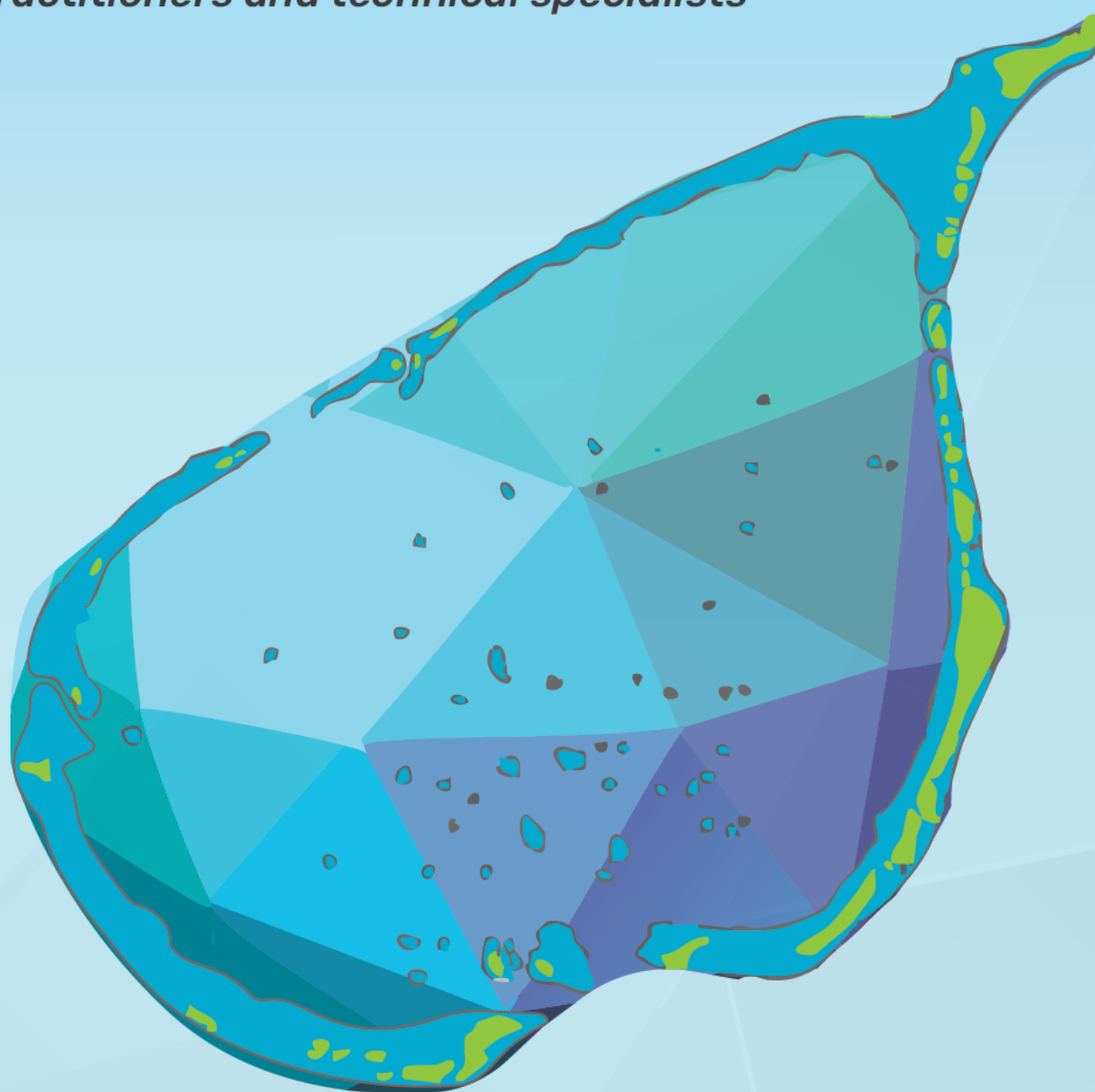


The first Natural Capital Accounts of the Maldives (Laamu Atoll)

Methodology report for accounting practitioners and technical specialists



Ministry of Tourism
and Environment



ENDhERI



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This report was prepared by the University of New South Wales (UNSW), with support from the Rekam Nusantara Foundation (RNF) and experts from the Maldives National University (MNU) per the Terms of Reference 438-ENV/438/2022/27.

The report addresses the following deliverables:

- Economic valuation for selected Natural Capital of Laamu Atoll,
- Natural Capital Accounting in accordance with SEEA Ecosystem Accounts based on agreed scope (compiled for 2 different years),
- Selected Natural Capital Accounts of Laamu Atoll linked to the national accounts maintained and reported on by Maldives Bureau of Statistics,
- Documents developed for Natural Capital Accounting implementation support – Guides and Operation manuals.

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Executive summary

This report presents the first Natural Capital Accounts for Maldives, that align with the UN System of Environmental-Economic Accounting (SEEA) framework. Accounts were compiled for Laamu Atoll, as a case study, testing the concepts and definitions of the SEEA for the Maldivian context. The pilot led to the comprehensive assessment of the extent, condition, and economic value of key marine and coastal ecosystems, specifically coral reefs, seagrass meadows, and mangroves.

Key ecosystems were mapped to produce an ecosystem account and baseline analysis, using 10 m resolution and high resolution (0.5 – 1.5 m) satellite imagery respectively. Key findings from the ecosystem extent accounts show that in 2020, Laamu Atoll contained approximately 6,692 hectares of coral reef, 4,220 hectares of seagrass, and 4.8 hectares of mangrove ecosystems. Between 2017 and 2020, there were marginal decreases in coral reef (-0.6%) and seagrass (-0.9%) extent, while mangrove extent remained stable.

Condition accounts were compiled with available data, although further monitoring is needed to generate a timeseries. The condition indicators, however, enabled an estimation of several critical services, including:

- Wild fish provisioning from reef ecosystems supported an estimated annual catch of 28.6 metric tons, supporting local food security.
- Carbon sequestration by mangroves and seagrass meadows captured approximately 3,484.7 metric tons of carbon in 2020, valued at 10.66 million rufiyaa.
- Coastal protection services benefited buildings across residential and tourism islands by protecting 33 km of coastline, with an annual valuation of 82.85 million rufiyaa.
- Approximately 44.3% of all tourism spend on Laamu could be related to coral reefs.

The measurement of services in physical terms revealed their importance to the local community and economic sectors. The monetary valuation of these services, where possible, demonstrated their significant economic value.

This initial natural capital accounting exercise highlights both the substantial value of Laamu Atoll's ecosystems and current data gaps. Key recommendations include:

- Establishing a centralized environmental data repository.
- Developing a systematic remote sensing monitoring program.
- Strengthening data collection for tourism and recreational services.
- Building local capacity for natural capital accounting.

These accounts provide an evidence base for policy-making and sustainable development planning in Laamu Atoll, while offering a framework that could be expanded to other atolls across the Maldives.

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Abbreviations

AGB	Above Ground Biomass
AGC	Above Ground Carbon
BGB	Below Ground Biomass
BGC	Below Ground Carbon
BSU	Basic Spatial Unit
CPI	Consumer Price Index
DBH	Diameter at Breast Height
ENDhERI	Enhancing National Development through Environmentally Resilient Islands
EPA	Environmental Protection Agency
GDP	Gross Domestic Product
GEF	Global Environment Facility
GET	Global Ecosystem Typology
GOAP	Global Ocean Accounts Partnership
IUCN	International Union for Conservation of Nature
JICA	Japan International Cooperation Agency
MBS	Maldives Bureau of Statistics
MoTE	Ministry of Tourism and Environment
MLSA	Maldives Land Survey Authority
MTCC	Maldives Transport & Contracting Company
MVR	Maldivian Rufiyaa
NCA	Natural Capital Accounts
NCP	Net Community Productivity
NGO	Non-Governmental Organization
NIR	Near-Infrared
SCC	Social Cost of Carbon
SEEA	UN System of Environmental-Economic Accounting
SEEA EA	UN System of Environmental-Economic Accounting - Ecosystem Accounting
SEQI	Seagrass Ecological Quality Index
SNA	UN System of National Accounts
SST	Sea Surface Temperature
UN	United Nations
UNDP	United Nations Development Programme
UNEP	United Nations Environment Program
USD	United States Dollar
WDC	Women's Development Committee

1. Introduction

The Ministry of Tourism and Environment (MoTE) is implementing the Enhancing National Development through Environmentally Resilient Islands (ENDHERI) project. Financed by the Global Environment Facility (GEF) and supported by the United Nations Environment Program (UNEP), this initiative aims to enhance reef protection, resilience, and ecosystem recovery by reducing developmental impacts within selected project sites in the Maldives. The project emphasizes public awareness and integrates the values of marine biodiversity and other natural capital into national planning.

One of the significant components of the ENDHERI project is the development of Natural Capital Accounts (NCA) for the Maldives. The NCA initiative is designed to assist the Government of the Maldives to implementing new environmental policies and transitioning towards Green Growth atoll development. The primary goal is to sustain marine natural capital and strengthen the resilience and recovery of reef ecosystems. This project specifically focuses on Laamu Atoll, aiming to minimize pollutants from land and marine-based activities, reduce marine-based drivers of reef degradation, and enhance reef ecosystem integrity and resilience through sustainable management practices.

The NCA project aims to assist the Government of the Maldives in achieving integrated coastal zone management within a Managed Marine Area/Biosphere Reserve framework. By applying innovative sustainability practices and standards, the project seeks to enhance reef ecosystem integrity and resilience through sustainable management. The specific objectives include:

- Establishing NCAs for freshwater resources, marine and coastal ecosystems, and key marine species critical for sustaining local industries.
- Reducing pollutants from both land and marine-based activities.
- Minimizing marine-based drivers of reef degradation.
- Enhancing reef ecosystem integrity and resilience through sustainable management practices.
- Data collection for NCA.

1.1. Need for Ocean Accounting

Accounting has long been used by institutions to systematically identify, record, and communicate financial and economic events by transforming raw data and statistics into meaningful insights that support better decision-making at all levels. There is growing global recognition, however, that present accounts that focus on economic metrics do not capture the importance of nature to society and the economy. Parallel accounting standards and guidance have been developed to better recognize the importance of these relationships, including the System of Environmental-Economic Accounting (SEEA) and Ocean Accounting guidance.

These aligned approaches bridge the gap in traditional accounting by recognizing that the environment provides vital resources and services that should be systematically measured and valued. This framework helps countries understand how their natural resources contribute to economic prosperity while also tracking environmental degradation and depletion.

Ecosystem Accounting, a key component of SEEA, is a framework for compiling and standardizing data across social, environmental, and economic domains in line with national accounting methodologies. It provides a basis for generating a variety of statistics and indicators to monitor ecosystem health, the provision of ecosystem services, and flows to society and the economy. By integrating environmental and economic information in a consistent way, Ecosystem Accounting enables policymakers to better understand trade-offs between development and conservation, make more informed decisions about resource use, and track progress toward sustainability goals.

1.2. Scope of report

This methodology report provides a comprehensive technical guide for compiling NCAs for the Ocean (henceforth, “Ocean Accounts”) for Laamu Atoll following the System of Environmental-Economic Accounting - Ecosystem Accounting (SEEA EA) and Ocean Accounting frameworks.¹ The report is complementary to the High Level report for Decision Makers, providing details the specific methods used to measure and assess ecosystem extent, condition, and services for key marine and coastal ecosystems including seagrass meadows, mangrove forests, and coral reefs.

