural services provided by mangroves and the indigenous population and how the dimensions of the well-being of local communities are associated with their cultural practices. The chapter sheds light on the literature uncertainties and the importance of studying attitudes and perceptions of local people toward the cultural ecosystem services for forest management and policy planning processes.

Keywords Mangroves · Cultural ecosystem services · Local community · Spiritual beliefs · Religious practices

13.1 Introduction

Mangroves are the rich, diverse, and unique assemblage of ecosystems that inhabit the interface of terrestrial, estuarine, and marine systems in coastal intertidal zones. They provide a diverse range of goods and ecosystem services which are significant in sustaining the livelihoods and well-being of coastal communities. Due to the

K. Bimrah (✉) · I. Saizen
Laboratory of Regional Planning, Graduate School of Global Environmental Studies, Kyoto University, Kyoto, Japan
e-mail: saizen.izuru.4n@kyoto-u.ac.jp

R. Dasgupta
Institute of Global Environmental Strategies, Hayama, Kanagawa, Japan
e-mail: dasgupta@iges.or.jp

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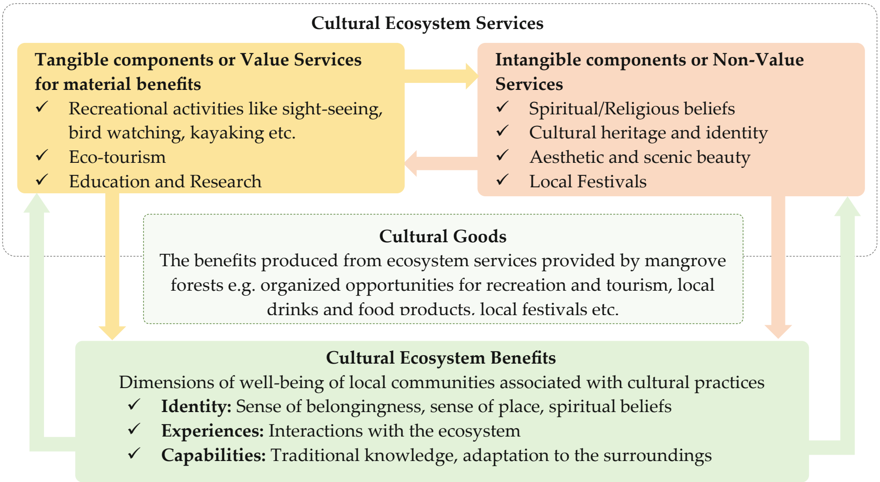

Fig. 13.1 Conceptual framework showing the linkages between the tangible and intangible components of cultural ecosystem services

growing recognition of these ecosystems in climate mitigation and adaptation, the ability of mangroves to capture and store carbon occupies the central disclosure of mangrove ecosystem services. This is followed by the provisioning services such as timber, fuelwood, medicinal, and food resources which enhance the economic benefits and food security of the local coastal communities. Nonetheless, mangroves also provide a multitude of cultural ecosystem services such as recreation, tourism, aesthetic experiences, education, cultural identity, and cultural heritage which are equally important for the well-being of communities.

The Millenium Ecosystem Assessment (2005) defined cultural ecosystem services as "the non-material benefits people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation, and aesthetic experiences" (Millenium Ecosystem Assessment Report 2005). The cultural ecosystem services, in most cases, have non-material value as compared to the material value. An exception is possibly the "recreation and tourism" which can be quantified monetarily, in contrast to the rest of cultural ecosystem services (i.e., spiritual, religious, aesthetic, inspirational, and sense of place) which are difficult to quantify. Such services are considered to be "intangible" because not only they are difficult to quantify but also are enmeshed with multiple aspects of people's culture and ecosystem use. The conceptual framework for understanding the linkages between the tangible and intangible components of cultural ecosystem services is shown in Fig. 13.1.

The material dimension of cultural ecosystem services such as tourism and recreational activities including hiking, boating, wildlife watching, etc. can be evaluated monetarily in terms of the revenue generated through it. Globally, 4000 mangrove attraction sites have been identified which are attracting millions of visitors annually (Spalding and Parrett 2019). For example, there are various local festivals like Rash Mela and Sundarbans Folk Festival held by the communities of mangrove forests in Sundarbans, Bangladesh, which attracts Hindu pilgrims and tourists annually. It helps the local economy with an estimated annual income of US $ 42,000 from tourism-related services (Al et al. 2014). Although it is difficult to evaluate the monetary value of intangible components, they are significantly rooted in the sociocultural identity of the local people. They are linked with strong spiritual beliefs and religious practices such as the establishment of sacred areas, festivals, taboos, etc.

In general, cultural ecosystem services have received little attention within the broad spectrum of coastal ecosystems services. However, the exclusion of cultural ecosystem services from ecosystem service assessment and valuation can severely encumber coastal management, policy planning, and decision-making. The local coastal communities have a symbolic relationship with the mangrove forests which goes beyond the monetary value and materialistic approach (de Souza Queiroz et al. 2017). Hence, understanding the cultural importance of mangroves is significant as they represent an important facet of the livelihood and cultural identity of the local community. In this chapter, we aim to understand the interactions between the indigenous population and mangrove forests and how the cultural ecosystem services provided by mangrove ecosystems have been evaluated and assessed so far. The chapter also highlights the knowledge gaps and why it is important to understand the perceptions and attitudes of local people toward mangrove forests for their management and restoration.

13.2 Perception of Local Communities Across the World Toward Cultural Ecosystem Services Provided by Mangrove Forests

The cultural heritage, community traditions, and folklores are a function of place, people, and their beliefs and may change as a location transitions from one country to another. For instance, since the third century, Hindus have worshipped the mangrove species *Excoecaria agallocha* in an ancient temple Chidambaram, nearer to Pichavaram mangrove forests in Tamil Nadu, India. Locals believe that a holy dip in the temple's pond surrounded by mangroves can cure their diseases. Some of the other spiritual beliefs and religious deities that local communities across the world believe in are shown in Fig. 13.2.

It is evident that the perceived value of these cultural ecosystem services differs between different individuals and social groups based on the attitudes and perceptions of local people. It can be understood better with the help of a case study of Sundarban Mangrove Forest as shown in Box 13.1. The understanding of their needs and aspirations is context-specific which depends on geographical settings, socio-economic characteristics of the community and local management institutions.

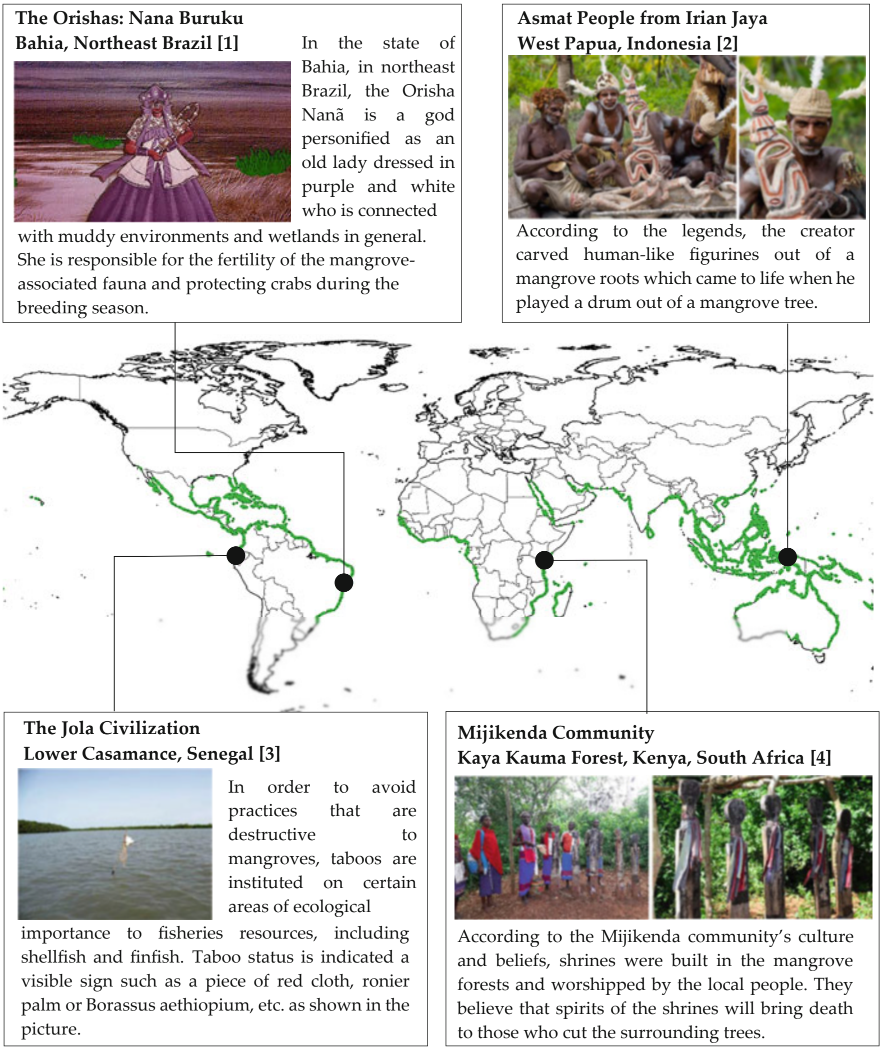

Fig. 13.2 Spiritual links between mangrove forests and local communities, with deities and legends associated with different components of mangrove ecosystems. [1] (Original Botanica 2016); [2] (Gudkov 2017); [3] (Diatta et al. 2020); [4] (Mbugua 2018)

Box 13.1 Cultural Beliefs and Religious Practices of Social Groups Within Sundarban Mangrove Forests, India and Bangladesh

Sundarbans Mangrove Forest are spread across approximately 10,000 sq.km. in the eastern Indian state of West Bengal and western Khulna Division of Bangladesh.

It is the largest continuous tract of mangrove forest in the world which inhabits 58 species of mammals, 55 species of reptiles and around 248 bird species. It is a home to 12 million human population in the greater Sundarbans region.

The population majorly comprises of Hindu, Bengali and Muslim communities which have different religious practices and cultural beliefs. These beliefs also differ based on their occupation and level of dependence on mangrove forests for their livelihood.

Sundarban Mangrove Forests

Bonbibi Worship

Bonbibi, the lady of the forest, is a guardian spirit of the forests venerated by both the Hindu and the Muslim residents of the Sundarbans. She is called upon mostly by the honey-collectors and the woodcutters before entering the forest for protection against the attacks from the tigers.

Shajangali (Bon Bibi's brother) is more closely related with Muslim community due to the typical attire he is shown wearing whereas Bon Bibi's dress and adornments are more closely tied to Hinduism.

Bonbibi Idols being worshipped by the local community

(continued)

Box 13.1 (continued)

Dakshin Rai

Dakshin Rai is a revered deity in the Sundarbans in India and Bangladesh who is considered as the overall ruler of Sundarbans. The God is worshipped by all those who enter the Sundarban forests of West Bengal, for subsistence, irrespective of their caste, creed or religion as it is believed that he rules over beasts and demons.

Temple of Dakshin Rai

Rash Mela Celebrations

The Rash Mela celebrations is a 100-year old unique heritage of Sundarban forests, where a number of Hindu pilgrims gather to perform holy bath and seek mercy of Bonbibi, the guardian spirit of the forests. The fair is one of the major sources of revenue generation for the indigenous population.

Despite the importance of mangrove forests to the local communities, the societal benefits contradict the potential negative influences and perceptions, or "ecosystem disservices" that mangrove forests can have on the local communities. They are inhabited by dangerous animals, and the interweaving trunks and rooting branches of mangroves cut off all views of the land and are often perceived as dark and gloomy. They act as the breeding ground not only for various aquatic species but also for disease vectors such as mosquitoes. The ecosystem disservices have a negative impact on human well-being through harm by animals, biological impact on physical health, and abiotic impact on aesthetic and cultural aspects (Friess et al. 2008). However, it is highly unlikely that the local indigenous population inhabiting the mangrove forests would perceive these ecosystem disservices in the same way. A paradigm shift in the perception of local communities can be observed as they tend to be inclined more toward the benefits received from them as their livelihood activities are solely dependent on the ecosystem services received from mangrove forests as shown in Fig. 13.3.