For each accounting component, we describe the data collection protocols, analysis procedures, and account compilation methods, including approaches for both physical and monetary valuation. The report also documents important methodological considerations such as classification systems, indicator selection, and account compilation procedures.

While all major ecosystem account types have been compiled for Laamu Atoll, the temporal range and completeness varies based on data availability (see Table 1.1, Table 1.2). Analysis at the atoll scale were performed for 2017 and 2020, using Sentinel 2 data (10 m resolution). This allowed for rapid analysis of extent across multiple ecosystem types (coral reef, seagrass, mangrove, macroalgae, and other substrate) and identifying changes across the atoll (i.e., change matrix).

High resolution data (< 1.5 m) focused on specific ecosystems and were analysed for mangroves (2013-2023) and seagrass (2018-2024) for seagrass, drawing primarily from high-resolution satellite imagery validated through field surveys. Condition accounts are more limited temporally, with comprehensive field data collected in 2023-2024. For ecosystem services, we outline methods used to quantify and value key services where sufficient data existed, while also providing guidance for future measurement of services that currently lack adequate data. Throughout, we emphasize practical implementation considerations to support ongoing Ocean Accounting efforts both in Laamu Atoll and more broadly across the Maldives.

¹ SEEA Ecosystem Accounting: <https://seea.un.org/ecosystem-accounting>; Ocean Accounting Framework: <https://www.oceanaccounts.org/knowledge/>

Table 1.1 Ecosystems extent, condition and asset value accounts produced, aligned with SEEA EA guidance.

Ecosystem	Extent		Condition		Asset value
	Resolution	Years	# variables	Years	
Coral reef	S + HR	2017, 2020 (S), 2021 – 2024 (HR)	6	2019, 2021, 2022, 2024	-
Seagrass	S + HR	2017 – 2024 (S, HR)	5	2023, 2024	Yes (carbon only, 2023)
Mangrove	S + HR	2014, 2016, 2017, 2019, 2020, 2022, 2023 (S, HR)	6	2023, 2024	Yes (carbon only, 2023)
Macroalgae	S	2017, 2020 (S)	-	-	-
Other substrate	S	2017, 2020 (S)	-	-	-

S = Standard resolution (10 m), HR = High resolution (< 1.5 m)

Table 1.2 Ecosystems services accounts produced, aligned with international guidance. All services were based on factors from 2023 and 2024. Macroalgae and other substrate were not assessed for ecosystem services.

Ecosystem	Ecosystem services					
	Wild biomass consumption	Coastal protection	Sediment supply	Recreational value	Nursery services	Carbon sequestration
Coral reef	P+M	P+M	P+M	P+M	P	-
Seagrass	-	-	P+M	P	P	P+M
Mangrove	-	-	-	P+M	-	P+M

#P = Physical value, M = monetary value. *DD = Data deficient – further data is required to estimate this service.

2. Natural Capital Accounting for the Ocean

Accounting serves as a fundamental information system that helps organizations and societies understand their activities, resources, and performance. By systematically identifying, recording, and communicating financial and economic events, institutions produce insights from raw data. At the organizational level, accounting helps businesses track their financial health, identify emerging problems and opportunities, and allocate resources more effectively. Financial accounting provides standardized external reporting, while management accounting gives leaders the detailed internal information needed for strategic planning and operations management. Performance measurement systems extend this further by tracking specific initiatives, teams, and outcomes.

At the broader economic level, accounting enables governments and policymakers to understand national and regional economic activity, allocate public resources, and monitor the effectiveness of policies. This macro perspective is essential for economic planning, policy development, and public sector accountability. The systematic nature of accounting makes it possible to compare performance across entities and time periods, providing crucial context for decision-makers.

The Ocean Accounts framework offers significant potential to support evidence-based policymaking and sustainable management of the Maldives' marine resources. By providing a standardized, comprehensive approach to measuring and valuing ecosystem assets and services, SEEA can inform a wide range of policy and management decisions.

The Ocean Accounts describe the interactions between the economy and the environment, the stocks and flows of environmental assets (natural capital) that provide benefits to people, and the social and governance factors that influence and are affected by these assets and benefits. The framework enables the Maldives to make informed decisions about sustainable ocean management by integrating environmental, economic, and social data into a cohesive system.

2.1. Framework Structure

The Ocean Accounts describe the interactions between the economy and the environment, the stocks and flows of environmental assets (natural capital) that provide benefits to people, and the social and governance factors that influence and are affected by these assets and benefits.

Ocean Accounts are interconnected modules pursuant to guidance maintained by the Global Ocean Accounts Partnership (GOAP). The modular approach enables progressive implementation aligned with national priorities, while maintaining consistency with international standards such as the UN System of National Accounts (SNA) and UN SEEA (see Figure 2.1). These modules include:

1. **Environmental Assets (extent and condition):** Measures the extent and condition of marine and coastal ecosystems and natural resources.
2. **Flows to the Economy (ecosystem services):** Quantifies and values ecosystem services and economic contributions from ocean-related activities.
3. **Flows to the Environment:** Assesses impacts of economic activities on marine ecosystems, such as pollution and resource extraction.

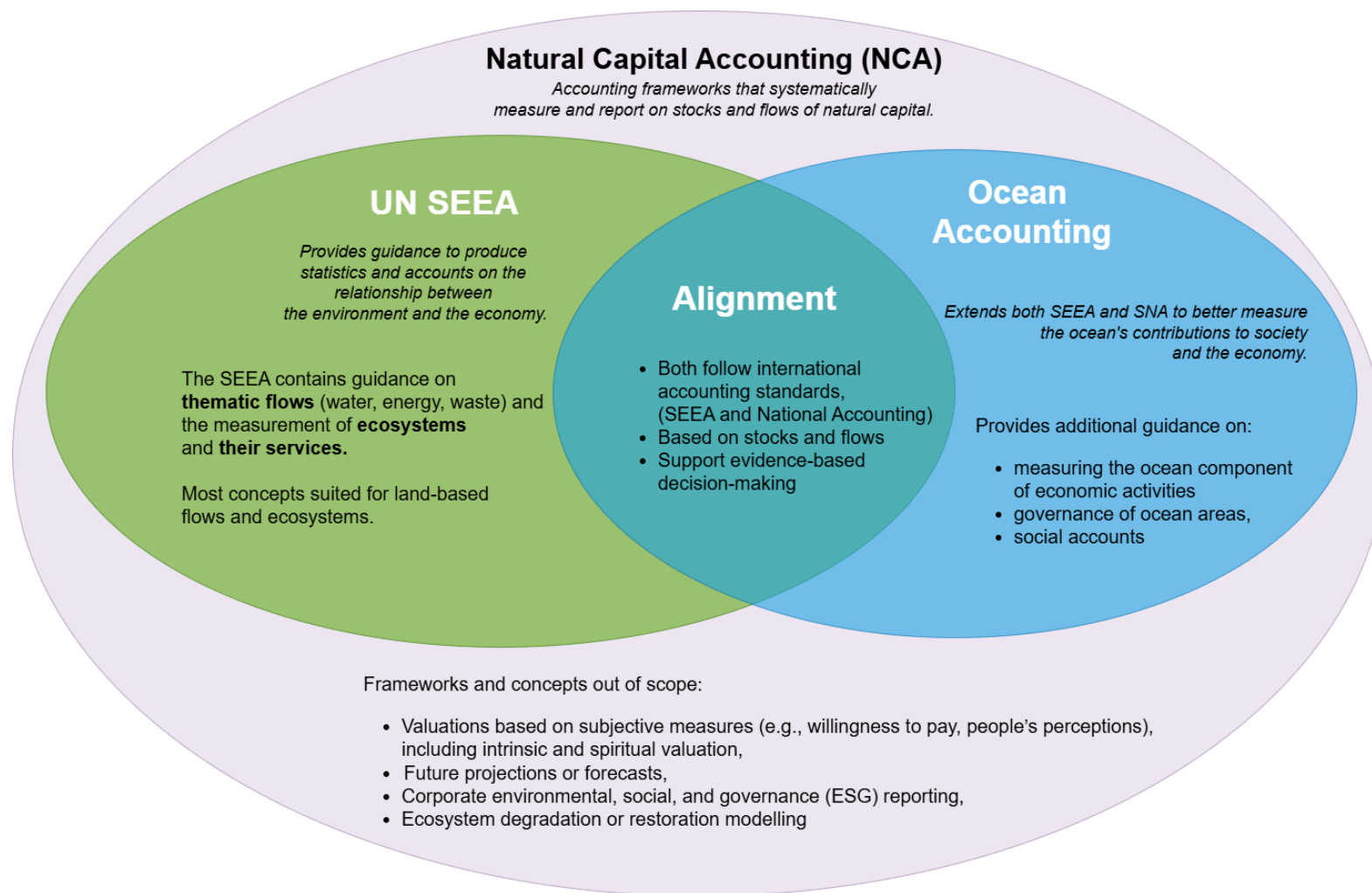


Figure 2.1 Relationships between Natural Capital Accounting the UN System of Environmental Economic Accounts (SEEA) and Ocean Accounting guidance. SNA = System of National Accounts, responsible for tracking economic activity and producing indicators such as GDP.

2.2. Alignment with SEEA Ecosystem Accounting

The SEEA EA is an integrated and comprehensive statistical framework developed to organize data about habitats and landscapes, measure ecosystem services, track changes in ecosystem assets, and link this information to economic and other human activities. It advances related statistical guidance in that:

- It aligns with the concepts of the System of National Accounts, and
- Accounts for the extent, condition and supply of services in a spatially explicit manner.

The SEEA EA considers environmental assets and their flows to the economy, which enables the valuation and recognition of ecosystems' contributions to climate change mitigation, adaptation and societal well-being, while providing the basis for incorporating the value of ecosystems into decision-making and sustainable development planning.

Ecosystem accounting involves creating interlinked accounts covering the four key modules (ecosystem extent, condition, services and asset accounts, Figure 2.2) described in Table 2.1, with specific definitions in Table 2.2. As an accounting framework, data are represented as “stocks” and “flows”. Stocks represent the quantity or state of ecosystem assets at a point in time (like a snapshot), while flows capture the movement of materials, energy, or services from ecosystems to the economy and society over a defined period. This distinction is fundamental to understanding how ecosystems contribute to human wellbeing – stocks record the asset, while flows record the benefits we receive from those stocks.

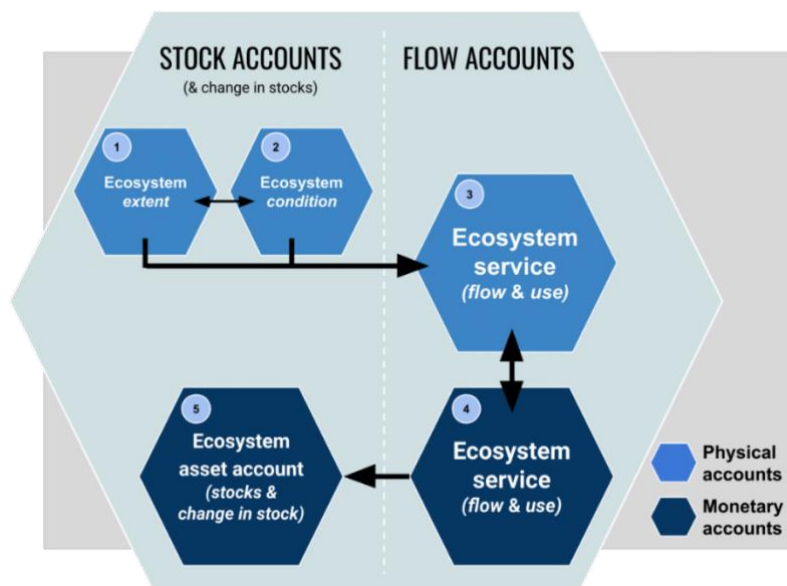


Figure 2.2 Ecosystem accounts and how they relate to each other, from SEEA EA.

Table 2.1. Definitions of terms to be used within the study, as used within the Ocean Accounting Framework (GOAP, 2021), and aligned with SEEA EA (UNSD, 2021) and SNA (UN, 2008) statistical accounting standards.

Term	Definition	Example
Ecosystem	A contiguous space of a specific ecosystem type characterized by a distinct set of biotic and abiotic components and their interactions	Mangrove, coral reef, seagrass
Basic Spatial Unit	The subdivision of the accounting area spatially to align data	10 m ² grid
Ecosystem Extent	The range and extent of ecosystems within an accounting area. Ocean Accounts endorses the use of the IUCN Global Ecosystem Typology	Cover of seagrass (in hectares or km ²)
Ecosystem Condition	The quality of an ecosystem measured in abiotic and biotic characteristics. Note that there are no standardised indicators for each ecosystem, although the SEEA EA provides guidance for the development of condition accounts	Mangrove tree height, above ground biomass or seagrass cover (%)
Ecosystem Services	The contributions of ecosystems to the benefits that are used in economic and other human activity. Services are categorized broadly into provisioning, regulating and cultural services. Services are measured either as a good or intangible product of the system	Wild fish and other natural aquatic biomass provisioning services, coastal protection services (regulating), Recreation-related services

Table 2.2 Description of accounting modules and examples, following SEEA Ecosystem Accounting.

Account name	Type	Definition	Example	Example Units
Extent Account	Physical (Stock)	Measures the size and geographic distribution of ecosystem types within an accounting area, tracking changes over time	Area of ecosystems (coral, seagrass)	Hectares (ha), Square kilometres (km ²)
Condition Account	Physical (Stock)	Assesses the quality/health of ecosystem assets using various biophysical indicators specific to each ecosystem type	Condition measures: Canopy cover, tree density, species composition	Percentage (%), Trees per hectare, Number of species, varied.
Ecosystem Services Account (Physical)	Physical (Flow)	Records the flows of ecosystem services from ecosystems to economic and social beneficiaries in physical terms	Physical measures of services: Fish nursery, habitat, coastal protection, carbon sequestration	Biomass (kg/year), Buildings protected, Tons carbon/year
Ecosystem Services Account (Monetary)	Monetary (Flow)	Values the flows of ecosystem services in monetary terms using various valuation techniques	Monetary valuation: commercial fisheries supported by nursery habitat, Coastal protection replacement cost, Value of carbon sequestration	Currency/year (e.g., USD/year, MVR/year)
Asset Account	Monetary (Stock)	Measures the overall value of ecosystem assets based on the expected flow of services over time (net present value)	Asset values derived from expected service flows, asset life, discount rate and changes in condition/extent	Currency (e.g., USD, MVR)

2.3. Classifications and typologies

Standardized classifications are essential for ensuring consistency, comparability and interoperability across Ocean Accounts. Key aspects requiring standardized classification systems include ecosystem types, ecosystem services categories (provisioning, regulating and cultural services), and economic activities and industries. Without standardized classifications, data integration across different spatial scales and jurisdictions would be extremely challenging, making it difficult to aggregate information, track changes over time, or make meaningful comparisons. Common classification systems are critical when transforming specialist data into accounts.

2.3.1. Ecosystem classification

For Ecosystem Accounting, classification systems for ecosystems need to be spatially explicit, mutually exclusive, and exhaustive across ecological realms. The IUCN Global Ecosystem Typology (GET) has emerged as the primary international reference classification system, designed to support standardized ecosystem accounting while allowing integration with national classification schemes.²

The GET uses a hierarchical structure with six levels, with the top three - realms, functional biomes, and ecosystem functional groups - classifying ecosystems based on their functional characteristics rather than species composition. For the Laamu Atoll natural capital accounts, three key ecosystem functional groups were selected based on data availability and ecological significance:

- Seagrass meadows (M1.1),
- Photic coral reefs (M1.3), and
- Intertidal forests and shrublands (MFT1.2, which includes mangroves).

While more detailed classification would be possible, these broad categories align with available data from remote sensing and field surveys while still capturing the major ecosystem types that provide key services in the atoll.

The IUCN GET complements the IUCN Red List of Species by providing a framework for understanding and assessing ecosystems that serve as critical habitats for threatened species. By classifying ecosystems based on their functional characteristics and ecological drivers, the GET helps identify the conditions and processes that endangered species depend on, supporting more targeted conservation efforts. For instance, in Laamu Atoll, understanding that seagrass meadows (M1.1) serve as critical feeding grounds for threatened species like green turtles helps prioritize conservation actions that protect both the species and their supporting ecosystems.

2.3.2. Ecosystem service classifications

There are several classification systems for ecosystems, with several defined services that do not align readily with existing flows covered within national accounts. The SEEA EA developed a reference list of selected ecosystem services by combining findings from multiple classification systems.³ The primary criterion for inclusion was that the service is considered relevant and important across multiple countries and contexts. While not a complete classification system itself,

² IUCN Global Ecosystem Typology: <https://www.iucn.org/resources/conservation-tool/iucn-global-ecosystem-typology>.

³ Particularly the Common International Classification of Ecosystem Services (CICES) and the National Ecosystem Service Classification System (NESCS Plus), as well as incorporating insights from other frameworks like MA, TEEB and IPBES-NCP.

this reference list for SEEA EA provides clarity on measurement scope and support consistency in ecosystem accounting, with relevant services to the Laamu Atoll pilot provided in the Annex. The reference list is structured into three broad categories (Table 2.3).

Table 2.3 Ecosystem service types and examples.

Service Type	Description	Examples	Unit of Measurement
Provisioning Services	Contributions that are extracted or harvested from ecosystems for direct use by economic units or households	Wild fish, timber harvest	Biomass (tonnes/year), volume (m ³ /year)
Regulating and Maintenance Services	Ecosystem functions that regulate biological processes and influence climate, hydrological and biochemical cycles to maintain beneficial environmental conditions	Climate regulation, coastal protection	Tonnes carbon sequestered (Mg C/year), area protected (ha)
Cultural Services	Experiential and intangible services related to the perceived or actual qualities of ecosystems that contribute to cultural benefits	Recreation opportunities, visual amenity	Number of visits, number of users

Non-use values are not within scope of the SEEA EA, as they do not involve direct or indirect interaction with the environment. These include:

- Existence value: the intrinsic value people place on knowing that something exists, even if they never plan to use or experience it directly. For example, people value knowing that rare marine species or remote coral reefs exist, even if they will never see them in person.
- Bequest value: the value people place on preserving natural assets for future generations to inherit and benefit from.

These values fall outside the SEEA framework because SEEA focuses specifically on measuring tangible ecosystem services and benefits that can be directly linked to economic activity or human use. The accounting framework aims to capture measurable flows between the environment and economy. Existence and bequest values, while valid and important, are abstract and subjective personal valuations that do not create measurable economic transactions or tangible services.

They represent deeper ethical and cultural values about nature's worth beyond its practical utility. The framework still allows for data to be recorded on related stocks and flows, such as the presence or abundance of iconic species. These values, however, are considered complementary valuations outside the main accounting framework.

2.4. Biodiversity and ecosystem services

The SEEA framework recognizes biodiversity as an enabling asset within ecosystems rather than an ecosystem service. It acts as a fundamental characteristic that supports and enhances the capacity of ecosystems to provide services. The framework addresses this through multiple lenses:

- Directly at the ecosystems scale.
- Species-specific services. For example, genetic resources for pharmaceuticals or charismatic species supporting tourism.
- Indirectly through the role of biodiversity in maintaining ecosystem resilience and function. For example, higher biodiversity in coral reefs can enhance their ability to provide coastal protection services and support fisheries productivity.

The SEEA reference list, developed by synthesizing multiple classification systems, provides a standardized way to measure and account for biodiversity-dependent services across different contexts and countries.

While biodiversity is crucial for ecosystem functioning and service provision, its value extends beyond what can be captured through service measurements alone. The SEEA addresses this through various components. Ecosystem condition accounts can track biodiversity metrics, while ecosystem service accounts measure the specific benefits flowing from biodiversity-dependent processes.

This dual approach recognizes that while some aspects of biodiversity's contribution can be directly measured through service provision (e.g., species supporting pollination), its broader role in maintaining ecosystem resilience and function requires additional consideration through condition accounts and enabling asset classifications. This structure allows the framework to capture both the direct and indirect ways that biodiversity supports ecosystem service delivery while maintaining consistent measurement approaches across different contexts.

2.5. Spatial analysis framework

The implementation of Ocean Accounts for Laamu Atoll required a structured spatial framework that treats ecosystems as assets within an accounting system, following the SEEA EA. The framework consists of three key spatial components: (1) Basic Spatial Units (BSU), (2) a master layer, and (3) an accounting area. The accounting area for this project encompasses the entirety of Laamu Atoll, with additional results produced for the protected areas designated under the Environment Protection and Preservation Act (Law 4/93). The accounting area comprised the bounds of Laamu Atoll, to a water depth of 25 m.

BSUs provide the fundamental spatial infrastructure for combining diverse data sources on the economy, environment, and society. This standardized grid system covers both the terrestrial islands and marine areas of the atoll and was used for standard resolution (10 m) data for 2017 and 2020 only. The BSU resolution was selected to align with remote sensing capacity and balance detailed ecosystem representation with practical data processing considerations. Remote sensing data using BSUs was restricted to Sentinel-2, with 10 m resolution for visible/NIR bands.

A master layer is the entirety of the grid (composed of BSU, Figure 2.3) for Laamu Atoll and establishes the boundaries between marine and terrestrial areas across the atoll's 88 islands, incorporating both inhabited and uninhabited areas. This comprehensive layer includes the full extent of the atoll, stretching over 48 km from north to south and 28 km from east to west. The master layer provides the spatial context for distinguishing between different ecosystem types.