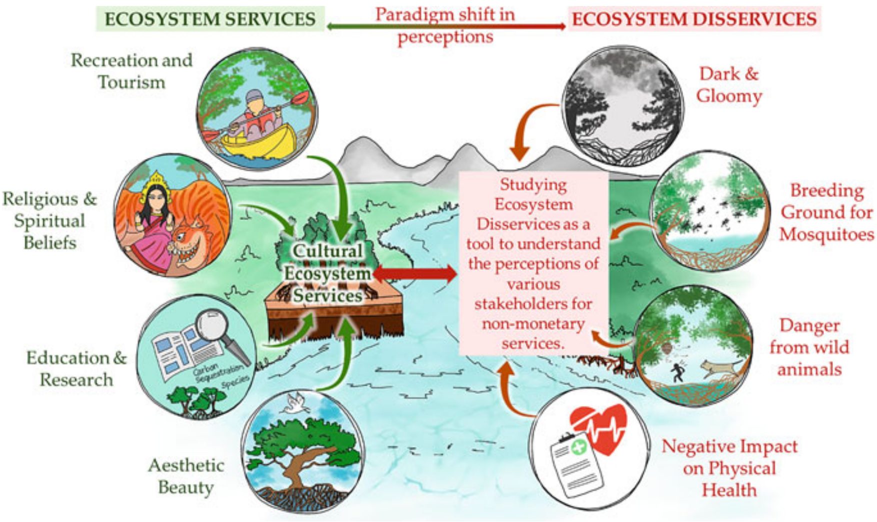

Fig. 13.3 Ecosystem services and disservices from mangrove forests

13.3 Assessment of Cultural Ecosystem Services

Although in the past few decades, the cultural ecosystem services did not receive adequate priority as compared to other ecosystem services; researchers and local authorities have realized its significance. It is important to understand the attitude and perspective of the indigenous population for community-based management of mangrove forests. However, in the last few years, various studies have been carried out by researchers across the world to evaluate and assess both tangible and intangible components of cultural ecosystem services. Some of these research studies have been discussed in Table 13.1.

The methodology adopted to evaluate the cultural ecosystem services focused mainly on the preparation of Public Participation Geographic Information System (PPGIS) through household surveys and focused group discussions. It helped in studying the intangible components like spiritual beliefs, traditional knowledge, perception of local communities in terms of participation in conservation activities, etc. as they are specific to location and social groups. de Souza Queiroz et al. (2017) and Roy (2016) in their studies conducted focused group discussions and household surveys through multistage random sampling to understand the symbolic relationship that local communities share with the mangrove forests. The responses and data collected were thereafter analyzed to generate a list of perceived priorities of ecosystem services. Uddin et al. (2013) carried out the economic valuation of cultural ecosystem services such as tourism activities, traditional festivals, education, and research through direct and indirect methods.

Table 13.1 Research studies that have assessed cultural ecosystem services by mangrove ecosystems

S.no.	Title	Year	Study area	Aspects studied	Cultural ecosystem services assessed	Method of evaluation
1.	Neglected ecosystem services: Highlighting the sociocultural perception of mangroves in decision-making processes (de Souza Queiroz et al. 2017)	2017	Brazilian community of Cumbe, Northeastern Brazil	Analysis of how mangrove ecosystem services are embedded into community livelihoods	• Recreation/ tourism • Aesthetics • Inspiration for culture and art • Spiritual • Maintenance of traditional ecological knowledge • Science and environmental education • Creation and maintenance of social relationships • Personal satisfaction • Mental and physical relaxation	• Focus group discussions were conducted to obtain desired information such as the importance (symbolic and material) of the mangroves for the life, how have mangroves changed throughout history, etc. • The valuation survey was based on Likert scale design • The responses were thereafter analyzed using ANTHROPAC software, generating a list of the perceived ecosystem services priority
2	Local community attitudes toward mangrove forest conservation: Lessons from Bangladesh (Roy 2016)	2016	Sunderbans, Khulna, Satkhira, and Bagerhat districts of south-western coastal part of Bangladesh	The attitude and perception of local communities toward mangrove restoration and conservation	Perception of local communities were studied in terms of • Importance	• Household survey and focus group discussion was conducted using multistage random sampling • The data collected was

					of mangrove forests for their livelihood • Participation in conservation • Property rights allocations • Alternative uses/management of mangrove forests	analyzed using principal component analysis (PCA) • Hierarchical cluster analysis was carried out using Ward's method
3	Economic valuation of provisioning and cultural services of a protected mangrove ecosystem: A case study on Sundarbans Reserve Forest, Bangladesh (Uddin et al. 2013)	2013	Sunderbans Mangrove Reserve Forest, Bangladesh	Estimation of economic value of provisioning and cultural ecosystem services	• Tourism (river cruising, wildlife watching) • Traditional/ spiritual festivals • Education and research • Scenic beauty	• Economic valuation through direct and indirect methods
4	Mangroves: A natural ecosystem of cultural and religious convergence (Mitra 2020)	2020	Sunderbans Mangrove Reserve Forest, Bangladesh	Identification of major gods/ goddesses worshipped in Sunderbans and devotion of people toward them	• Religious affinity • Spiritual beliefs	• Devotion Assessment Matrix (DAM) was developed • Combined Mangrove God Devotion Scale (CMGDS) in context to Indian Sundarban mangrove ecosystem was constructed
5	Historical and contemporary cultural ecosystem service values in the rapidly	2015	Singapore	How cultural values placed in mangrove forests of Singapore have evolved over a	• Spiritual/religious • Recreation	• Analysis of past day cultural ecosystem services through archival analysis

(continued)

Table 13.1 (continued)

S.no.	Title	Year	Study area	Aspects studied	Cultural ecosystem services assessed	Method of evaluation
	urbanizing city state of Singapore (Thiagarajah et al. 2015)			period of time and how it has affected the local people	and Tourism • Aesthetic • Inspirational • Educational • Cultural identity/sense of place • Cultural heritage	• Analysis of present-day cultural ecosystem services through photographic records from Flickr, semistructured interviews

Although significant efforts have been made by researchers worldwide to understand and analyze the cultural ecosystem services provided by mangrove forests, there is no specific framework or methodology that can be adopted to assess the intangible cultural services at a large scale globally. One of the primary reasons is that the perception of services provided by mangrove forests varies according to the local communities and their beliefs. Therefore, the policies and approaches for forest management in such areas should be tailored as per the needs of the local communities.

13.4 Uncertainties in Methods

The available literature for evaluating mangrove ecosystem services is not yet robust as it lacks estimation of many ecosystem services, especially cultural ecosystem services, such as spiritual and aesthetic value. Most of the published studies focus on certain ecosystem services which can be easily measured in terms of their monetary value or scientific significance based on the availability of benefit transfer values. Given the extensive range of mangrove ecosystem services and the variety of valuation methods that need to be comprehensively studied, it is argued that assessment and valuation studies require a multidisciplinary approach that takes into consideration the local stakeholders, anthropologists, social scientists, ecologists, and economists (Himes-Cornell et al. 2018).

There are also literature and methodological uncertainties in understanding how to value them. The "tourism and recreation" categories are a notable exception as tools are readily available to value it. Regardless of being less frequently valued, "research and education services" can likewise be valued, by using monetary values from research grants, field, and research costs. However, the gap in our knowledge comes with assessing intangible components of cultural ecosystem services, that is, spiritual and religious beliefs, cultural heritage and identity, aesthetic and scenic beauty, etc.

13.5 Conclusion

As the mangrove ecosystems across the world have been facing multiple threats due to coastal development and deforestation, due consideration should be given to the societal uses of these ecosystems. It is important to study the extent of those uses and how valuable these ecosystem services are for the local communities. In view of the mangrove ecosystem valuation literature published in last few years, substantial gaps are found in the valuation methods and the ecosystem services that have been evaluated, especially cultural ecosystem services. They are of vital importance to the local stakeholders and indigenous people. A bottom-up approach should be adopted for evaluating the intangible components of cultural services provided by mangrove forests. It is important to understand how local communities perceive and depend on mangrove ecosystem services and their priorities in forest management and conservation. Assessing these cultural services and beliefs of local people will play a vital role in community-based forest management and decision-making processes.

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Chapter 14
Capacity-Building Around Indigenous and Local Knowledge (ILK) Systems for Effective Climate Adaptation in the Low-Lying Coasts and Small Islands

Binaya Raj Shivakoti, Nagisa Shiiba, and Peter King

Abstract Indigenous (or traditional) and local knowledge (ILK) systems are increasingly recognized as a potential solution for climate change adaptation and disaster risk reduction. Most ILK systems incorporate or are built around several nature-based approaches in the low-lying coasts such as social and livelihood systems relying on mangrove ecosystems. However, ILK systems have their limits to adaptation and hence are not fully capable of overcoming the magnitude of threats posed by climate change or extreme hazards to the vulnerable communities living in in low-lying coasts or Small Islands Developing States (SIDS). The potential of ILK needs reinforcement by technological innovations as well as adequate investments to reengineer solutions. For that, the role of capacity building is important to enabling community or indigenous groups to systematically identify and document ILK practices, assess vulnerabilities of ILK, co-develop scientifically robust solutions based on ILK, and institute mechanisms for the promotion and upscaling of solutions. This chapter proposes a comprehensive approach for building local capacities around ILK for climate change adaptation and resilience building against future risks. The chapter stresses a sustainable approach to capacity building that could be retained, improved, and continued over time.

Keywords Adaptation · DRR · SIDS · Capacity building · Indigenous knowledge

14.1 Introduction

Indigenous and local knowledge (ILK) systems refer to the understandings, skills, and philosophies developed by societies with long histories of interaction with their natural surroundings (UNESCO 2020). ILK systems are the result of interaction

B. R. Shivakoti (✉) · N. Shiiba · P. King
Institute for Global Environmental Strategies (IGES), Hayama, Kanagawa, Japan
e-mail: shivakoti@iges.or.jp

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between humans and nature over generations. They are passed down in various forms such as songs, stories, folklore, beliefs, community norms, language, rituals, and practices and often form the basis for identity. Continuity of ILK for generations testifies to their relevancy and effectiveness to support one or more human needs sustainably while establishing a harmonious coexistence with nature. There is increasing realization of the role of ILK for sustainability through scientific investigations (Lam et al. 2020).

ILK systems are often the default choice for decision-making about fundamental aspects of day-to-day life, including responses to climate change impacts for many communities. ILKs are touted as a potential option for climate change adaptation in various assessment reports, agreements, and decisions (Shivakoti et al. 2021). For instance, the inclusion of ILK into ecosystem-based adaptation (EbA) is positioned as critical for successful climate adaptation at the community level projects (Nalau et al. 2018). The significance of climate change adaptation is rooted in the inherent nature of ILK, which is about natural harmony, sustainability, and balance (Koya et al. 2018).

For climate change adaptation, a key motivation for adopting ILK is that it could be a cost-effective and low-risk intervention for climate change investments, given its proven track record as well as the minimal learning curve when compared with exogenous interventions (Shivakoti et al. 2021). ILK systems are grounded to the local realities. In instances, where planned interventions for adaptations are absent, ILK systems are often the only coping option available to the local communities. Education, information, and community approaches, including those informed by ILK, can accelerate wide-scale behavior changes consistent with adapting to and limiting global warming to 1.5 °C (IPCC 2018). The application of appropriate technological innovation and promotion of ILK systems can lead to increased local ownership, engagement, utilization of biodiversity, and nature's contribution to people while adapting to the impacts of climate change (IPBES 2018). For disaster risk management, ILK can provide an important contribution to the development and implementation of plans and mechanisms such as for early warning systems (UNISDR 2015).

Given the merits and potentials of ILK for climate adaptation, there are also several barriers to their application for climate change adaptation in a dedicated manner and subsequent mainstreaming into formal adaptation planning and implementation processes. In general, the call for promoting ILK for climate change adaptation is rather aspirational and yet to be translated into the local context where ILK exists or is being practiced. Because of that, they are hard to detect or identify and thus are least documented. By the same token, a deep understanding of the state of their practice, regarding external impacts including climate change, is mostly unavailable. It is less clear whether ILK systems are robust enough to withstand the increasing impacts of climate change or they are on the verge of reaching their limits to adaptation. With increasing climate impacts as well as the influence of globalization, ILK systems may likely fade over time due to the loss of their effectiveness. Similarly, knowledge holders practicing ILK are usually limited to the aging population due to the lesser involvement of youths, who are moving to cities or developed areas for better socioeconomic opportunities.

Better integration of ILK with scientific research and policy processes is necessary to overcome the barriers and devise innovative ways to promote ILK for climate change adaptation (Remling and Veitayaki 2016). Blending indigenous and scientific knowledge could constitute a form of peer-to-peer learning in participatory and action-based research (Woroniecki et al. 2020). For instance, using ILK and remote sensing was found useful to overcome the limitation of scientific data and enhance the details and scope of assessment of mangrove ecosystem changes (Brown et al. 2018). In developing countries, particularly small island states, climate forecasting is often not well received by local communities due to budget constraints and limited capacity, which is why ILK systems play an important role in decision-making at different levels (Chand et al. 2014).