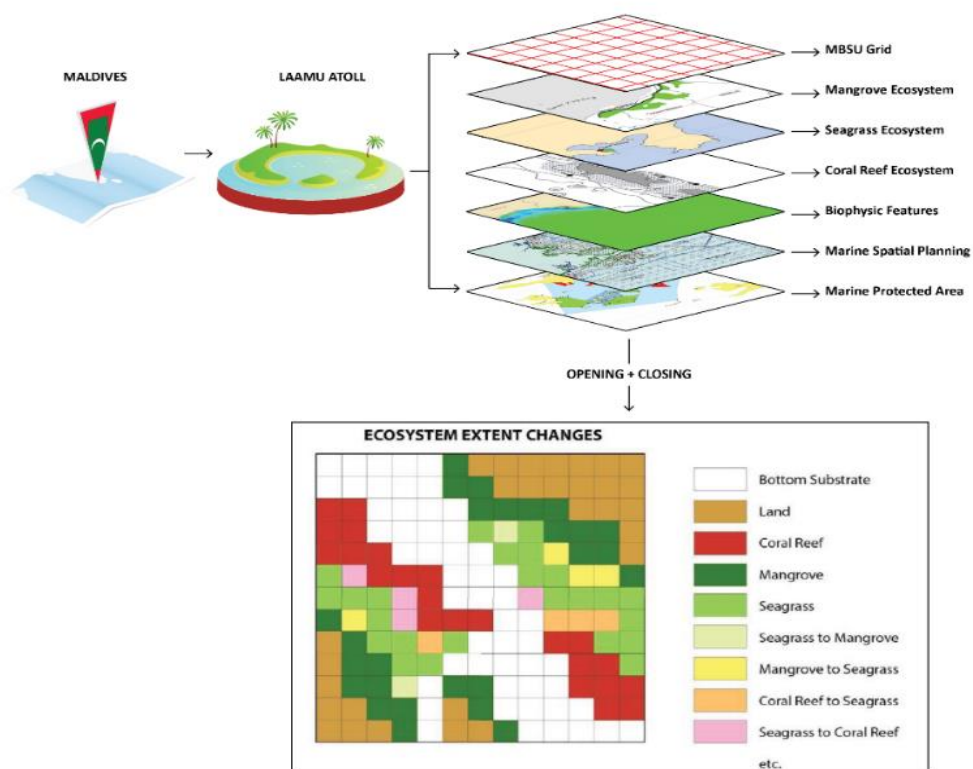


Figure 2.3 Layering data for the grid to assess the benthic classification and subsequently, change over time.

3. Case study: Laamu Atoll

The development of Natural Capital Accounts for Laamu Atoll followed a systematic approach aligned with the SEEA EA framework. The accounting process involved five key stages: initial data collection from multiple sources, harmonization of diverse datasets, transformation of raw data into meaningful metrics, compilation of standardized accounts, and demonstration of application to decision-making (Figure 3.1). The systematic workflow developed by the project addresses common challenges in environmental-economic accounting, such as data fragmentation across institutions and varying methodologies, while providing a framework that could be scaled to other atolls across the Maldives.

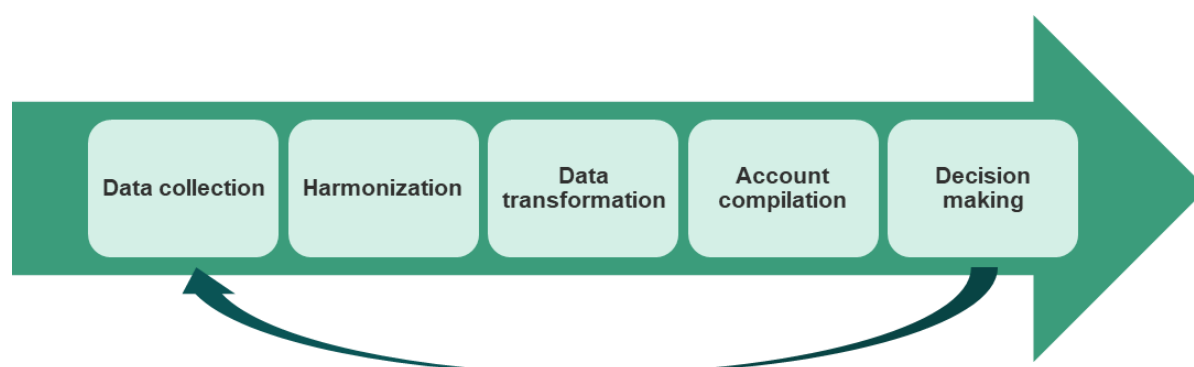


Figure 3.1 The accounting approach for Ocean Accounts, aligned with SEEA EA.

3.1. Addressing data needs

To compile accounts in Laamu Atoll, three steps were performed, namely: initial scoping, compilation of a data inventory, and harmonization and transformation of data.

The inception workshop, held in Male', Maldives (13-14 March 2023), brought over 40 participants from government ministries, private sectors, and NGOs to identify policy priorities and management challenges related to natural capital. The workshop identified seagrass, mangrove and coral reefs as priorities, and related services that should be attempted for quantification, specifically related to fisheries, tourism, and coastal protection.

Data collection began with stakeholder consultation and a literature review to identify potential data sources. Stakeholders consulted included government agencies, development partners (including UNDP and JICA), NGOs, and research institutions active in Laamu Atoll. The data inventory then led to the identification of data gaps, namely:

- Seagrass extent and condition,
- Mangrove extent and condition, and
- Data deficiencies related to nature dependencies with tourism and fisheries.

In response, three field campaigns were planned to gather ground truthing data, and additional condition data for seagrass and mangrove ecosystems. In parallel, imagery from multiple satellite platforms (Planet, Airbus, and ESA Copernicus) were assessed to develop an extent account, and perform high-resolution spatial analysis.

The harmonization phase addressed the challenge of standardizing diverse data types into compatible formats. This included aligning satellite imagery to common spatial resolutions and projections, integrating ground truth data with remote sensing outputs, and standardizing ecosystem classifications using the IUCN Global Ecosystem Typology (see Section 3). This step was particularly important given the variety of data sources and formats encountered across different institutions and time periods.

Data transformation involved processing imagery, collating available data and performing statistical analyses to compile the accounts (Sections 6 – 9). The following were performed:

- Satellite imagery was processed using ENVI software to produce statistics of areal extent per ecosystem.
- Field measurements were assessed using R Statistical Software (v4.1) to produce ecosystem condition metrics.
- Spatial analyses for ecosystem services (carbon sequestration, coastal protection, sediment nourishment) were performed using ArcGIS Pro (v3.1). This involved the spatial integration of economic data with environmental data.

3.2. Account compilation

Account compilation began with the systematic organization of spatial and statistical data within the inventory for extent, condition and service accounts.

- The process starts with ecosystem extent accounts, which map and quantify distinct marine ecosystem types such as mangroves, seagrass beds, and coral reefs within the defined accounting areas. The extent accounts were the foundation for subsequent accounting steps by establishing the physical boundaries and distribution of marine ecosystems (explored in Section 4).
- Ecosystem condition accounts incorporated indicators that reflect the overall health and functioning of marine ecosystems. These metrics were specific to each ecosystem (explored in full in Section 5). Specific data were also critical for calculating ecosystem services.
- Ecosystem service accounts were first compiled for physical values, and where feasible converted into monetary values (Section 6).
- Asset accounts were compiled for the monetary value of carbon stocks, focus only on seagrass meadows and mangroves (Section 7).

Ocean account data can then be transformed into actionable decision-making tools through:

- **User-friendly dashboards:** allows policymakers to query and visualize information relevant to specific policy questions.
- **Standardized indicators and metrics:** tracks progress toward specific management objectives, such as changes in ecosystem service values or carbon sequestration rates.
- **Spatial planning:** Accounts data could be overlaid with other layers to identify optimal use of land and ocean space.
- **Automated reporting:** Accounts assist in regular status reports for the health and extent of ecosystems (including within MPAs) over time.

3.3. Laamu Atoll context

3.3.1. Geography and Climate

Laamu Atoll (1.92° N and 73.43° E) is a southern coral atoll in the Republic of the Maldives. Also known as Haddhunmathi Atoll, Laamu Atoll is situated 240 km south of Malé, the capital city, between the Gaafu Alifu Atoll to the south and the Thaa Atoll to the north. As the second largest atoll in terms of land area, Laamu is comprised of 73 coral islands, eleven of which are inhabited (MBS, 2020). The atoll has an estimated surface area of 884.63 km², with approximately 56 reefs (203.70 km²).

Laamu Atoll experiences a monsoonal climate with seasonal fluctuations in precipitation. There are two distinct seasons: the dry season (north-east monsoon) and the wet season (south-west monsoon). The north-east monsoon extends from January to March. The temperature of Laamu Atoll, like the rest of the Maldives archipelago, remains stable throughout the year. The highest temperature recorded in the Maldives was 33.5 °C on April 19, 2019, at Hanimaadhoo (Haa Dhaalu Atoll). Over the last 15 years, annual rainfall ranged from 1,333 mm to 2,711 mm, with the highest rainfall recorded as 2,711 mm in 2016. The average relative humidity in the Maldives ranges from 27.3% to 82.6%, while the Laamu Atoll (Gan) value was 81.5% in 2019 (MBS, 2020).

3.3.2. Laamu population and economy

According to the 2022 Census, the estimated population of Laamu Atoll was 15,901 (MBS, 2022a). The resident Maldivian population over the age of 15 within the labour force was 5,238, of which 93% were employed (MBS, 2022b). Fonadhoo is the capital island in Laamu atoll, which hosts the Laamu Atoll Council (also Haddhunmathi Atoll Council), which comprise of an elected president and the presidents of all island councils. Each island council is led by elected councillors. Each island also has an elected Women's Development Committee (WDC). There are 13 public schools on the atoll, with 12 providing secondary level education.

In 2019, approximately 20% of the employed population were involved in agriculture (from L. Gan and L. Fonadhoo), with less than 4% involved in fishing as a primary activity. Over 55% of the employed population were involved in agriculture (L. Gan and L. Fonadhoo) as a secondary activity (MBS, 2019). Fisheries constitute the primary economic activity in Laamu Atoll, closely followed by agriculture.² The tourism sector has the largest percentage share in the Nominal GDP 2022 at 21%. This represents the country's fastest-growing economic sector. The nominal GDP share of fisheries and agriculture is 3.8% and 1.1% respectively.

According to OneMap, maintained by the Maldives Land Survey Authority,⁴ there are 90 islands within Laamu Atoll, 74 of which are named. There are 11 islands categorized for tourism, and 5 as industrial islands. There are 58 islands of varying sizes that are uninhabited. Maandhoo is the only mixed usage island and has the Horizon Fisheries complex.

⁴ OneMap: <https://onemap.mv/>

3.3.3. Marine Protected Areas in Laamu Atoll

In 2021, the Maldives designated six sites of ecological significance on Laamu Atoll as protected under the Environment Protection and Preservation Act and Protected Areas Regulation (No. 2018/R-78) (Table 3.1 and Figure 3.2).

Table 3.1. Protected Areas in Laamu Atoll, Maldives.