However, there are no established templates to pursue the ILK-science-policy interface and to find locally relevant adaptation solutions. Capacity gaps remain at different levels to ensure a truly participatory and need-based action research and development of ILK solutions. Given this background, this paper aims to highlight the capacity building needs around ILK for climate change adaptation by focusing on low-lying coastal areas and small island developing states (SIDS), which are considered one of the most vulnerable and in the frontline to face climate change impacts.

14.2 ILK in the Context of Increasing Climate Change Impacts in Low-Lying Coasts and Small Islands

Low-lying coasts and small islands are in the frontline to fight against climate change impacts. Increasing warming amplifies the exposure of small islands, low-lying coastal areas, and deltas to the risks associated with sea-level rise for many human and ecological systems, including increased saltwater intrusion, flooding, and damage to infrastructure (IPCC 2018). Sea level rise poses a long-term existential risk, while recurring extreme events such as typhoons, saline water intrusion, and storm surges are already impacting the communities living in these areas. Climate change, sea-level rise, and extreme climatic events are harming species, habitats, and ecosystem structure and functions and posing great threats to coastal ecosystems, especially to coral reefs, seagrass beds, kelp forests, mangroves, and salt marshes, and in turn are increasing coastal erosion and vulnerability of low-lying coastal areas, islands, and atolls (IPBES 2018).

Many communities living in SIDS, particularly in rural areas, employ ILK extensively, given their proximity to nature and high dependence on natural resources (Nalau et al. 2018). Many Pacific Islanders hold a wealth of traditional knowledge on their local ecosystems, how to manage them and strong adaptation skills due to their intrinsic connections with land and sea (Pearson et al. 2020).

Communities often prefer the use of local knowledge and resources to cope against coastal erosion and protect ecosystems (Narayan et al. 2020). Indigenous communities, such as Orang Suku Laut (OSL), Konky Strait, and Lingga in Indonesia, are found to rely extensively on the mangrove ecosystem and services for their living, such as wood, medicine, and protection against unfavorable climatic conditions (Firdaus et al. 2019). Traditional knowledge allows the OSL to manage and conserve mangroves such as determining the type of resources to be used, determining logging areas, agreeing on timing for harvesting resources, and assigning quotas, traditional rituals, etc. It is important to understand, respect, and utilize traditional knowledge for building climate change adaptation strategies such as the case of iTaukei communities (indigenous Fijians) who hold and practice the traditional knowledge on sustainable management of mangrove ecosystems for generations (Pearson et al. 2020). It is also observed that iTaukei have traditionally dealt with flooding disasters through having a strong kinship mutual assistance network or dwelling in houses on stilts.

It is critical to have the perspective of local people when planning adaptation measures to climate change. For example, traditional land rights must be taken into consideration in urban planning processes, and identifying the most critical ecosystems for locals is a step of importance to overcome the tension between urban development and ecological considerations (Shiiba et al. 2021).

14.3 Key Capacity Gaps for Applying ILKs for Climate Change Adaptation in Coasts and Small Islands

With the intensification of climate impacts, local communities will be increasingly exposed to high-intensity extreme events and irreversible changes such as sea-level rise. The coping capacity afforded by ILK will undergo severe testing. Janif et al. (2016) pointed out that the loss of traditional environmental knowledge has already been evident in the Pacific Islands over recent decades against backdrops of globalization, modernization, and other social changes. Without additional safeguards or enhancements, ILK risks losing its effectiveness. A coordinated approach involving an interface of communities-research-policy provides an enabling environment needed for their conservation, enhancements, and upscaling. Before establishing such a trilateral collaborative formation, however, it is also important to identify and address key capacity gaps at different levels, in particular, at the community level. Community involvement in research and project implementation is not a new approach. A wealth of knowledge, experience, and methodological framework already exists on community participation. Meanwhile, holders of ILK, mainly indigenous and local communities, are also participating and sharing their concerns at different occasions. Important programs and initiatives, such as REDD+ and many other international initiatives, ask for the participation of the local and indigenous communities as a requirement to ensure free, prior and informed consent (FPIC), which is a specific right given to indigenous peoples and recognized in the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP).

Despite the progress made so far, communities lack several key capacities to maximize their chances to access external resources and know-how and connect with the wider processes happening at the national and international levels. In coastal cities, there is a complex interplay of various factors that exacerbate communities' vulnerability to climate change such as improper land use, overfishing, and unsustainable use of natural resources. A wide variety of traditional experiences, wisdom, and knowledge thus should be used for effective climate change adaptation, but they may not be fully utilized. For instance, local policy and actions often address issues in silos, which results in failure to exploit the full capacity of communities toward coastal adaptation (Yoshioka et al. 2021).

As a holder and practitioners of ILK, communities are already experts in the subject matter. What they usually lack are the tools and resources to understand the ongoing changes and resultant vulnerabilities, measures to integrate modern technologies or approaches to strengthen and modernize the knowledge base, and communicating their capabilities and support needs. This way communities can continue their customary practices while addressing the modern challenges. In this respect four key capacity gaps that need to be addressed are:

- Capacities to systematically identify and document the merits as well as challenges related to ILK. Building such a capacity is critical for communication about ILK and for seeking needed support or external intervention for their promotion.
- Capacities to co-design locally appropriate tools and measures to strengthen ILK in collaboration with researchers, policymakers, and other stakeholders (such as private sector, media, etc.)
- Capacities to implement designed adaptation interventions based on ILK to address exposures and the vulnerabilities.
- Capacities to strengthen the institutions, governance, and incentive system for the build back better of ILK and to ensure their continuity such as attracting the participation of youth as future leaders.

14.4 Need for a Sustained Approach of Capacity Building

Capacity building is a continuous effort, and the listed capacity gaps in the preceding section have to be approached with a long-term vision in mind. Past efforts have demonstrated that capacity-building efforts were often input-based, supply-driven, ad-hoc, and short-term (i.e., limited to the project or program cycle under which they were implemented) (Khan et al. 2018). There is limited evidence on the outcomes of past capacity-building efforts such as whether systems and processes were left behind. Continuing with past approaches of capacity building is no longer an option and goes against the spirit of the Paris Agreement, which calls for a country-driven capacity building to foster ownership, guided by lessons learned, and done in an effective, iterative, participatory, cross-cutting, and gender-responsive manner (UNFCCC 2015). Under the agreement, the Paris Committee on Capacity-building (PCCB) addresses current and emerging gaps and needs in implementing and further enhancing capacity building in developing countries in a consistent, coherent, effective, and sustainable manner.

Investing in the local capabilities is one of the important requirements for ensuring long-term capacity building. In the case of ILK, it means strengthening the traditional, indigenous, and informal institutional system and processes so that communities can understand climate risks and uncertainties, generate solutions, and facilitate and manage adaptation initiatives over the long term without being dependent on project-based donor funding (Soanes et al. 2021). Capacity building should be guided by the needs of communities or holders of ILKs to ensure its ownership as well as to address the core capacity gaps. The process of designing capacity building has to be led by the community themselves such that resultant activities could be uptake effectively.

A sustained approach to the capacity building will cover three dimensions: capacity building, capacity utilization, and capacity retention (Khan et al. 2018). Capacity building can be directed toward an individual, a community, or to systematic/institutional levels. Noted that capacity building is only the first step of an iterative process, not the end goal. Depending on the level, it could range from developing individual level skills, knowledge, and competence. At the community and institutional level, it deals with the establishment of efficient structures and processes of governance. The utilization dimension confirms the application of the built capacity where it is most needed as well as the integration of actions into predetermined processes and structure. It tries to alleviate the existing concerns about the underutilization of built capacities. The final and the most critical is about capacity retention which is about ensuring continuity of the former two such as retention of qualified ILK holders or local scientists. The retention, therefore, looks for establishing the incentive mechanisms under the institutional setup created.

14.5 Capacity Building Elements for the Application of ILK for Climate Change Adaptation

The question of capacity building around ILK has two main issues. First, how to sustain and continue them in the long term. Second, how to improvise and reinforce them for climate change adaptation without compromising their core elements or characteristics. The preceding section provides a background on the need for a sustained approach to capacity building, which could be applied to fulfil the two issues relating to capacity building as well as to address the four key capacity gaps and needs listed before.

To overcome the needs, gaps, and issues of capacity building, three mutually reinforcing elements could be considered in the case of ILK: knowledge system, institutions and processes, and communication.

14.5.1 Knowledge System

The knowledge system comprises the foundation of ILK and envisions trilateral cooperation of community, researchers, and local government. Capacity building on the knowledge system aims to address the knowledge and information gaps on ILK. Recognizing, characterizing, and systematic documenting of ILK is crucial for building a solid knowledge base upon which further investigations and innovations could be carried out. Communities or holders of ILK can take a lead to compile all relevant information they know. Capacity building here mainly focuses on extracting those pieces of information which are relevant for identifying the merits and deficiencies of ILKs when compared to future exposures and vulnerabilities. The compilation could involve analyzing historical contexts (how and why they came into existence), assets (natural capital, sociocultural capital), the benefits and outcomes (nature's contributions), and deficits and threats (inherent as well as those caused by external impacts).

The knowledge system further consists of "learning by doing" kind of capacity building to retain key attributes as well as to overcome deficits. It envisions a locally led process of co-designing scientifically robust measures to reinforce ILK through innovation and the application of decision support tools. The capacity building mainly intends to fill the gaps in the use of necessary tools and techniques to assess and analyze climate risks and vulnerabilities as well as learning hard and soft measures of adaptation interventions that could be integrated with ILK.

The third aspect of capacity building around the knowledge system focuses on the implementation of planned measures. Since implementation has to do more with the improvisation of existing ILK, communities should lead it to ensure that norms, value systems, and core characteristics of the knowledge system are retained. Here capacity building should not be viewed as an externally facilitated process. Instead, it could be ideally a locally driven self-learning process in which external support is not a prerequisite but is available as demand-driven inputs.

14.5.2 Institutions and Processes

Building institutional capacity and resultant processes are critical for the utilization and retention of the ILK systems and improved governance. Although some previous studies have indicated that traditional knowledge and ecosystems monitoring can be validated by scientific explanations, local knowledge and the ability to monitor environmental change does not always guarantee counteractions (Lauer and Aswani 2010; Nkomwa et al. 2014). Strengthening institutional capacity allows the community to take coping strategies based on their observation of change. In the Pacific societies, for instance, customary governance systems such as village-based natural resource management bodies often provide an institutional setting for adaptive management (Lauer and Aswani 2010). Institutions and processes provide necessary incentives for stakeholder participation and continuation and development of ILK systems such as securing investments, technology development and transfer, and defining and measuring outcomes such as increase/decrease in adaptive capacity or resilience building. For instance, increased institutional capacity could provide leverage for accessing and using climate funds and support, which are often left under-utilized at the higher level due to lack of community capacity to access, process, and mobilize them transparently and effectively.

Capacity-building efforts therefore should focus on increasing the attractiveness around ILK, such as for youths, to ensure passing down the knowledge system to future generations. Efforts will be needed to channel the available resources and support received, such as for developing the knowledge system and for the strengthening of institutional processes.

14.5.3 Communication

One of the key issues for the promotion of ILK for climate change adaptation or biodiversity conservation is its inadequate mainstreaming with the policy, planning, and decision processes at the different levels. In the absence of effective communication mechanisms, the scope of ILK is often restricted within the communities holding or practicing it. Given the distributed and diversified nature of ILK systems among communities even within a narrow geographic coverage, there is a huge practical challenge on how to communicate and transfer the know-how of ILK systems to other communities, government, or the international level. Research engagements often help to fill the communication gaps, but they are not sufficient to reach all communities in question. So, an effective approach to communication will be necessary so that the information could be transferred rapidly among different stakeholders. There is a need for wider application of information and communication technology (ICT) such as the use of social media to connect and communicate among and beyond communities. Specific efforts of capacity building are needed to overcome the communication gaps at different levels. At the community level (within and across), capacity-building efforts are needed to transfer the know-how and ILK solutions to ensure wider adoption. Such communication can happen in different forms such as the use of local/community media, social media (Facebook, WhatsApp, Viber), or viral videos (YouTube, TikTok). For instance, the use of participatory media at the community level such as oral storytelling and photography can make indigenous knowledge accessible for intergenerational discussion toward climate change adaptation processes (Inamara and Thomas 2017). Meanwhile, another level of communication can be more formal and structured.

There is a huge communication gap between the local level and national/international levels (including research community and policymakers) as a result of this capacity deficiency. As a result, communities are often struggling to get proper recognition of their local efforts at the national and international levels. Institutional capacity building for improved communication therefore can help to highlight potential ILKs, highlight needs, and seek support (technical, financial, capacity building) and recognition of ILK contribution in the formal adaptation communication.

14.6 Conclusion and Recommendations

Climate change is a current reality for people and communities living in the low-lying coasts and small islands. Protecting those communities from sea-level rise, saltwater intrusion, coastal erosion, storm surge, typhoons, and heavy rains is a matter of survivability and future existence. Indigenous and local knowledge (ILK) systems, built around the centuries of interaction between nature and people, provide multiple benefits, build resilience, and protect communities from natural hazards. Despite a wider recognition and calls for application for adaptation including in the nationally determined contributions of several countries, ILK systems only form the basic coping responses. The dedicated application of ILK systems in adaptation planning or designing solutions are largely unavailable. One of the reasons for the inadequate uses of ILK for adaptation is the existing capacity gaps at the local level to ensure their future sustainability and reengineering to improve their effectiveness. To overcome the capacity gaps, the paper proposes three elements to be employed in a coordinated manner and led by the local community to ensure capacity building, its retention, improvements, and continuity over time.

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Chapter 15
Ecosystem Services and Well-Being in the Sundarbans of Bangladesh: A Multiple Evidence Base Trajectory

Rashed Al Mahmud Titumir and Md. Shah Paran

Abstract The chapter attempts to categorise the ecosystem services (ES) and their multiple values as well as scrutinise the well-being of human and nature interfaces in the Sundarbans—the largest single-tract contiguous mangrove forest in the world. It also examines the factors negatively and positively affecting the ecosystem's balance and thus the well-being of the forest and its people. The chapter demonstrates that both humans and nature are dependent on each other and form a human-nature sociality in the ecosystem through which they coexist; therefore the appropriation of nature (conservation, restoration, sustainable uses, access and benefit sharing) instead of expropriation (anthropogenic pressures) promotes virtuous cycle in the ecosystem and harmonious relations between human and nature. The chapter adopts multiple evidence base (MEB) approach, comprising (a) participatory observations and focus group discussions, (b) public participation geographic information system (PPGIS), (c) survey and (d) corroborative scientific evidence. The study particularly draws on the insights of forest people who pursue their livelihoods in the Sundarbans as traditional resource users like wood collectors (*Bawalis*), fishermen (*Jele*), honey and wax collectors (*Mouals*) and crab collectors.

Keywords Ecosystem services · Human-nature relationships · Human sociality · Well-being · Multiple evidence base approach · SEPLS · The Sundarbans

R. A. M. Titumir (✉)
Department of Development Studies, University of Dhaka, Dhaka, Bangladesh

The Unnayan Onneshan, Dhaka, Bangladesh
e-mail: rtitumir@unnayan.org; rt@du.ac.bd

M. Shah Paran
The Unnayan Onneshan, Dhaka, Bangladesh

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15.1 Introduction

This chapter attempts to categorise the ecosystem services (ES) and their multiple values and examines the way ES contributes to human well-being. It not only explores human well-being but also tries to understand the well-being of nature. It examines the factors negatively and positively affecting the ecosystem's balance and thus the well-being of the forest and its people. The chapter demonstrates that conservation, restoration, sustainable uses, access and benefit sharing promotes harmonic relationship between human and nature and transforms the quality of life. Both human and nature are dependent on each other and form a human-nature sociality in the ecosystem through which they coexist; therefore the appropriation of nature instead of expropriation creates a virtuous cycle in the ecosystem and harmonious relations between human and nature. The chapter adopts a multiple evidence base (MEB) approach, comprising (a) participatory observations and focus group discussions, (b) public participation geographic information system (PPGIS), (c) survey and (d) corroborative scientific evidence. The study particularly draws on the insights of forest people who pursue their livelihoods in the Sundarbans as traditional resource users (TRUs) like wood collectors (*Bawalis*), fishermen (*Jele*), honey and wax collectors (*Mouals*) and crab collectors and are the members of two cooperatives—*Koyra Bonojibi Bohumukhi Unnayan Samity* and *Munda Adivasi Bonojibi Bohumukhi Unnayan Samity* at the Koyra Upazilla of Khulna district in the south-western region of Bangladesh, a part of the Sundarbans.

The Sundarbans is the largest contiguous composite mangrove ecosystem of the world enriched with high biodiversity. The various types of ecosystems, including terrestrial, forest, coastal and wetland, make her home to unique aquatic and terrestrial flora and fauna. A large number of traditional resource users maintains livelihoods in this mangrove forest and thus provide a unique hotspot for biodiversity conservation and sustainable use. This globally acclaimed heritage site, including its sanctuaries and ecologically critical areas, which also acts as a natural wall to climatic variabilities (cyclones), is vulnerable due to expropriation (anthropogenic pressures) amidst fragile institutions and an ineffective command-driven governance system. On the positive side, the customary sustainable practices and indigenous and local knowledge relating to conservation, restoration, sustainable uses and access, and benefit sharing constructs transformative pathways.

The benefits from the ecosystems appear in the form of multiple goods and services, which 'contribute to making human life both possible and worth living' (Díaz et al. 2006; Millennium Ecosystem Assessment 2005a, b; Layke et al. 2012; van Oudenhoven et al. 2012). These benefits include food production, building materials, medicines, regulation of microclimate, disease prevention, provision of productive soils, and clean water resources, as well as landscape opportunities for recreational and spiritual benefits (Costanza et al. 1997; Daily 1997; Millennium Ecosystem Assessment 2005a, b; Banzhaf and Boyd 2007; Wallace 2007). Ecosystems provide goods such as food crops, seafood, forage, timber, biomass fuels, natural fibre, pharmaceuticals, and geologic resources. It also provides industrial products and services such as the maintenance of biodiversity and life-support functions, including waste assimilation, cleansing, recycling and renewal, and intangible aesthetic and cultural benefits (Bengtsson 1997; King et al. 2000; De Groot et al. 2002). Major categories of ES involve provisioning services, regulating services, cultural services, and supporting services (Millennium Ecosystem Assessment 2005a).

The supporting services are goods and other service, which sustain various aspects of human well-being. The regulating functions affect human well-being in multiple ways, for instance, the purification of air, fresh water, reduced flooding or drought, stabilisation of local and regional climate, and checks and balances that control the range and transmission of certain diseases, including some that are vector-borne. Cultural services such as totemic species, sacred groves, trees, scenic landscapes, geological formations, or rivers and lakes influence the aesthetic, recreational, educational, cultural and spiritual aspects of human experience. In addition, supporting services are necessary for sustaining each of the other three services that indirectly affect human well-being (Millennium Ecosystem Assessment 2005a).

ES contributes to human well-being in numerous ways. Unfortunately, the services from the ecosystems are extremely undervalued, since most of the services cannot be traded in the market. Hence, it is difficult to estimate the true value of ES (Daily et al. 1997). Moreover, market-penetrating prices do not consider the multiple values of nature (Titumir et al. 2019). The value of nature cannot be understood solely through monetary valuation. Conceptualising values consider a 'plurality of world views' of nature because people differ in how they understand the word 'value' and how they attribute importance to nature (González-Jiménez et al. 2018). Similarly, there are different scientific concepts of value—intrinsic, instrumental and relational values, which cannot be conceptualised only by a market-pricing mechanism. As these values are subjected to experience-based and/or traditional branches of knowledge, exploring human-nature relationships from different perspectives, operating with specific paradigms and methodologies, is considered to be a crucial way of valuing nature (González-Jiménez et al. 2018).

15.2 Conceptualising Human-Nature Interdependence

The following framework demonstrates the interconnectedness of human and nature, along with the well-being resulting from the benefits received from ES, which are also subjected to production, ecological and political conditions (Fig. 15.1). It reveals that the types of ES keep thriving if nature's well-being is certain. When the drivers of change (production, ecological and political conditions) affect the ecosystem positively, the services of the ecosystem derive from nature's well-being contribute to human well-being in many forms. If the drivers negatively affect the nature, then well-being of both nature and human being is disrupted.

The policy level conditions are institutional and governance system, power and class, property rights and legal arrangements. The production level conditions

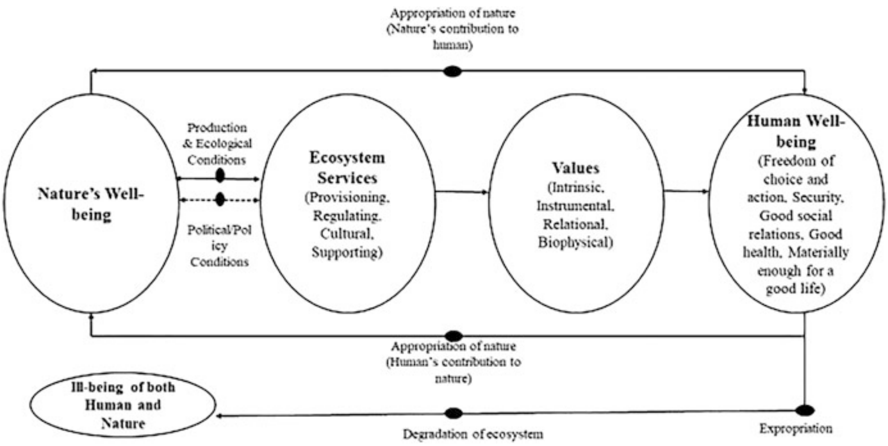

Fig. 15.1 Ecosystem services and well-being. (Source: prepared by authors)

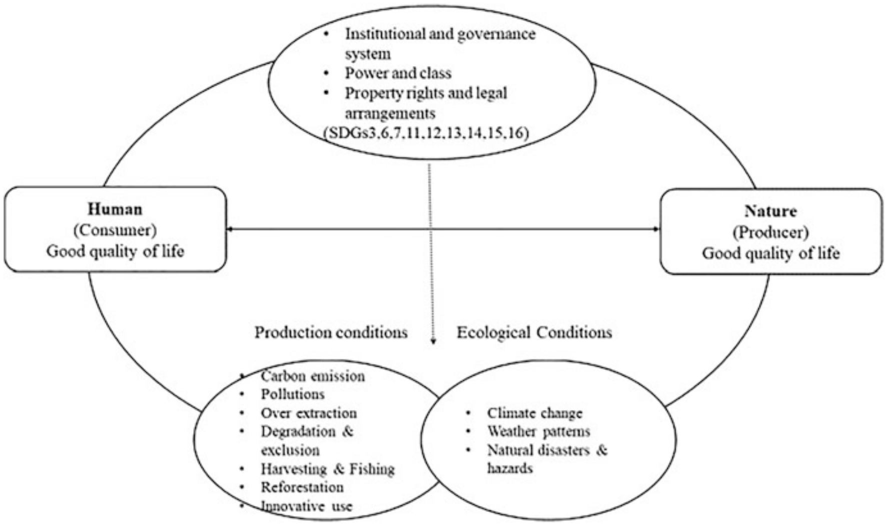

Fig. 15.2 Transformative pathways for human-nature relationships. (Source: prepared by authors)

include the level of carbon emission and pollutions, the rate of extraction, degradation and exclusion, the nature of harvesting and fishing, the rate of reforestation and innovative use, etc. On the other hand, the ecological factors are climate change, weather patterns, natural disasters and hazards, which determine the provision of ES and level of well-being of ecosystem (Fig. 15.2).

The appropriation of nature (conservation, restoration, sustainable uses access and benefit sharing) ensures a harmonious relationship between human and nature, which transforms quality of life of both. Identifying the direct (production and ecological conditions) and indirect drivers (policy/political conditions), this framework depicts that transformative changes occur if each other's interdependency, access and benefit sharing and well-beings are valued, apart from treating environment as economic goods alone (Figs. 15.1 and 15.2). To explore human and nature's interconnected relationship, it is crucial to categorise nature's contribution to human (provisioning, regulating and cultural) as well as human's contribution to nature (anthropogenic assets and drivers). All these are linked to well-being and sustainability of both factors (Fig. 15.2).

The plethora of amenities offered by the Sundarbans combines numerous values and contributes to well-being. The well-being, as understood by TRUs, is the healthy and secure life for both the forest and themselves, maintaining ecosystem balance. According to them, if the forest and its biodiversity remain safe and sound, they can also have healthy and good quality of life. Securing healthy life for human, animal and ecosystem simultaneously, as they signify, is the mainstay to realise well-being in the ecosystem. This understanding leads them to contribute to conservation, preservation and restoration of nature, which lead to well-being of the ecosystem (Fig. 15.1).

Therefore, the interdependent relationship between TRUs and the Sundarbans ascertains living in harmony with nature (Fig. 15.1). In contrast, according to TRUs, if alienation of human being from nature prevails, it leads to commodification and thus massive extraction of resources, which result in disruption of the ecosystem and biodiversity loss (Fig. 15.1). While TRUs consider the Sundarbans as their life and count on the true intrinsic value of the nature, outsiders are alienated from the nature. Hence, outsiders (illegal encroachers and politically powerful business syndicate) seldom care of conserving the nature.