No	Conservation Area	Coverage areas (ha)	Conservation target	Category number and description
1.	L. Gaadho	614.92	Turtle nesting area, mangrove and seagrass area	(6) Species/habitat management area
2.	L. Gan Boda Fengan'du Area	15.03	Mangroves and wetlands	(7) Protected area with sustainable use
3.	L. Maabaidhoo Koaru Area	174.49	Brackish lake, wetlands, and mangroves	(7) Protected area with sustainable use.
4.	L. Fushi Kan'du Area	346.67	Green turtles (<i>Chelonia mydas</i>), hawksbill turtles (<i>Eretmochelys imbricate</i>), reef manta rays (<i>Mobula alfredi</i>), other types of rays, and species of sharks	(6) Species/habitat management area
5.	L. Bodu Finolhu and Vadinolhu Kandu Olhi Area	706.01	Napoleon wrasses to breed, as well as reef manta rays (<i>Mobula alfredi</i>), Hawksbill turtles (<i>Eretmochelys imbricate</i>), green turtles (<i>Chelonia mydas</i>), and different species of sharks	(7) Protected area with sustainable use
6.	L. Hithadhoo Wetland and Surrounding Marine Area	43.30	Saltwater lakes, mangroves (red mangroves <i>Rhizophora mucronata</i> , yellow mangroves <i>Ceriops tagal</i> , and black mangroves <i>Lumnitzera racemose</i>), and wetlands	(7) Protected area with sustainable use
	L. Gaadhoo – Hithadhoo Kan'du Area	776.07	Green (<i>Chelonia mydas</i>) and hawksbill turtles (<i>Eretmochelys imbricate</i>), reef manta rays (<i>Mobula alfredi</i>), and Napoleon wrasses (<i>Cheilinus undulates</i>), and other species	(6) Species/habitat management area

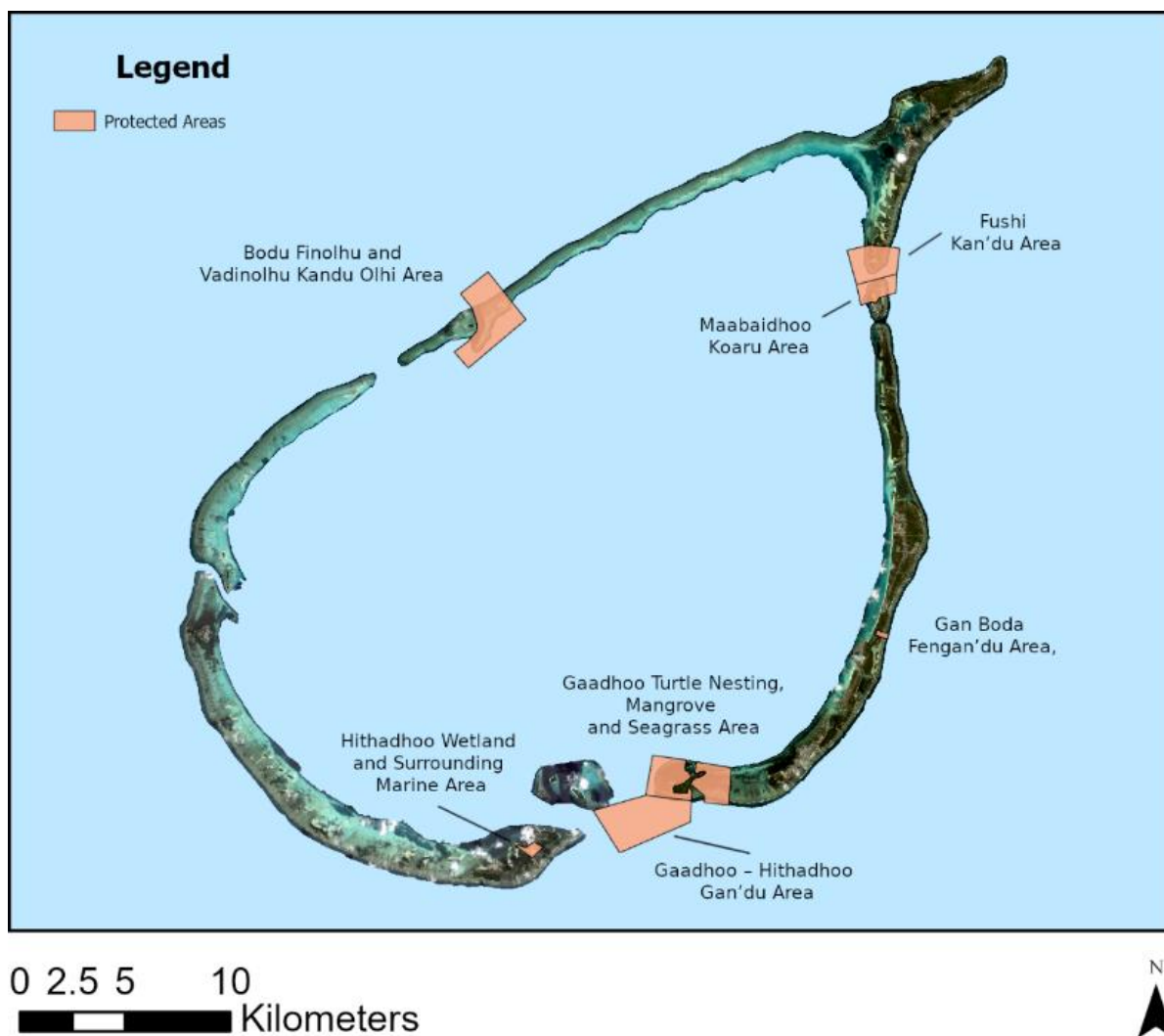


Figure 3.2 Protected Areas of Laamu Atoll, Maldives in 2025.

4. Extent Accounts

A common starting point for Ocean Accounting is the organization of information on the extent of different ecosystem types within an accounting area, and how that extent is changing over time.

They serve multiple purposes:

1. Provide a standardized way for stakeholders to discuss ecosystem composition and changes.
2. Create a framework to organize and present other ecosystem data (condition, services).
3. Enable tracking of changes between ecosystem types over time through opening and closing balances.
4. Support spatial data infrastructure for measuring ecosystem condition and modelling services.

Extent accounts record the total area and changes between different ecosystem types within the defined accounting area. Each ecosystem is defined into discrete (i.e., non-overlapping) ecosystem assets, which are only of a single ecosystem type. The key components are:

- Opening and closing stock: the total area (e.g., square kilometres, hectares) per ecosystem type at the beginning and end of the accounting period.
- Additions: the increase in area per ecosystem between the opening and closing years.
- Reductions: the decrease in area per ecosystem between the opening and closing years.

Extent accounts can be presented both as tables and maps. Maps help visualize:

- Spatial distribution of ecosystems at specific points in time.
- Changes in ecosystem boundaries over the accounting period.
- Potential drivers of change when combined with data on human activities and pressures.

For this project, two distinct approaches were used (Figure 4.1), namely:

1. Production of an extent account and change matrix using standard resolution (10 m) for multiple ecosystems (coral reef, seagrass, mangrove, macroalgae, and other substrate) at the atoll scale.
2. High resolution analysis (0.3 – 1.5 m) of ecosystems (coral reef, seagrass and mangrove to produce a baseline (as opposed to accounts) over multiple years.

The use of different satellite platforms demonstrated the impact of spatial resolution on the resulting statistics for each ecosystem within Laamu Atoll.

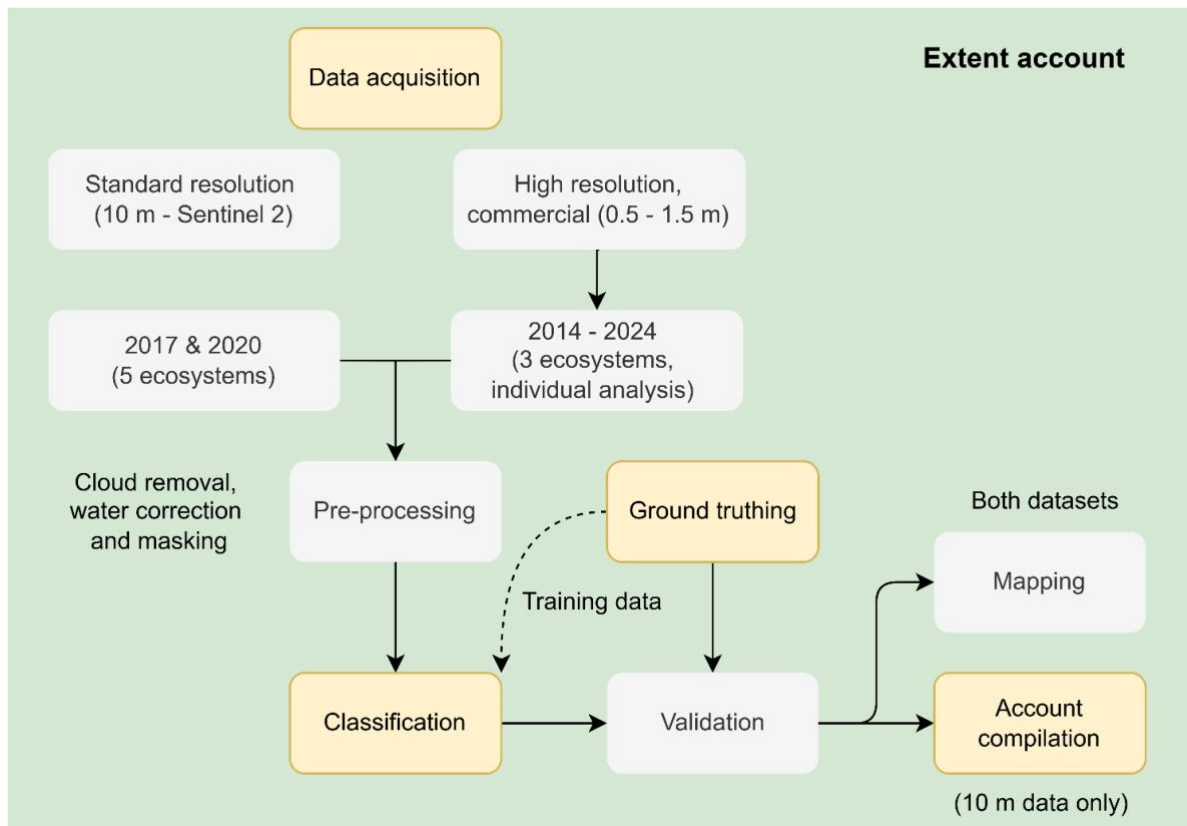


Figure 4.1. Workflow for ecosystem extent classification and account compilation. Note the two streams of analysis, with accounts only compiled for 10 m dataset.

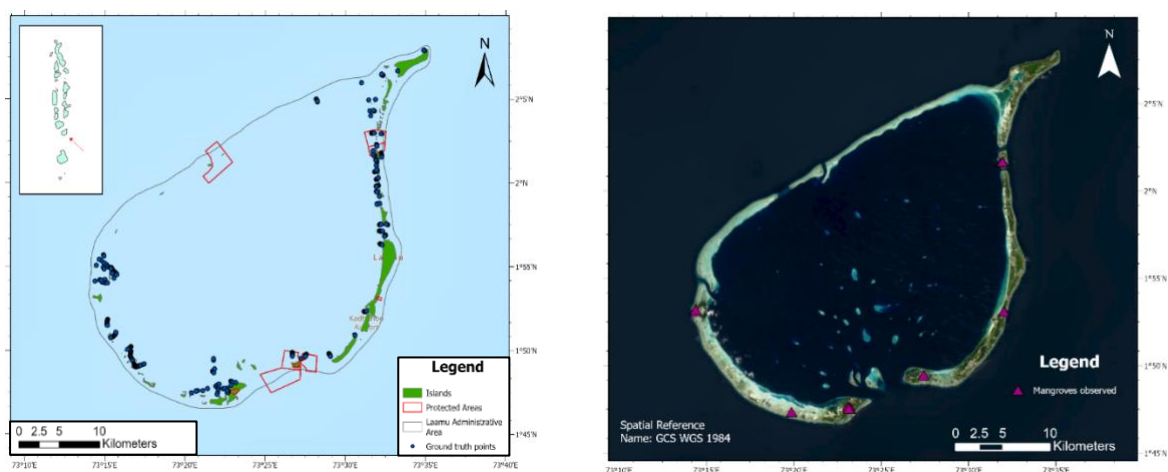


Figure 4.2 Sites with mangroves observed across Laamu Atoll (Left) and high resolution of L. Hithadhoo Mangrove (Right - Pleiades, 2022).

4.1. Benthic classification and ground truthing

Ground truthing is essential for accurate benthic classification. The strategy for the Laamu Atoll involved a comprehensive approach that combined local stakeholder consultation with field validation. Before conducting the analyses, the project team held consultations with Laamu stakeholders in March 2023 to identify appropriate sampling locations, especially focused on mangroves. In addition, the team brought experts from Rekam Nusantara Foundation to share experiences and lessons learnt during their Ocean Accounting process on an atoll in Indonesia.

This collaborative approach helped ensure the accuracy and reliability of data acquired through remote sensing techniques. Part of the field validation process involved the collection of ground truth data and other field observations to assess the accuracy of the remote sensing imagery. A total of 357 locations were strategically selected as ground truth points. This systematic approach provided essential validation data to support the remote sensing analysis and habitat classification efforts.

4.1.1. Overview of classification techniques

Remote sensing classification is the process of categorizing pixels in an image into distinct classes based on their spectral, spatial, and temporal characteristics. The choice of classification method depends on factors such as data resolution, the complexity of the study area, the availability of training samples, and the desired accuracy. There are several methods to perform classification, namely:

Supervised classification: where the user provides training data by selecting representative sample areas for each land cover type. The algorithm then assigns the remaining pixels in the image to the predefined classes based on statistical analysis. Common methods include:

- **Maximum Likelihood Classification (MLC):** Assumes that data in each class follow a normal distribution.
- **Minimum-Distance-to-Means Classification:** Calculates the distance between a pixel's spectral value and the mean value of each class, assigning the pixel to the closest class.
- **Random Forest (RF):** A machine-learning approach that builds multiple decision trees for classification.

Unsupervised classification: groups pixels into clusters based on their spectral properties without prior user-defined training data. The analyst then assigns labels to these clusters. A commonly used algorithm is K-Means Clustering, based on minimizing variance.

Supervised classification was applied to both Sentinel-2 and high-resolution imagery for Laamu Atoll, utilizing ground-truth data to ensure accurate land cover mapping. The method was chosen as in-situ observations from field campaigns provided well-defined training samples, allowing for precise classification of features.

4.1.2. Supervised classification using Sentinel-2

A supervised classification approach was applied to Sentinel-2 imagery to classify key land use and habitat types in Laamu Atoll, specifically distinguishing between mangrove, seagrass, coral reef, macroalgae, and other substrates. This classification was based on extensive ground truth data collected during field surveys, ensuring high accuracy in mapping coastal and marine habitats. The

analysis utilized ENVI (Harris Geospatial), with the Spectral Angle Mapper (SAM) algorithm chosen for its effectiveness in differentiating marine substrates.

To prepare the imagery for classification, a comprehensive pre-processing workflow was conducted on Sentinel-2 Level 2A (atmospherically corrected) imagery from 2017 and 2022. Images were selected to minimize cloud cover, glint, and atmospheric distortions. Key pre-processing steps included:

1. **Masking land areas** using OneMap island boundaries to separate sub-tidal and intertidal/terrestrial habitats, with additional focus on the intertidal area of L. Hithadhoo mangrove.
2. **Cloud masking** to eliminate interference from atmospheric conditions.
3. **Depth-based segmentation** using Allen's Coral Atlas bathymetry data to isolate sub-tidal areas shallower than 25 meters.⁵
4. **Water column correction** through the Depth Invariant Index Calculation to standardize reflectance across different depths.

The classification process used 357 ground truth points to train the model, and post-classification refinement was carried out in ArcGIS Pro to filter isolated pixels and enhance spatial coherence. The results were validated against over 300 field-collected images and video transects, ensuring the accuracy and reliability of the final habitat maps.

4.1.3. Supervised classification using High resolution data

A similar classification process was applied to the high-resolution data, although separately analyses to map the extents of coral reefs, mangroves, and seagrass across Laamu Atoll. The classification outputs included a probability-based seagrass presence map, a refined coral reef habitat map, and an updated mangrove extent map. For mangrove classification, the analysis focused on L. Hithadhoo, the only true mangrove forest on the atoll. Mapping was performed using imagery from Pleiades and PlanetScope satellites. The mangrove areas were clipped and classified using ENVI, with manual digitization applied for accuracy corrections.

Coral and seagrass classification leveraged Earth Observation techniques, integrating training data from open-access databases and ground-truth points collected during field surveys. Expert knowledge and image interpretation further refined the classification. To enhance accuracy, all available satellite images from a given year were mosaicked. The imagery was then classified using machine learning techniques (random forest classifier), which was trained on known presence and absence data to predict occurrence. The classification output was a probability map for seagrass for each pixel and mapped habitat for the coral reef. A threshold probability of seagrass occurrence was chosen via expert interpretation. Due to relatively low water turbidity and image availability, the probability was able to be set low at 15%, to produce the final seagrass presence map. Validation using resampling indicated an error between 10-20%, with further validation needed to align across multiple years.

⁵ See: <https://allencoralatlas.org/methods/>

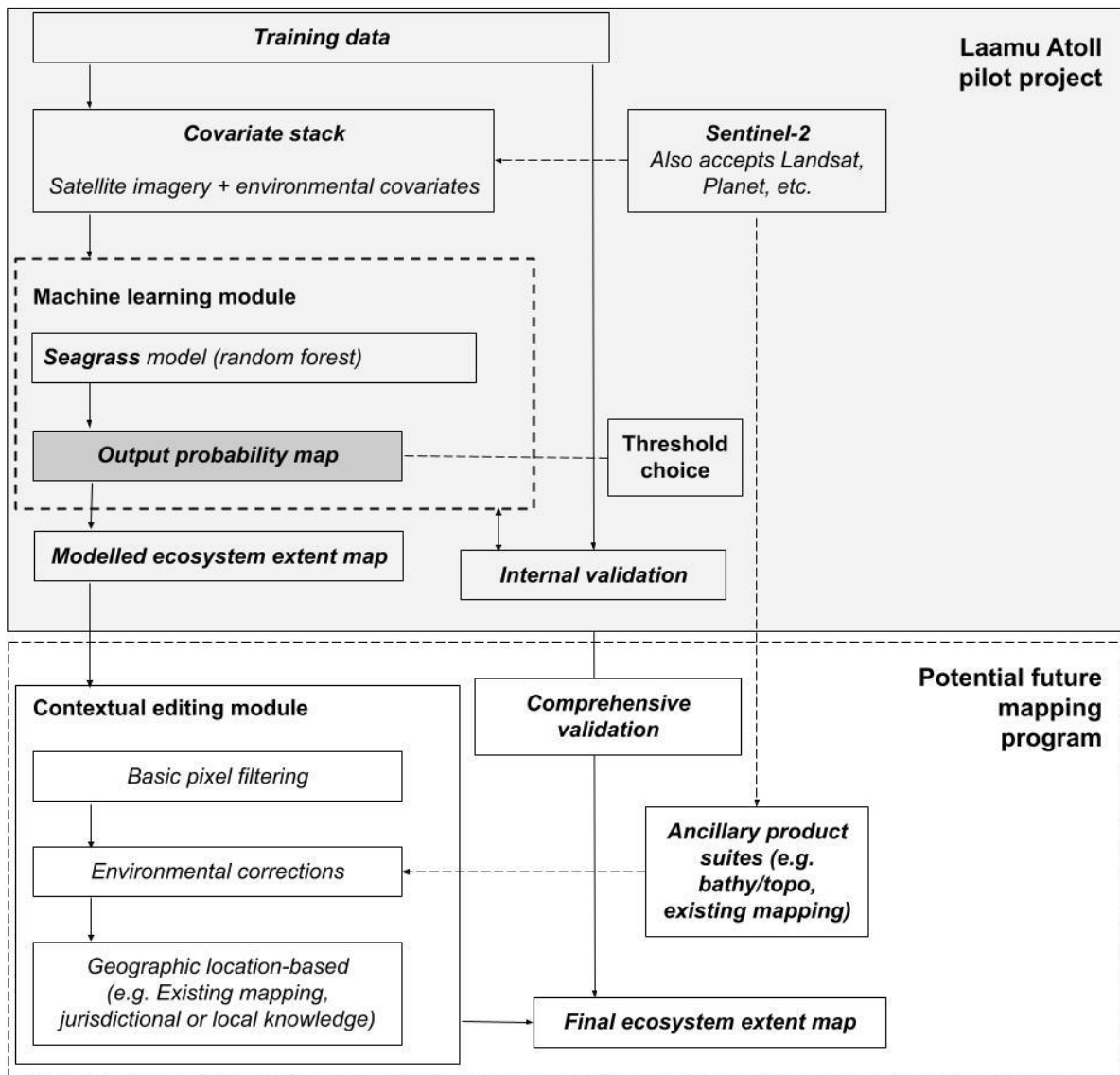


Figure 4.3 Mapping framework for coral and seagrass ecosystems on Laamu Atoll.

Table 4.1 Data sources for benthic classification to produce Ecosystem Extent accounts.

Type of data	Data type	Date(s) of collection	Resolution	Source
Ground truthing points	Point	March 2023	-	Field survey
Satellite imagery - SPOT 6/7	Geo-referenced raster image	20 March 2017, 25 March 2017, 26 March 2017, 10 January 2020, 17, January 2020 and 30 November 2020	1.5 m	https://www.intelligence-airbusds.com/
Satellite imagery - Sentinel-2	Geo-referenced raster image	2017 & 2020 (Multiple)	10 m	https://dataspace.copernicus.eu/
Satellite imagery - Pleiades	Geo-referenced raster image	26 June 2017 & 11 February 2020	0.3 m	https://www.intelligence-airbusds.com/
Satellite imagery - Planet SuperDove (3 m)	Geo-referenced raster image	2/09/2022, 17/06/2023, 9/05/2024, 4/06/2022, 17/06/2023, 2/10/2023, 19/03/2024, 26/01/2024, 28/03/2022	1.5 m	https://www.planet.com/
Protected Areas boundaries	Polygon	-	-	EPA, Ministry of Climate Change, Environment and Energy, Maldives
Boundaries of islands in Laamu Atoll	Polygon	-	-	MLSA One Map (https://onemap.mv/)

4.2. Ecosystem extent and change

Once spatial data was organized, the total area of each ecosystem type was structured into a table per accounting period (i.e., annually). The compilation process involved first classifying all areas into mutually exclusive (non-overlapping) ecosystem types. A standardized approach was developed to analyse ecosystem changes between 2017 and 2020 across the study area. The process overlaid a uniform grid across the region. Each grid cell was then classified according to its dominant ecosystem type, using a simple majority rule - if an ecosystem covered the largest percentage of the cell area, the entire cell was classified as that ecosystem type. For example, a cell containing 51% coral reef would be designated entirely as coral reef, regardless of other ecosystems present within that cell.