15.3 Ecosystem Services (ES) and Well-Being

Traditional resource users (TRUs) get various types of goods and services from the forest, which contribute to their well-being. At the same time, the customary and traditional rules and practices of TRUs help conserve the ecosystem. The mutuality and cooperation between the forest and the TRUs have been identified as significant precondition to each other's well-being.

Total four FGDs were conducted (one in each category) with six respondents in each amongst four different groups of TRUs of *Koyra Bonojibi Samiti*, who pursue their livelihood as *Bawalia, Mouals, Jele* and crab collectors. Each of the groups developed a resource map depicting the current state of respective resources in the forest. The woodcutters (*Bawalis*) identified and drew the resource map on flora, fishermen (*Jele*) categorised and drew the resource map on fish, honey collectors (*Mouals*) depicted the distribution of beehive (*mouchak*) in the forest about honey and wax and crab collectors told about the current state of crabs. The area selected for the PPGIS study is 40 km in length and 30 km in width. The region is located between 22°28′30″ north to 22°1′0″'north latitude and 89°13′30″ east to 89°30′0″' east longitude. This region is the part of the Khulna Range—one of the four administrative areas of the Sundarbans.

15.3.1 Current State of ES

The fishermen (*Jele*) group described the state of various fish which they collected from the waterways in the forest. They usually catch fish like *java, dadnee, shrimp (bagda, chai, chaka), vetki, paissha, baila, chanda*, etc. These fish are often sold in the market, while some of these are also consumed by the fishermen themselves. They argued that some fish were used for medicinal purposes (e.g. *java fish*), which resulted in high prices for those products in the market. All six participants of FGDs in the *jele* group argued that the amount of fish collection was steadily declining. They attributed the use of pernicious nets like '*bishal jal*' and poisoning the water as key factors behind the depletion of fish. The respondents argued that administrative bodies often take bribes and allow the powerful groups adopt unsustainable extraction practices. They take no actions against these, even though they are supposed to. Moreover, over the years, the flow of water is declining which causes serious degradation of fish species in the water areas of the forest (see drivers of changes in Table 15.1).

Cutting timber in the forest is legally banned. The woodcutters (*Bawalis)*, however, collect *golpata* and other creepy plants for medicinal use and fuel. They categorised various floral species like *bain, keora, goran, geowa, sundari, pashur, dhundhul, kakra, khailsa, hental, bonshosha, bonlebu, choitboroi, gab, onra, bhuikumra*, etc. All of these species cannot be found in the same area. Distribution varies on the salinity of the forest. They argued that powerful syndicate often cut timber illegally, even though *Bawalis* are not allowed to cut woods. The decline in the forest area is occurring due to the illegal extraction, as well as frequent hazards caused by cyclones. Natural disasters like cyclones have negative impacts on the forest to a great extent. In addition, when a big tree is cut down, it destroys all other small trees and plants surrounding it.

All six participants in the honey and wax collectors (*Mouals*) group's FGD argued that beehives are found more widely in dense forests. Hence, it is obvious that if the number of trees decline, the number of honeycombs will also decline. *Mouals* follow some traditional rules when collecting honey. They collect honey and wax during the months of April, May and June. They cut a specific section (about two thirds) of the honeycomb and leave the rest for reproduction. This is to ensure that no young bees are killed during honey collection. In addition, beehives are squeezed by hand. They never use metal tools that may be dangerous to the bees. They produce smoke using dry leaves but never put fire on the beehive. The outsiders who do not know the traditional practices and rules often end up killing young bees. Moreover, a group of people also cut beehives in order to collect wax, which kills young bees and destroys future reproduction. During FGDs the *mouals* themselves came up with a solution to stop this unsustainable practice. According to them, 40 kg honey produces 2–2.5 kg wax. Therefore, if a honey collector collects more than 2/2.5 kg amount of wax against each 40 kg honey, then he must have cut the whole beehives, leaving no part for future breeding. As a result, people adopting unsustainable practices to collect honey can easily be identified. This also depends

Table 15.1 Drivers of changes in the Sundarbans. (Source: Compiled by authors)

Drivers	Remarks
Direct drivers	
Production conditions	
Carbon emissions	Developmental projects and industries near the mangrove omit CO_2 and other toxic gases that negatively affect the ecosystem
Pollutions	Air pollution due to emissions of toxic gases, water pollution due to salinity intrusion along with industrial wastage, and soil pollution due to increased salinity from sea level rise, and shrimp farming negatively affecting the ecosystem
Extraction of resources	Unsustainable and over extraction of sources degrades biodiversity and ecosystem
Degradation and exclusion	Rent-seeking behaviour induces over extraction, which leads to the degradation of resources where powerless and poor section gets excluded
Harvesting	Unsustainable harvesting like shrimp farming near the forest harms the ecosystem
Fishing	Use of pernicious nets, poisons to catch fish and over extraction lead to resource degradation
Reforestation	Community afforestation near the rivers and embankments benefit the ecosystem
Innovative use of resources	Customary-sustainable practices and innovative use of resources, such as CMAASC help conserve the natural forest creating alternative livelihood options
Ecological conditions	
Climate change	Climate change negatively affects the ecosystem, causing frequent cyclones, floods, increased salinity and sea level rise
Weather patterns	Change in weather patterns due to climate change negatively affect the ecosystem
Natural disasters and hazards	Frequently hit the ecosystem causing serious harm
Indirect drivers	
Political/policy level conditions	
Institutions	Institutions are the rules of the games, extractive institutions are causing over extraction of natural resources
Governance	Weak and corrupted governance indulges in rent-seeking practices and fails to conserve the forest
Power and class	Powerful syndicate uses rents to have illegal extraction of resources
Property rights	TRUs are denied their rights which causes over extraction of the resources
Legal arrangements	Low enforcement of existing laws, which barely protects TRUs perspectives

on the effectiveness of administrative bodies, who are often involved in unfair means of resource extraction from the forest.

Crab collectors argued that the use of harmful nets like "*bishal jal*" and poisoning the water kills eggs, small crabs as well as the breeding ground of crabs. Such

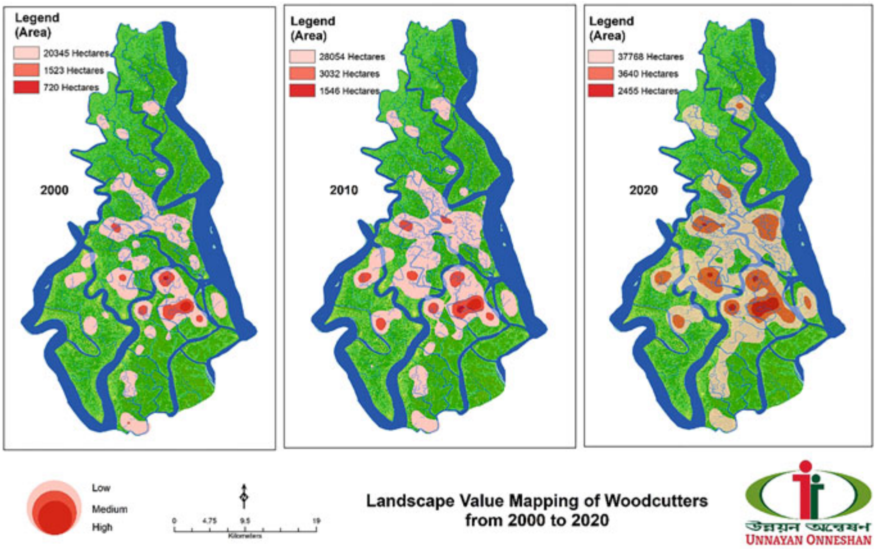

Fig. 15.3 Landscape value mapping of woodcutters. (Source: Unnayan Onneshan 2020a)

unethical practices are now posing major threats to crabs and other aquatic resources, even though crab collection has not declined significantly. As the number of crab collectors using unsustainable means is increasing gradually, the amount of crabs in the waterways is decreasing. They say that more crabs are caught in muddy water. If there is an increased flow of water in the rivers and canals, water becomes muddy, thus increasing the number of crabs. The flow of water, however, has decreased due to the presence of dams and barrages in the upstream rivers.

According to *Bawalis* in PPGIS, it is evident from the map of landscape valuation that in two decades (2000–2020), the value of the area where precious timber or trees are found has increased a lot (Fig. 15.3). Increasing value of a forest area to the *Bawalis* means more wood is extracted from that place with higher availability of valuable trees. In other words, the extraction of valuable trees from those areas has increased in two decades. Hence, the massive increase in the value of different areas of the forest on the basis of precious timber indicates a massive increase in extraction of trees in two decades. As a result, there has been a significant reduction in forest coverage during this time (Fig. 15.3).

According to honey and wax collectors (*Mouals*), it appears from the map that in two decades (2000–2020) the value of different areas of the forest have declined significantly based on the availability of honey and bee-wax (Fig. 15.4). The value of different region of the forest decreased as the availability of honey and wax has also declined (Fig. 15.4). Findings from ecological value mapping of honey and wax suggest that availability of these resources is declining gradually. As a result, value of different parts of forest in terms of honey and wax is decreasing in this region.

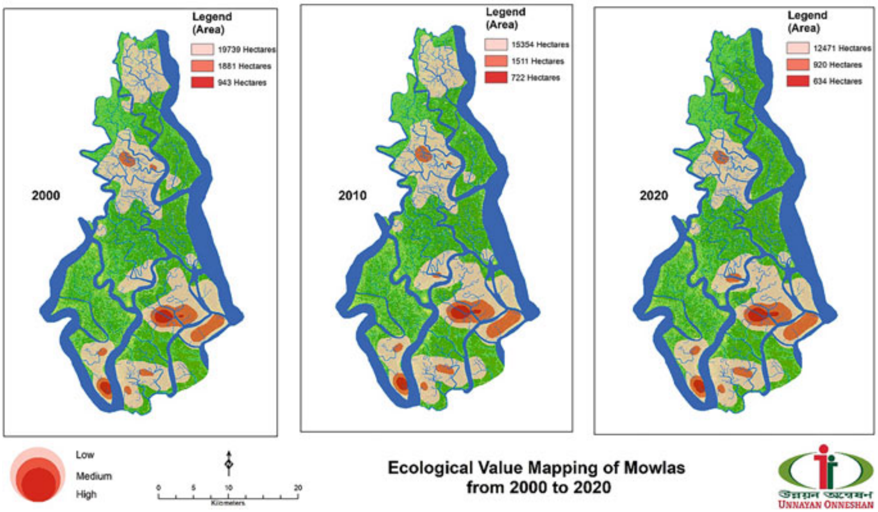

Fig. 15.4 Ecological value mapping of honey and wax collectors. (Source: Unnayan Onneshan 2020a)

The ecological value mapping of fishermen and crab collectors also depicts the degradation of fishing areas and crab collecting areas in the waterbodies of the forest, respectively. The value of different parts of the rivers, canals and creeks has significantly decreased in two decades, which indicates that over extraction of fish and crabs have been going on in those areas leading to less availability of aquatic resources (Unnayan Onneshan 2020a). These findings also corroborate with the FGDs conducted among fishermen and crab collectors, respectively.

15.3.2 Ecosystem Services, Multiple Values and Well-Being

Ecosystem services classified by Millennium Ecosystem Assessment (2005a), has been categorised to multiple values following the IPBES valuation approach. The services contributing to human well-being have been identified through FGD, semi structured survey and secondary corroborative sources. The different item/usage of resources and services contributing to well-being and their corresponding values are depicted in Table 15.2.

The provisioning services (foods, woods, fuel and water) of natural resources recommend the instrumental value. These are fish, shrimp, prawns, shells, honey, salt, crabs and fruits as foods; furniture, boats, and pillars of house, household cooking from woods; and transportation, shrimp and crab cultivation using water (Table 15.2). The supporting services (nutrient cycle, soil formation, primary production) are the underlying and biophysical values of nature. These services include mineralisation of nitrogen and phosphorus by fish through excretion, forest (roots of

Table 15.2 Ecosystem services and types of values. (Source: Compiled by authors)

Ecosystem services	Item/usage contributing to well-being	Types of value
Provisioning services		
Foods	Fish, shrimp, prawns, shells, honey, salt, crabs, fruits	Instrumental value
Woods	Furniture, boats, pillars of house	Instrumental value
Fuel	For household cooking	Instrumental value
Water	Transportation, shrimp and crab cultivation	Instrumental value
Supporting services		
Nutrient cycle	Mineralisation of nitrogen and phosphorus by fish through excretion	Intrinsic value
Soil formation	Forest (roots of trees) prevents soil erosion	Intrinsic value
Primary production	Removing toxic elements like SO_2, CO_2 to reduce air pollution and reproduction of various species of flora and fauna, raw materials (algae, sand, seaweed)	Intrinsic value, bio-physical value
Regulating services		
Climate regulation	Natural wall against climate change such as storms, cyclones and salinity intrusion	Instrumental value
Flood regulation	Protection from storms, floods, tsunami, etc.	Instrumental value
Disease prevention	Medicinal usage of different floral and faunal species such as cortex of Poshur *(X. mekongensis),* Hargoza *(Acanthus ilicifolius)*, Fruits of Sundori *(Heritiera fomes)*	Instrumental value
Water purification	Prevents salinity, rivers and waterways work for movement and storage of water	Instrumental value
Cultural services		
Aesthetic	Seascape, landscape, abundance of beautiful biodiversity, etc.	Relational
Spiritual	Certain beliefs such as *'Bonobibi'* and religious rituals	Relational
Educational	Knowledge creation and research scope	Relational and instrumental value
Recreational	Nature watching, sailing, recreational fishing, etc.	Relational and instrumental value

trees) preventing soil erosion, removing toxic elements like SO_2 and CO_2 to reduce air pollution and reproduction of various species of flora and fauna, raw materials (algae, sand, seaweed) etc. (Table 15.2). The regulating services (regulation of climate and flood, disease prevention and water purification) also record the instrumental value. For example, Sundarbans' working as natural wall against storms, cyclones and salinity intrusion, medicinal usage of different floral and faunal species (Table 15.2). On the other hand, cultural services are mainly related to relational values. These are seascape, landscape, abundance of beautiful biodiversity, certain beliefs such as '*Bonobibi*' and religious rituals, knowledge creation and research scope, nature watching, sailing, recreational fishing, etc. (Table 15.2).

The forest provides livelihoods, enjoyment and recreation. It also serves as the protecting belt of the coastal region. The TRUs associate this forest as their lives on which their existence depends. The values contribute to the well-being of the TRUs. There are many factors that affect the well-being of both the forest and humans (Table 15.1).

15.3.3 Drivers of Changes

The direct and indirect drivers affect the well-being of the forest and the TRUs. The main problems identified by the TRUs during FGDs include climate change, over extraction of resources, unsustainable practices such as poisoning, rent-seeking behaviour of administrative bodies and institutional fragility (Table 15.1). The anthropogenic pressures damage the forest owing to the weak institutional and governance systems. The changes in the well-being of the forest due to the production and ecological and political conditions are negatively affecting the well-being of the human being. The amount of resources is depleting due to over extraction and changing climate variables as well. All these impacts are adversely affecting the well-being of the TRUs.

There are, many factors that affect the quality and amount of ecosystem services. These factors can be categorised in three different conditions: the policy level or institutional conditions, the production level conditions and the ecological conditions. If the policy level conditions function inclusively, they positively affect the ecosystem's well-being. In contrast, if policy level conditions take extractive nature, it causes disruption in the ecosystem and thus ill-being of human, animal and ecosystem. Extractive institutions are causing over extraction of natural resources. Politically and economically powerful groups are grabbing the forest illegally. People's settlements are increasing gradually around the forest. Despite the ban, illegal tree felling is causing deforestation. Although forest co-management system is there, the existing system has marginalised the rights and traditional knowledge of the forest-dependent people. For instance, they require clearance from the forest department every year against a certain amount of money to gather their resources. Allegations of irregularities and corruption have been found in getting clearance certificates. So the forest people tend to collect more resources than they need to meet these extra costs (Table 15.1).

If the production level conditions move forward in sustainable and green processes, the quality of the ecosystem remains healthy. Otherwise, anthropogenic pressures lead to massive depletion of the nature and thus ill-being of all biotic and abiotic feature of the ecosystem. For example, commercial activities are also increasing in ecologically critical area surrounding the forest. Excessive extraction of forest resources is damaging the biodiversity. Besides, many species face damage owing to harmful methods of resource extraction. Poison and harmful nets are often used for fishing. In contrast, community afforestation near the rivers and embankments benefit the ecosystem. Customary-sustainable practices and innovative use of resources, such as CMAASC help conserve the natural forest creating alternative livelihood options (Table 15.1).

The ecological factors also determine the provision of ES and level of well-being of ecosystem. For example, climate change negatively affects the ecosystem. The ecosystem and biodiversity are being threatened with extinct due to the frequent natural disasters. Several organic and inorganic ingredients (salinity, rainfall, soil pH, mineral ingredients, etc.) of the forest are being altered owing to the climate change, an alarming signal for ecosystem. Low-lying coastal areas are at the most risk of flooding with seawater. Salinity is increasing in the water and soil of the coastal regions. The frequent hit of cyclones, floods, increased salinity and sea level rise are damaging the ecosystem balance and creating livelihood distress of the TRUs (Table 15.1).

15.4 Traditional Resource Users and Well-Being

A Likert scale analysis, a survey scale developed for measuring attitude and widely used to measure the strength/intensity of attitude, perception and opinions is used to depict the perception of the TRUs regarding well-being. A total of eight questions were asked during this survey. There were 115 respondents. The answers were explored using a four-point scale (highly satisfied, satisfied, somewhat satisfied, not satisfied at all) asking how satisfied they were in terms of life and livelihoods, security, health, freedom of choice and social relations.

The first question asked how satisfied the respondents were with his/her life. Of all the respondents, 43% replied that they were satisfied with their life, while 32% replied that they were highly satisfied. On the other hand, 25% argued that they were somewhat satisfied. The second question is about the satisfaction of their life style and the success of their activities. The majority of the respondents (60%) replied that they were somewhat satisfied, and only 2% replied that they were not satisfied at all. The third question was how happy they were with their life. The majority (56%) in this case replied that they were somewhat satisfied with happiness in life, while others responded to being satisfied (23%) or highly satisfied (19%). The forth question inquired the satisfaction level about the security of life and livelihoods of the TRUs. The majority of the respondents (69%) argued that they were somewhat satisfied. The fifth question explored the level of satisfaction in terms of health. In this case, again the majority of the respondents (63%) replied that they were somewhat satisfied. The sixth one inquired the satisfaction regarding their social relations. Being satisfied, 35% of the respondent implied that they had good social relations. The majority of the respondents (60%) were somewhat satisfied. The seventh question asked about the level of satisfaction, regarding the ability of meeting the basic needs and demands of life. Again, the majority of the respondents (66%) said that they were somewhat satisfied. The eighth question asked about the satisfaction level regarding freedom of choice and freedom of profession. The majority of the respondents (57%) believe that they were highly satisfied with this,

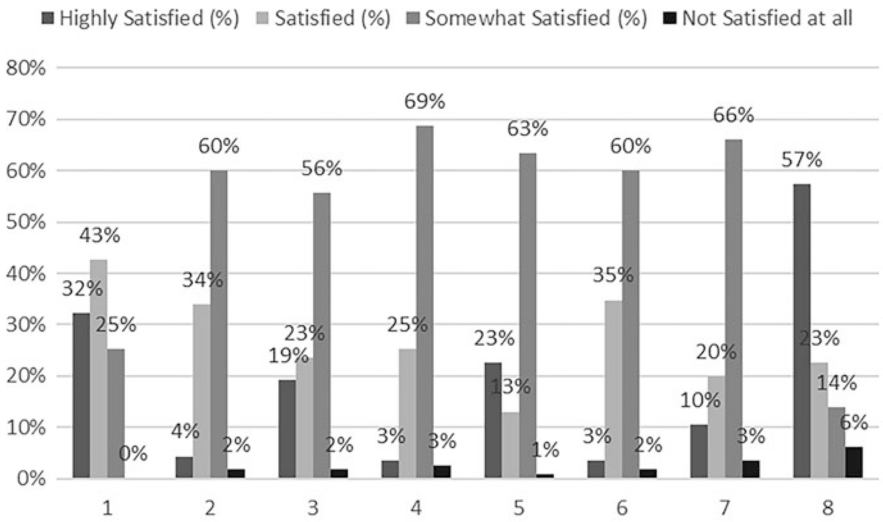

Fig. 15.5 Well-being perception of TRUs. (Source: Authors' calculation)

while 23% believe that they were satisfied. In this case, 6% of the respondents replied that they were not satisfied at all.

The Likert scale analysis implied that, in most of the cases, the majority of the respondents were somewhat satisfied. Though the level ranges mostly between 'high satisfaction' to 'somewhat satisfaction', the difference between the level of satisfaction is noteworthy. The majority of the TRUs perceive that they were not fully satisfied with life, livelihoods, security, health, social relations and freedom of choice (Fig. 15.5).

15.4.1 Corroborative Evidence

Corroborative literatures also support the findings from the Likert scale analysis adopting the perception of TRUs regarding the context of well-being. It is observed that species like *Heritiera* and *Ceriops* are on the brink of decline in future, increasing the amount of *Excoecaria* and *Bruguiera* which is abundant at present. This kind of ecosystem will be unable to provide the beneficial services. There is also a possibility of decrease in the regulating and supporting services like storm protection, shoreline protection and enhanced primary productivity. On the counter position, with increasing abundance of *Excoecaria* and *Bruguiera*, products from these species such as soft wood for making furniture and ornaments and medicinal values such as anti-tumour promoting drugs (Konoshima et al. 2001) would be utilized better than it is being now. Increase in *Excoecaria* and *Bruguiera* might also be beneficial for the ecosystem services such as soil formation and retention along with organic matter and nutrient enrichment in the forest floor. Overall, since the forest extent is forecasted to fall short by the end of 2100, the magnitude of ecosystem services is expected to reduce. This is especially from those species that are less tolerant to salt (Mukhopadhyay et al. 2018).

Increasing climate impacts such as floods, cyclones and salinity intrusion are hitting the communities hard. Houses, equipment and livelihood investments are frequently destroyed by cyclones. The harshness and severity of these cyclones are much more significant than the number of cyclones occurring. About 53% of the world deaths due to cyclones occur in Bangladesh and about 23% in India (Rahman and Rahman 2015). However, it is worthy to note that these two countries are hit by only 4.27% of the world's storms (Titumir et al. 2022).

15.4.2 Impact of COVID-19 on Traditional Resource Users (TRUs)

In this context of existing hardships, the COVID-19 pandemic and nationwide lockdown have posed catastrophic impacts on the lives of millions of forest people. The ongoing crisis will increase the poverty rate among the forest people to 40% (Unnayan Onneshan 2020b). A survey was conducted in two cooperatives to understand the impact of COVID-19 on TRUs (see Titumir and Paran 2022). The number of households in two cooperatives is 200 including approximately a total of 1500 household members. For survey, the households were categorised as wood collectors (*Bawalis),* fishermen (*Jele*), crab collectors, honey and wax collectors (*Mouals*) and Munda indigenous community. The number of households surveyed are 135 in two cooperatives who are registered as members and are traditional resource users (TRUs). The income patterns of households during COVID-19 era reveals from survey that number of households having income loss is 103, which is 76.30% of total households surveyed. The average monthly income loss is BDT 4075 (Table 15.3).

The pandemic has resulted in reduction in expenditure to meet the basic needs by the households (Table 15.4). Reduction in food expenditure, health expenditure and clothing and shelter expenditure are 11.35, 3 and 13%, respectively. Twenty-six percent household members are unemployed. Ninety-eight percent households have taken loans from multiple sources such as relatives, NGOs or informal lenders during COVID era. Fifty-seven percent households have used their savings to bear the family expenditure (Table 15.4).

Table 15.3 Impact on households' income during the pandemic. (Source: Titumir and Paran 2022)

Total no. of households	Average no. of household members	No. of households facing income loss during the pandemic	Average monthly expenditure of households	Average monthly income before COVID-19	Average monthly income in COVID-19	Average monthly income loss due to COVID-19
135	6.5	103	BDT 17700	BDT 15575	BDT 11500	BDT 4075

Table 15.4 Different impact of COVID-19 on households. (Source: Titumir and Paran 2022)

Impact/item	Percentage
Reduction in food expenditure	11.35
Reduction in health expenditure	3
Reduction in clothing and shelter expenditure	13
Income loss	26.16
Unemployed household members	26
Households under government's social safety net programmes	37
Households receiving immediate relief/cash assistance by the government during pandemic	53
Household facing income loss	76.30
Households taking loans to bear the living expenses during COVID	98
Households able to meet basic needs before the pandemic to some extent	100
Households borne expense by breaking their savings	57

15.5 Human-Nature Sociality and One Health Approach: A Transformational Pathway

A whole of the society approach on conservation and sustainable use of biodiversity in the Sundarbans can ensure and enhance one health that include human, animal and ecosystem health all together. A whole of the society approach brings all under the umbrella practices of sustainable production and consumption as well as equal access and benefit sharing. It ascertains well-being and good quality of life for human, animal and ecosystem simultaneously. Promoting one health however requires concerted actions. Firstly, ensuring rights-oriented social entitlement to everyone—such as universal access to education, health and social security programmes. Secondly, providing livelihood security that includes food security, job security and social security. Thirdly, promoting human-nature cooperation through green production system such as clean and green energy. Fourthly, promotion of customary sustainable practices and traditional knowledge in forest management (Fig. 15.6).