The spatial analysis began by removing grid cells outside the study area. Ecosystem data from 2017 and 2020 was then integrated with the standardized grid cells, ensuring that each cell contained ecosystem information for both years while preserving all input features and attributes. This allowed for direct temporal comparison within each spatial unit. The final change detection was performed using R Statistical Software, where the dominant ecosystem type in each grid cell was compared between 2017 and 2020 to identify areas of ecosystem transition. The total grid area was 164,263.40 ha.

4.2.1. Opening and closing extent account

Opening and closing stocks for each ecosystem type are recorded, along with additions (through natural expansion or restoration) and reductions (through conversion or degradation) that explain the changes between accounting periods. The difference between the opening stock and the closing stock is the net change in ecosystem extent, which can be positive or negative. A positive net change means that the total area of ecosystems has increased, while a negative net change means that the total area of ecosystems has decreased. The total area remains the same between the two years (Table 4.2), although rounding may introduce errors.

The change in ecosystem stocks between two years is derived from a **change matrix**, which tracks the transitions between different ecosystem types over a specified accounting period. The rows of the matrix represent the ecosystem types at the beginning of the accounting period, and the columns represent the ecosystem types at the end of the accounting period. Each cell shows the area of land that transitioned from one ecosystem type to another during the accounting period (Table 4.3).

Table 4.2 Opening and closing account for coastal ecosystems for 2017 and 2020 in Laamu Atoll, Maldives. Slight differences in total area due to rounding.

Entry	Units	Coral Reef	Seagrass	Mangrove	Macroalgae	Other Substrate	Totals
Opening (2017)	ha	6734.0	4257.4	4.9	42.9	150910.2	161949.4
Additions		0.5	0.5	0.0	0.0	74.5	75.6
Reductions		-42.4	-37.6	0.0	-2.1	4.8	-77.3
Closing (2020)		6692.1	4220.4	4.9	40.8	150989.5	161947.7
Net Change		-41.9	-37.1	0.0	-2.1	79.4	-6.4
Net Change (%)	%	-0.6	-0.9	0.0	-4.9	0.0	0.0

Table 4.3 Change matrix for Laamu Atoll, Maldives. Differences in total area are due to rounding.

From 2017 ↓ / To 2020 →	Coral Reef	Seagrass	Mangrove	Macroalgae	Other Substrate	Total 2017
Coral Reef	6691.6	0	0	0	42.4	6734
Seagrass	0	4219.9	0	0	37.6	4257.4
Mangrove	0	0	4.9	0	0	4.9
Macroalgae	0	0	0	40.8	2.1	42.9
Other Substrate	0.5	0.5	0	0	150909.2	150910.2
Total 2020	6692.1	4220.4	4.9	40.8	150989.5	161947.7

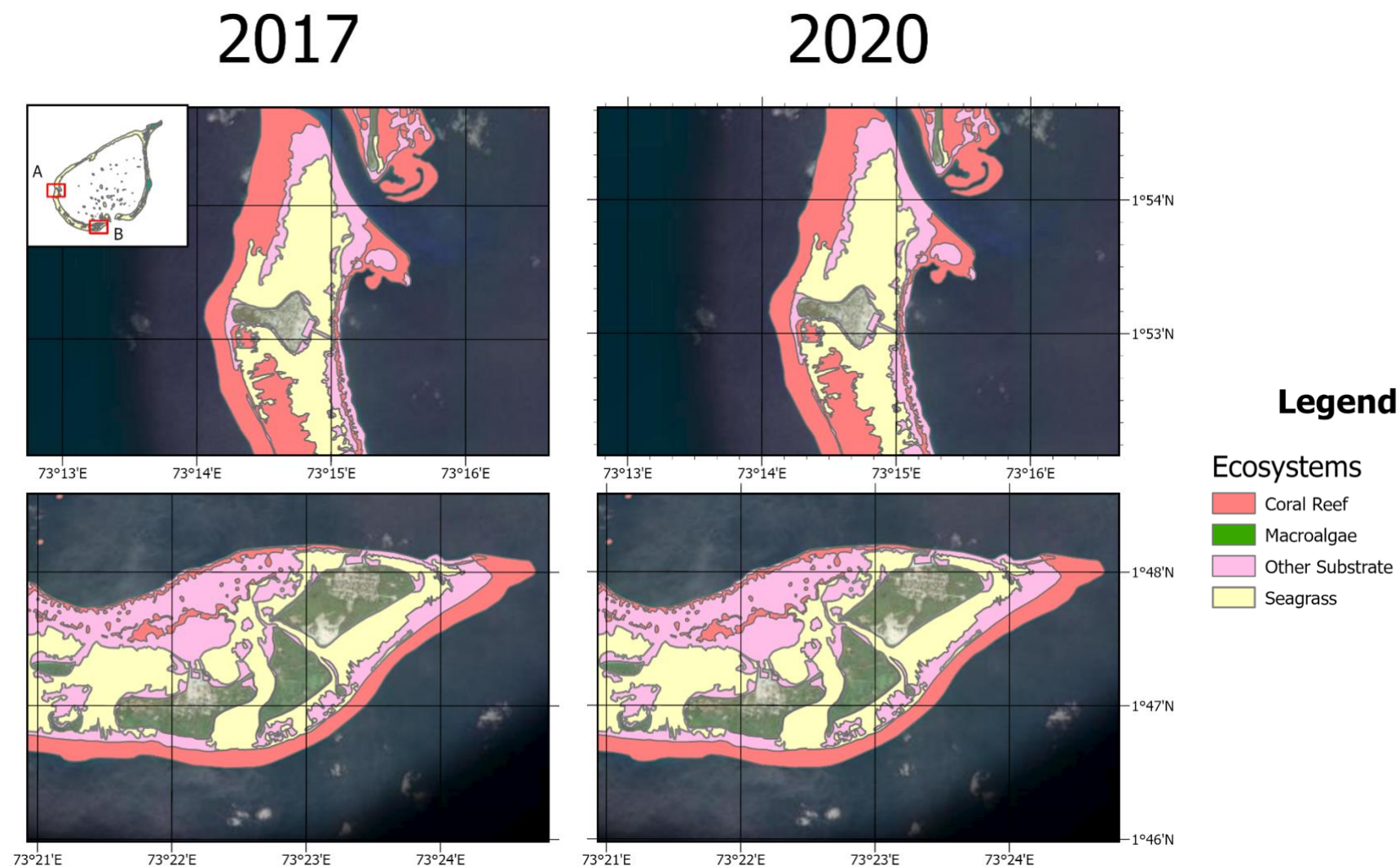


Figure 4.4 Ecosystem extent in (A) Maavah and (B) Kunahandhoo, Medhoo and Hithadhoo, Laamu Atoll, comparing 2017 (opening) and 2020 (closing) for key ecosystems. Mangroves are presented separately.

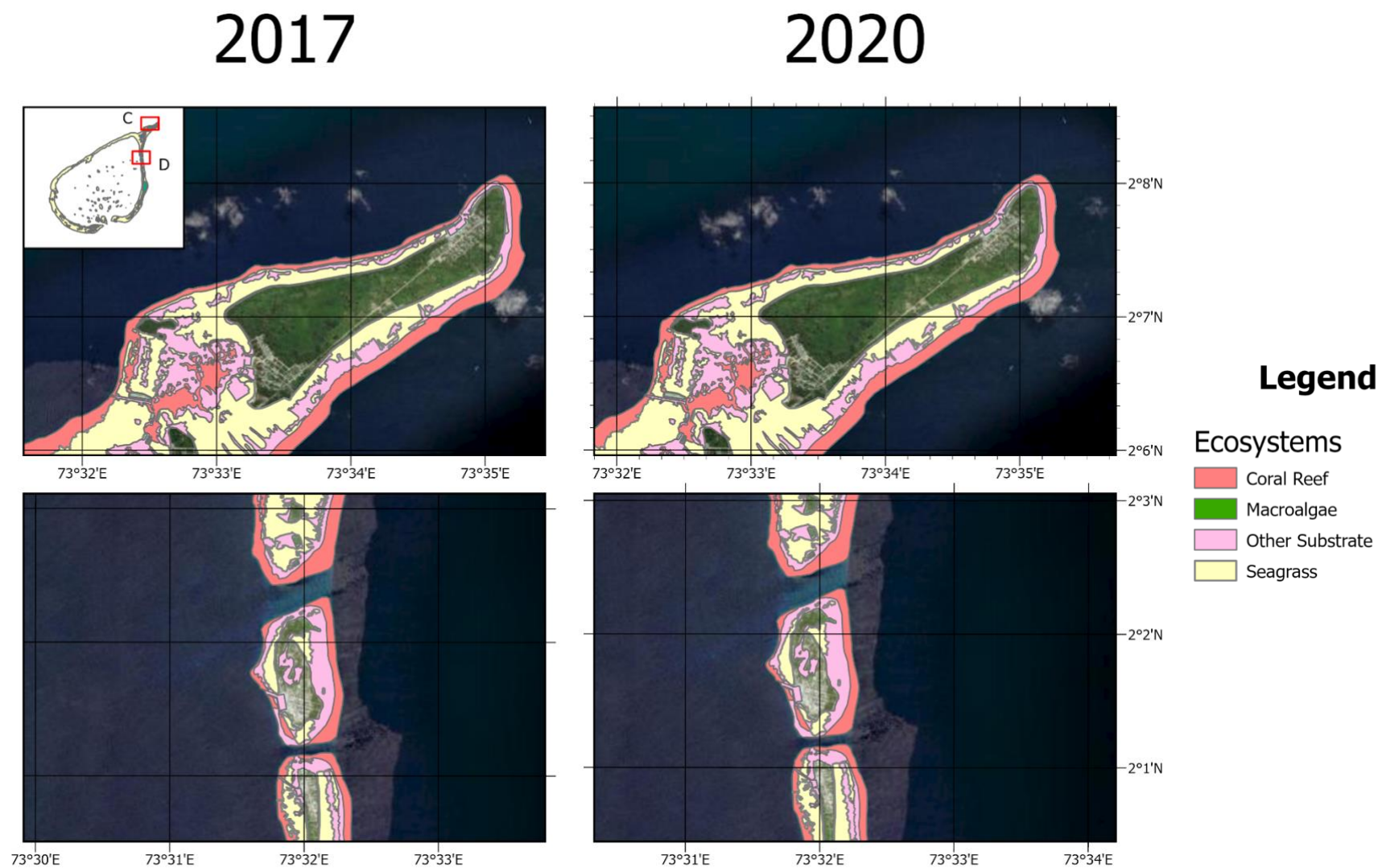


Figure 4.5 Ecosystem extent in (C) Isdhoo and (D) Maabaidhoo, Laamu Atoll, comparing 2017 (opening) and 2020 (closing) for key ecosystems.

4.3. High resolution accounts

The individual analyses of coral reefs, mangrove and seagrass in Laamu Atoll between 2013 and 2024 reveals slight fluctuations in the extent of mangroves, seagrass, and coral reef habitats. Mangrove coverage demonstrates a steady increase from 2.77 hectares in 2014 to a peak of 2.93 hectares in 2020 and 2022, followed by a minor decline to 2.91 hectares in 2024. The variations observed may partly result from differences in the quality of satellite imagery and algorithms used to calculate these extents. Further research is required to determine if these small changes reflect ecological dynamics or are due to measurement.