The Sundarbans provides the people's existence, livelihoods, social harmony, the breeding of their offspring, natural safety and security and well-being. TRUs also

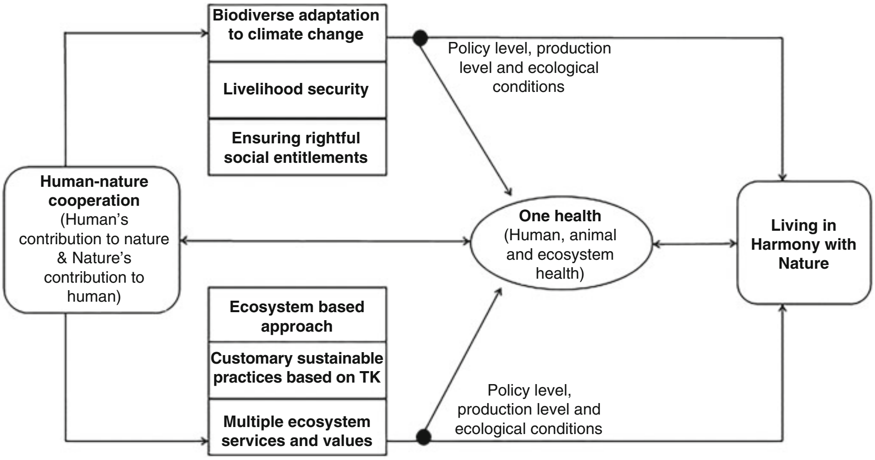

Fig. 15.6 Living in harmony with nature: modified one health approach for post 2020 period. (Source: Titumir and Paran 2022)

play significant role to conserve and protect the Sundarbans. They follow customary sustainable practices that are foundation of mutual well-being and interdependence relations. Two cooperatives selected for the case study have been sustainably utilising and conserving the resources of the SEPLS, maintaining the well-being of both the Sundarbans and themselves. However, there are plethora of challenges and issues in managing the Sundarbans' ecosystem. In response, to adapt and mitigate these challenges, indigenous people and local communities (IPLCs) have taken various actions. These actions lead to increased regenerative capacity of the Sundarbans and well-being of ecosystems, increased income and standard of living and low-impact life style and sustainable production and consumption by IPLCs, which contribute to positive health outcome (Fig. 15.6).

IPLCs have adopted various innovative and participatory local approaches and actions to manage the SEPLS sustainably for ecosystem health, animal health, human health and livelihood security. These include mobilising themselves for claiming rights and protecting the SEPLS, securing land through struggle, negotiation with local government, conservation practices based on TK, community-based monitoring and information system (CBMIS), community plantation, homestead plantation, innovative biodiverse adaptation and nature based production, that is, sustainable aqua culture (CMAASC, Crab Culture), sustainable forest product culture (*golpata* culture, honey and wax culture), working with local government and forest department as watchdog to stop illegal hunting, harvesting and cutting of trees and stop usage of poison and harmful nets to catch fish. These activities enhance ecosystem health, animal health and human health through forming a virtuous cycle. Healthy ecosystem provides more services to the human being and thus helps promote and maintain human health (Fig. 15.6).

These activities, however, depend on regional and global partnership as well as on policy level, production level and ecological conditions. The policy level conditions are indirect drivers of change, while the production level and ecological conditions are the direct drivers of change in the ecosystem. When the drivers of change (production, ecological and political conditions) affect the ecosystem positively, the multiple services of the ecosystem contribute to human well-being. If the drivers negatively affect the ecosystem, the well-being of both human and nature gets disrupted. It is found that the appropriation of nature (conservation, restoration, sustainable uses access and benefit sharing) ensures a harmonious relationship between human and nature, which transforms quality of life of both. Human-nature cooperation counts human's contribution to nature as well as nature's contribution to human being and contribute to maintain a healthy ecosystem – one health, leading to living in a harmony with nature (Fig. 15.6).

15.6 Conclusions

This chapter deals with multiple values of ecosystem services and well-being of human and nature and the factors affecting the ecosystem. The benefits from the ecosystems appear in the form of various goods and services which help to make human life both possible and worth living. It was also revealed that the types of ecosystem services keep thriving if nature's well-being is on point. If the drivers of change such as the production and ecological and political conditions affect the ecosystem positively, then the services of the ecosystem derive from nature's well-being contribute to human well-being in many ways and vice versa.

The chapter demonstrates that the values of the ecosystem services are enormous in contributing to the survival and existence of the people. The well-being of the people relies on the well-being of the forest. The climate change and its rising impacts in the form of cyclones, salinity intrusion and sea level rise are causing damage to the forest and its people. Although the forest is protecting people and the region from climate impacts through various regulating services, it has to bear serious damages too. The over extraction of resources in addition to pollution from various anthropogenic variables is resulting in massive depletion of biodiversity and habitats of the forest. The fragile institutions and ineffective governance system are contributing to the destruction of the ecosystem in the forest.

As a result, the well-being provision of the human being—TRUs are declining. In terms of life and livelihoods, health, security, social relations and their freedom of choice, people are becoming less satisfied day by day. It can be seen that the traditional rules and practices can significantly help in maintaining the natural balance of the forest. This can occur if it is adopted through a formal governance system. Since the well-being of humans and nature is interconnected, the appropriation of the natural resources by maintaining a balance in the ecosystem becomes crucial. In this regard, the chapter presents a modified one-health framework for post 2020 period, which can promote human transition into living in harmony with nature. The framework calls for ensuring rights-oriented universal social entitlements, provision of livelihood security and promotion of human-nature cooperation through green production, ecosystem-based approach and biodiverse adaptation to climate change, underwritten by customary sustainable practices and traditional knowledge in SEPLS management.

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Chapter 16
Fostering Mangrove Ecosystem Services for a Resilient Future for the Asia-Pacific Region: A Knowledge Synthesis

Rajarshi Dasgupta, Shizuka Hashimoto, and Osamu Saito

Abstract As the threat of climate change intensifies across the Asia-Pacific region, there is an urgent need to foster resilient human societies in coastal areas in Asia. On a regional basis, conservation and restoration of mangroves are increasingly important to fulfill several intergovernmental targets, including the Sustainable Development Goals (SDGs), the Paris Agreement, and the Sendai Framework for Disaster Risk Reduction (SFDRR), among others. This chapter synthesizes major findings from 14 case studies included in this book and considers some key observations, opportunities, and challenges related to future mangrove sustainability and fostering climate-resilient societies. The chapter concludes with a call for integrating mangrove ecosystem services into coastal development and adaptation planning and identifies the possible avenues to strengthen the human-nature relationship along the Asian coast.

Keywords Mangroves · Asia-Pacific region · Ecosystem services

16.1 Introduction

Mangroves are important tropical ecosystems that are increasingly being discussed in the global arena for their extraordinary ecosystem services. Over the past three decades, understanding about mangroves has changed drastically, and today, many countries and territories emphasize the conservation and restoration of mangroves within their climate change action and regional development plans. Mangrove conservation is also increasingly being mentioned in intergovernmental policy discourses. For example, since 2015, the global community has adopted three

R. Dasgupta (✉) · O. Saito
Institute for Global Environmental Strategies, Hayama, Kanagawa, Japan
e-mail: dasgupta@iges.or.jp

S. Hashimoto
Department of Ecosystem Studies, The University of Tokyo, Tokyo, Japan

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major sustainability frameworks, namely, the United Nations 2030 Agenda for Sustainable Development, with its 17 Sustainable Development Goals (SDGs); the Paris Agreement on global climate change; and the Sendai Framework for Disaster Risk Reduction (SFDRR). In addition, in 2022, the world will adopt the new Post-2020 Global Biodiversity Framework for managing nature through 2030, replacing the existing Aichi Biodiversity Targets. Conservation and regeneration of mangroves cuts across all these major global agendas, and as such, it is an issue that is pivotal for fostering a sustainable and resilient society both at a local and global level. Particularly in the Asia-Pacific region, where more than 2.4 billion people live in low-lying coastal areas, the role of mangroves is indispensable to foster climate- and disaster-resilient communities.

16.1.1 Mangroves in Contemporary Policy Discourses

Mangroves and their ecosystem services have potential relevance to all the 17 SDGs but are especially important for SDG 14, (life below water) which focuses on ocean and coastal ecosystems. More precisely, target 14.2 calls for the sustainable management and protection of marine and coastal ecosystems and urges governments to engage in the restoration of such ecosystems to achieve healthy and productive oceans. Another important target related to mangroves is target 14.(a), which outlines the need for increased scientific knowledge and research capacity to improve ocean health and sustainability. Among the other SDGs, SDG 12 (responsible consumption and production), SDG 13 (climate action), and SDG 15 (life on land) have a close interrelationship with the conservation and rejuvenation of mangrove ecosystem services. Restoring mangrove forests further supports the elimination of poverty and hunger, as well as ensuring livelihood and economic growth of the coastal communities, thus playing a critical role in the localization of SDG targets in developing and least developed countries in the Asia-Pacific region.

The SFDRR mentions the need to address the underlying causes of disaster risks and to prevent the emergence of new risks. In line with this agreement, a number of researchers have identified the loss of mangrove ecosystem services as a perennial factor for rising disaster risks in coastal areas, particularly in the low-lying Asian mega deltas (DasGupta and Shaw 2015; Richards and Friess 2016). Following the adoption of the SFDRR, researchers emphasized minimizing the use of gray infrastructure and called for a paradigm shift toward establishing green infrastructure, such as mangrove forests for coastal defense purposes (Sebesvari et al. 2019; Sudmeier-Rieux et al. 2021). It is now well established that mangroves can reduce coastal flooding and provide strong protection from seaward hazards, reducing loss of life and damage to property. They also play an important role in the "*Build back better*" concept promoted by the SFDRR. Not only are they efficient, but they are also environmentally friendly and cost-effective. Mangroves are estimated to protect 12.5 million people from flooding every year, primarily in countries like Vietnam, India, Bangladesh, China, and the Philippines (IUCN 2020). Several empirical research studies have modeled the effects of mangroves in wave attenuation and storm surge reduction in various parts of the world. In addition, mangrove-based disaster risk reduction measures include general resilience building, particularly through provisioning of livelihoods, food, shelter, and eco-tourism activities.

The conservation and restoration of mangroves also provide great opportunities to mitigate greenhouse gas (GHG) emissions. Collectively known as blue carbon, coastal ecosystems, including mangroves, store a disproportionate amount of carbon, amounting to five times more than comparable terrestrial ecosystems. It is estimated that emissions from mangrove loss could reach 3392 Tg $CO_{2\ eq}$ by the end of this century given the current rate of deforestation (Adame et al. 2021). Similarly, restoration of lost mangroves worldwide could lead to the storage of an additional 69 million tons of carbon in aboveground biomass (IUCN 2020). Although the IPCC Guidelines for National Greenhouse Gas Inventories do not differentiate between blue carbon ecosystems and other terrestrial forests, of the 175 NDC submissions, 28 countries include blue carbon in their mitigation strategies, and 59 countries include it in their adaptation measures (Thuy et al. 2019). Within the Asia-Pacific region, only three countries, namely, Indonesia, Malaysia, and the Philippines, have so far explicitly referred to the blue carbon strategy and established a national agency responsible for developing such a strategy (Thuy et al. 2019). While mangroves play an important role in forest-based mitigation measures, it is also important to account for and mainstream the role of mangrove ecosystem services for their potential in ecosystem-based adaptation (EbA) measures. With more than 70 different uses of mangroves (DasGupta and Shaw 2013), their implications in building social and economic resilience are unparalleled. For foresting EbA measures, it is nevertheless important to know how future availability of mangrove ecosystem services is likely to change over space and time.

Similarly, according to a recent study, mangroves further contribute to 20 Aichi Biodiversity targets, particularly to targets 6 (sustainable fisheries), 11 (protection measures), 15 (ecosystem restoration and resilience), and 19 (knowledge, science, and technology), all of which are directly linked with the rejuvenation of mangrove ecosystem services (Bimrah et al. 2022). Despite some good progress over the past decade, the aforementioned targets are still unmet in most parts of the world. Therefore, mangrove conservation and restoration have direct implications in realizing these unfulfilled targets, which will possibly be adopted in the Post2020 Global Biodiversity Framework.

To meet all the abovementioned objectives, meaningful scientific information on mangrove cover, as well as ecosystem services provided by mangroves over space and time is pivotal for decision-making. Many recent scientific studies, including those by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), are also calling for scenarios and models to be used for better understanding of the potential future delivery of ecosystem services (DasGupta et al. 2019a; Hashimoto et al. 2019). In line with this, the book has outlined the different ways of assessing, mapping, and modeling mangrove ecosystem services in space and time. In particular, it looked at scenario development, analysis, and modeling approaches to understand the current and future availability of mangroves and their ecosystem services. The case studies herein were carried out in several Asian countries and regions, including India, Japan, Pakistan, Bangladesh, Taiwan, Indonesia, and the Philippines. The following sections of this chapter outline shared learning through key observations, opportunities, and knowledge gaps.

16.2 Key Observations, Opportunities, and Challenges

16.2.1 Significant Advancement of Geospatial Approach in Mangrove Mapping and Monitoring

With the recent advancement of open access tools and data, it is the geospatial approach that dominates mangrove research, both globally and locally. Several chapters in this book, namely, Chaps. 2, 3, 8, and 11, used remote sensing techniques to establish historical trends and then analyzed mangrove ecosystem services over space and time. Monitoring of mangroves through geospatial approaches has several advantages over the conventional forest estimation methods: (1) Remote sensing can acquire information over large areas on a retreaded basis, (2) accurate data can be produced from otherwise inaccessible locations, and (3) information can be provided on mangrove health and species through advanced tools of measurements. In addition to this, easy access to archived data provides a rare opportunity to analyze spatiotemporal trends of mangroves. For instance, in Chap. 2, Hussain and Rahman provided a spatiotemporal analysis of mangroves using the Landsat open-access time series data. In Chap. 3, a detailed method is proposed by the authors, which highlights the use of Google Earth Engine (GEE) to monitor mangrove restoration in abandoned aquaculture ponds. Such methods can be applied to any other mangrove habitat given is the data and tools are free and easily accessible. Moderate-resolution geospatial data was also used to monitor the loss and gain for mangrove forests in the Andaman Islands of India (Chap. 8). In this chapter, the authors were able to document the changes in mangrove cover after the tragic Indian Ocean Tsunami, which led to a tectonic shift on the island. Further, they assessed the aboveground biomass for the mangroves, as this counts as one of the most important ecosystem services, using remotely sensed data for land cover and land-use change. In Chap. 11, the authors used a combination of land-use maps and InVEST, an open-access tool for modeling ecosystem services, to monitor the changes in mangrove ecosystem services over two temporal intervals. Similarly, in Chap. 15, the authors used geospatial technology to map ecosystem values over space and time.

Despite the growing recognition of satellite remote sensing and geospatial technology in mangrove monitoring and modeling of ecosystem services, one particular challenge is the tidal effect on mangrove habitats, especially in low-lying deltas (DasGupta et al. 2019b). In particular, the reliability of temporal data, especially the moderate resolution satellite data, essentially makes it difficult to make a proper estimate of mangroves under tidal fluctuations. However, in recent years, drones and other area-based observation technology removed several research obstructions and bias previously encountered by researchers. Moreover, open-source data, hyperspectral data, and radar data are revolutionizing mangrove observation techniques.

16.2.2 Restoration Scenarios Are Taking Over Degradation Scenarios

Mangroves and other coastal ecosystems are also important carbon sinks of biomass origin. They are naturally resilient even after large-scale disturbances and are capable of recolonizing. These ecosystems are not only important for their contribution in addressing climate change mitigation, but they also offer a variety of benefits to the well-being of local communities. Although mangrove cover continues to decline in Asia, Reduced Emissions from Deforestation and Forest Degradation (REDD+) and other incentive mechanisms helped to regain mangroves in several parts of the region. In general, over the last decade, mangrove loss has been largely halted. International NGOs, UN agencies, and other aid agencies have worked specifically on restoring mangroves over the last two decades. In line with this, several chapters in this book also identified the enhanced efforts made by local governments, forest and allied departments, institutions, and NGOs toward mangrove restoration in recent years. In fact, Chaps. 2, 3, and 11 mentioned that mangrove cover and accompanying ecosystem services increased over time, giving rise to the possibility of a more sustainable future for mangroves. Further, mangroves could naturally recolonize abandoned aquaculture ponds, as shown in Chap. 3, which should be taken into consideration for proactive coastal zone management.

One typical uncertainty emerges with regard to understanding the response of mangrove ecosystems to climate change (Ward et al. 2010). Sea-level rise is likely to influence mangroves in all regions, particularly in low-lying Asian megadeltas and small islands. However, a proactive landscape planning approach where mangroves can migrate landward would ensure the delivery of vital ecosystem services. At present, mangroves in Asia have little opportunity to migrate landward, given the high population density in the region's crowded coasts, as well as the rapid expansion of aquaculture, tourism, and other industrial activities within the vicinity of existing mangroves. Therefore, to make space for possible upward migration, coastal managers need to implement proper zonation.

16.2.3 Participatory Approaches Help Identify Potentially Influential Drivers and Ecosystem Services

The future of mangroves depends heavily on how communities prioritize their conservation and the human-nature relationship in the complex socio-ecological systems where mangroves are located. Certainly, technology such as geospatial applications, including advanced tools for modeling ecosystem services, can flawlessly identify the spatiotemporal changes of mangroves. However, it is multi-stakeholder participation that remains the appropriate approach to identify the underlying factors for mangrove loss and restoration. Participatory multi-stakeholder approaches are imperative for understanding preferences in terms of ecosystem services, particularly within different forest user groups.

In this book, participatory approaches were adopted by several researchers to identify influential Social, Technical, Environmental, Economic and Policy (STEEP) drivers. Both Chaps. 5 and 6 used participatory stakeholder-based approaches to identify the drivers and pressures on mangrove ecosystem services. In Chap. 4, Takahashi et al. narrated a detailed analysis of diverse perspectives to build the island-scale land use and land cover scenarios for Ishigaki Island. Similarly, as highlighted in Chap. 15, communities share an intricate relationship with mangroves, and it is important to recognize the diverse perspectives for sustainable mangrove resource management. In addition, as evidenced in Chap. 9, it is also important to engage the media to champion mangrove conservation, so that information related to mangrove benefits can reach a mass audience, without resorting to scientific and political jargon.

Despite the prevailing participatory mangrove management in many Asian countries that has been instrumental in mangrove rejuvenation in recent years (DasGupta and Shaw 2017a, b), one fundamental challenge is to manage the high resource dependency shown by growing numbers of traditional resource users, which promotes illegal diversion of mangroves, overfishing, or overexploitation. Any potential conflicts among diverse resource user groups can be managed through the promotion of alternative livelihoods and a robust incentive mechanism for mangrove conservation, training, education, and capacity building (DasGupta and Shaw 2017a, b).

16.2.4 Tapping the Regulating Services for Eco-Engineering and Nature-Based Solutions (NbS)

Mangroves provide a plethora of ecosystem services that are essential for human well-being. However, in contemporary policy documents, mangroves have been particularly credited for their impeccable regulating services. Likewise, this book detailed a large number of case studies that focused on regulating services, such as carbon storage (blue carbon) (Chaps. 7, 8, and 9) and ecosystem-based disaster risk reduction (Eco-DRR) (Chapters 10 and 11), as compared to support services

(Chap. 12), provisioning services (Chap. 15), and cultural services (Chap. 13). Globally, mangroves are increasingly being mentioned as a tool for nature-based solutions (NbS) as compared to artificial structures for coastal protection. Many researchers further described mangrove cover as a "no regret" approach to coastal adaptation. However, scientific design studies that can be applied at the field scale require careful selection of species and their arrangements. In this book, several chapters highlighted the regulating ecosystem services of mangroves. In Chap. 10, for example, the authors developed a robust eco-engineering approach to reduce the risk of embankment failure using a combination of mangrove species. Nevertheless, they also cautioned that community participation is important to ensure the long-term sustainability of such arrangements and to maintain their protective functions. In addition, coastal planners should carefully select mangrove species and rely on only native species, rather than exotic species.

Within the scope of NbS, Chap. 11 identified that even a small patch of mangroves, when restored, can help to keep a city free from the threat of natural disasters and improve overall environmental quality. This is important knowledge, especially from the perspective of urban mangroves, which are fast disappearing. Historically, many Asian coastal megacities were reclaimed from mangroves, but they still have some mangrove cover, and research has pointed to the enormous role played by even small patches of mangroves (Curnick et al. 2019). Other regulating services provided by mangroves include the storage of blue carbon, which is widely covered throughout this book. It has been recognized that regulating services particularly in carbon storage and disaster risk reduction outnumber other types of important ecosystem services. Global research on mangrove ecosystem services also seems to be biased toward regulating and supporting services (Bimrah et al. 2022).

16.2.5 Indigenous and Local Knowledge (ILK) and Cultural Values Strengthen Mangrove Conservation and Restoration

Mangroves are associated with various myths, cultures, religious beliefs, and local and traditional ecological knowledge (Kovacs et al. 2017). As argued in Chap. 14, it is important to blend indigenous local knowledge (ILK) with contemporary scientific research, which can ensure an in-depth understanding of different attributes of ecosystem services, including spatiotemporal changes, changes in species composition, and external influences, among others. To capture the ILK, participatory action research and in particular the Public Participatory Geographic Information System (PPGIS) can be useful at the local level. In addition, it is important to strengthen traditional, indigenous, and informal institutional systems to assess various risks associated with future uncertainties in mangrove ecosystem services and adaptation options. Next, as mentioned in Chap. 13, despite significant efforts in recent years, current research on mangrove cultural ecosystems primarily outlines mangrove-based tourism or monetary benefits. However, other mangrove cultural ecosystem services, particularly those with intangible values, are rarely assessed. Furthermore, there is no specific framework or methodology that can uniformly assess mangrove cultural services on a large scale. Thus, to ensure a sustainable human-nature relationship, it is important to document the intangible values of mangroves, such as diverse landscape values and ethnobotanical uses (Dasgupta et al. 2021). In addition, efforts should be made to conserve these non-material, intangible values to strengthen the human-nature relationship across mangrove socio-ecological systems.

16.3 Conclusion

Assessing, mapping, and model-based estimation of ecosystem services across space and time is an important tool for decision-making in the face of uncertainties. While it is well known that mangroves play a critical role in human well-being in coastal areas and that their services are particularly important from both climate change mitigation and adaptation perspectives, there are several uncertainties related to the future delivery of these ecosystem services. Against this backdrop, this book presented 14 chapters from different parts of Asia, narrating the diverse tools and techniques of scenario planning, such as trend analysis, identification of potentially influential drivers as well as mapping/modeling of mangrove ecosystem services. These chapters also covered different types of mangrove ecosystem services, including provisioning, regulating and supporting, as well as giving their utilization/perceived values. This concluding chapter synthesized some of the common lessons learnt from the 14 chapters and identified major findings, achievements, and research gaps. In terms of shared learning, the following points briefly highlight research outcomes and information gained from this book.

- Remote sensing and current process-based models, including both spatial and nonspatial models, offer important information related to mangrove sustainability. These models provide deep insight into the present state and likely future of mangroves and are thus very helpful for decision-making.
- The drivers of mangrove degradation are often unique to their respective habitats and require careful consideration for scenario planning. Moreover, while it is important to consider historically important and influential drivers (e.g., agriculture, aquaculture), it is also important to look out for emerging drivers and potential surprises. For example, tourism development has been identified as one of the most influential drivers of future change to mangrove habitats.
- As most countries now prioritize mangrove conservation and restoration, the historical trend will most likely reverse in the future. Mangrove plantations are currently being established, but it is extremely important to restore mangroves with native species, so that there is a good possibility that ecosystem services are also restored simultaneously.

- Facilitating a transition in mangroves requires rejuvenation of mangrove ecosystem services at the local level. Intergovernmental frameworks and national policies certainly help, but developing a sustainable human-nature relationship is of foremost importance.
- In this book, as well as across the global research landscape, the regulating services provided by mangroves such as carbon sequestration and storm wave attenuation have been studied extensively. However, there is a general lack of research related to provisioning and cultural ecosystem services.
- While eco-engineering is an extremely cost-effective approach for mangroves, public participation is the key to its success and long-term sustainability.
- Even small patches of mangroves provide significant ecosystem services and can make profound impacts in biodiversity, climate regulation, pollution control, and disaster risk reduction.
- Indigenous and Local Knowledge and intangible ecosystem services shape the human-nature relationship and thus play a very important role in the future of mangroves.

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