Seagrass extents in Laamu Atoll show more pronounced variability, ranging from 4049 hectares in 2018 to 3473 hectares in 2022, and rising again to 3831 hectares in 2024. This variability may be influenced by seasonality and altered life cycles, with similar changes observed globally. Seagrass may also respond to inter-annual changes in water temperature and nutrient availability. The shifting patterns in seagrass extent underline the need for targeted field studies to validate these observations and explore the drivers behind these fluctuations.

The data on coral reefs and associated habitats (including areas with coral and algae benthic types) reflect minor declines over the study period. For reefs deeper than 25 meters, the extent decreased from 506,662 hectares in 2020 to 504,205 hectares in 2024. However, these differences may also stem from improved detection algorithms or differing resolution of imagery. Further detailed studies are necessary to distinguish genuine ecological changes from measurement discrepancies.

Table 4.4 Timeseries of coastal ecosystem area (ha) between 2013 and 2024 in Laamu Atoll, Maldives. Slight differences in total area due to rounding.

Year	Mangroves	Seagrass	Coral Reef*
2014	2.77	-	-
2015	-	-	-
2016	2.83	-	-
2017	2.84	-	-
2018	2.85	4049	-
2019	2.90	3583	-
2020	2.90	3894	5066.62 (1308.11)
2021	2.92	3628	5066.63 (1307.09)
2022	2.93	3473	5055.96 (1310.23)
2023	2.92	3511	5051.53 (1313.14)
2024	2.91	3831	5042.03 (1315.13)

* First number is reef > 25 m depth, while brackets are living coral habitat (extent of coral and algae benthic types).

4.3.1. Comparison between satellite platforms

Satellite platforms were compared to measure mangrove extent in Hithadhoo, namely Sentinel 2 (10 m) and Pleiades (0.5 m). The differences in mangrove extent between the high-resolution Pleiades (0.5 m) and Sentinel-2 (10 m) satellite platforms highlight the significant impact of spatial resolution on ecosystem mapping and accounting (Figure 4.6, Table 4.5). Sentinel-2 data consistently reported a total mangrove extent of 4.88 hectares in both 2017 and 2020, but it lacked the capability to distinguish between low- and high-density mangroves due to its coarser resolution. In contrast, Pleiades imagery provided finer detail, revealing distinct areas of low-density (e.g., 2.01 hectares in 2017) and high-density (0.83 hectares in 2017) mangroves, with slightly increased totals in 2020.

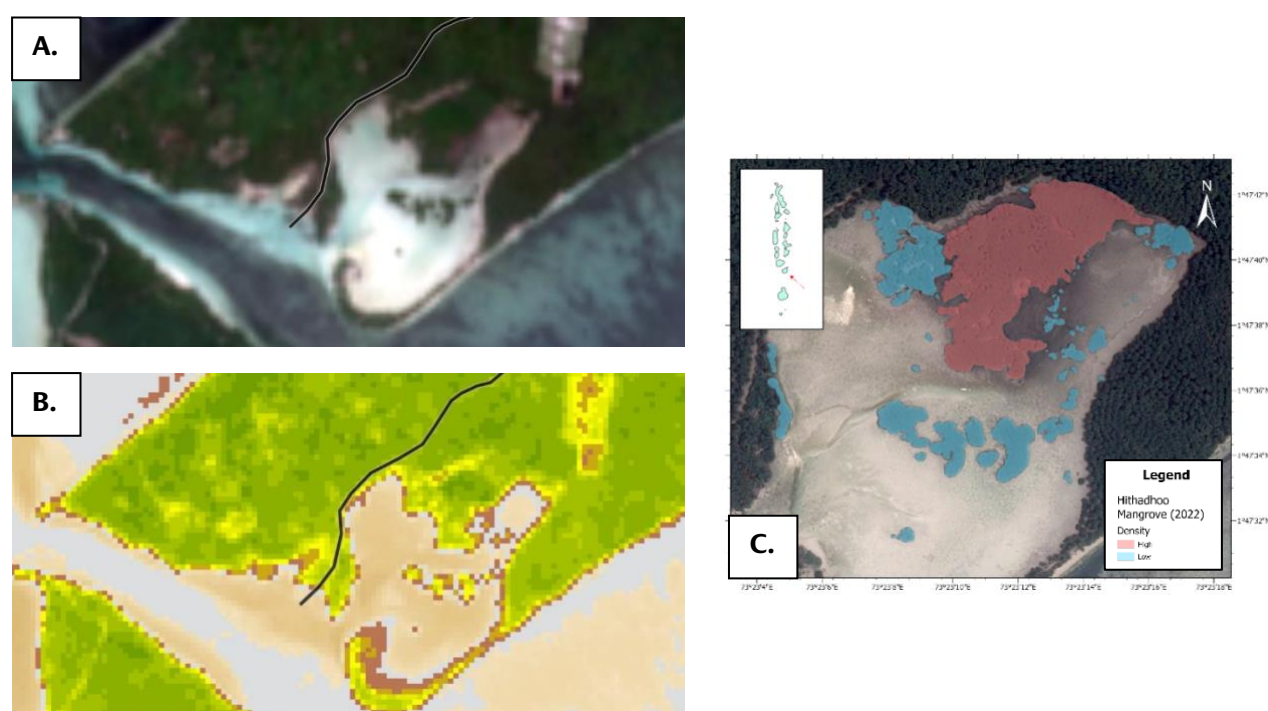


Figure 4.6 Comparison of Sentinel-2 (10 m) natural-colour imagery (A) and vegetation product (B), against (C) Pleiades ultra-high resolution satellite imagery (0.3 m) for mapping Hithadhoo mangroves.

Table 4.5 Comparison of mangrove extents within Hithadhoo using high resolution (0.5 m) and sentinel-2 (10 m) satellite platforms. Note separation of density was only possible with Pleiades.

Year	Satellite	Low density	High density	Total
2017	Sentinel 2	-	-	4.88
	Pleiades	2.01	0.83	2.84
2020	Sentinel 2	-	-	4.88
	Pleiades	2.05	0.86	2.90

5. Condition Accounts

Ecosystem condition accounts organize data on the environmental state (or health) of ecosystems and often link this to estimates of ecosystem services. Simply having an ecosystem does not guarantee the provision of services, especially if that ecosystem is degraded. To assess ecosystem condition effectively, it is essential to select variables that represent its health and capacity to provide services. These variables encompass aspects such as ecosystem structure, composition, functioning, and productivity, and are chosen based on the specific ecosystem under assessment.

Evaluating ecosystem condition requires a detailed understanding of its structural, functional, and biodiversity attributes. This involves gathering data on variables within these categories to reflect the ecosystem's overall health and integrity. According to Czucz et al. (2019), structuring condition information relies on defining key characteristics and associated metrics, with a systematic selection process that includes:

- Identifying key characteristics (e.g., components and processes),
- Selecting or developing metrics for these characteristics, and
- Ensuring the balance and comprehensiveness of these metrics, adjusting as needed.

Key characteristics may include abiotic elements (physical and chemical), biotic features, and landscape/seascape-level attributes. Field surveys play a critical role in measuring ecosystem condition by quantifying key indicators that may not be fully captured through remote sensing or modelling alone. The process for Laamu Atoll is provided in Figure 5.1.

Table 5.1 Structure, function and biodiversity variables relevant to ecosystem condition accounts.

Characteristics	Mangrove	Seagrass	Coral reef	Rationale
Structural	Average tree height, canopy cover, basal area, and density of adult trees	Average leaf blade length, percentage cover, meadow density	Percentage live cover	Related to ecosystem services such as carbon sequestration, coastal protection and erosion control
Functional	Net primary productivity, nutrient cycling, and water filtration rates		Disease, physical damage, plastic pollution	Related to regulating ecosystem services
Biodiversity	Species composition of mangroves and other associated flora	Species composition of seagrass and other associated flora	Species composition and associated fish families	Provide insights to biodiversity and resilience to disturbances

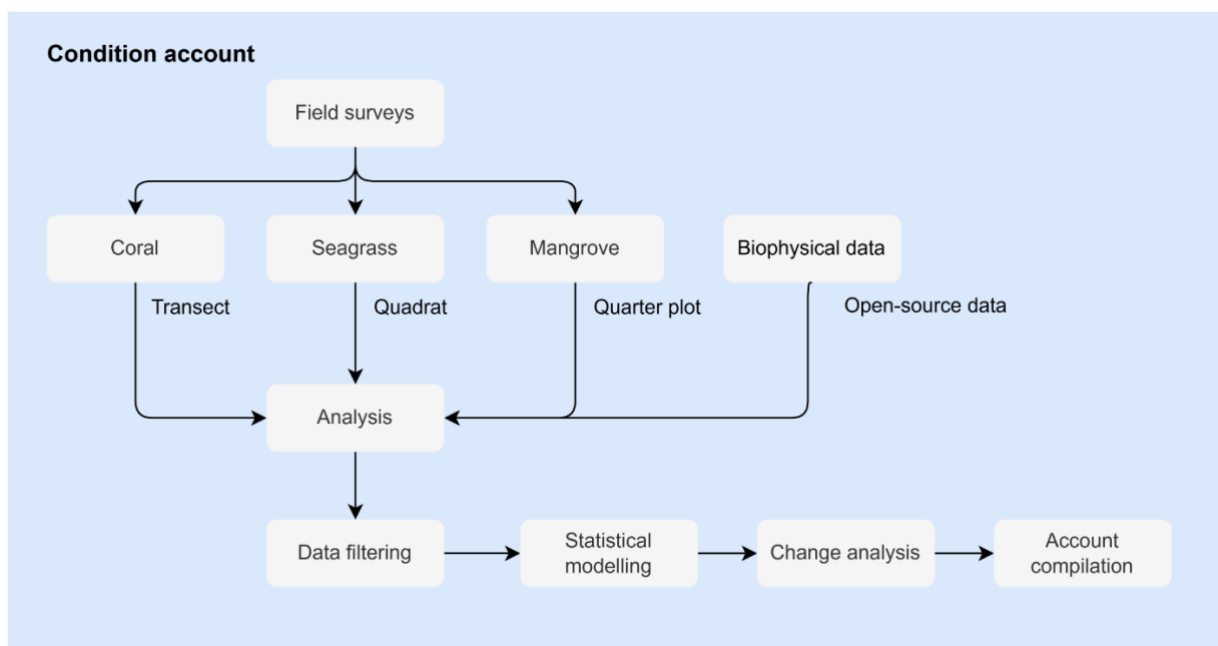


Figure 5.1 Condition account process.

5.1. Survey methods

5.1.1. Coral Reef

Modified belt transects were used to survey conditions within 17 coral reefs sites. Using SCUBA equipment, transect and other materials, coral reef surveys were conducted in April and May 2024 to obtain the following parameters:

- Benthic community composition (e.g., live coral cover).
- Coral community composition (coral genus and morphology).
- Fish abundance, richness and diversity.
- Invertebrate composition and abundance.
- Identify potential anthropogenic and non-human reef impacts.
- Biomass of commercially and ecologically important fish species.

A 100 m transect was divided into 4 x 20 m replicates, leaving a 5 m gap between each replicate (Figure 5.2). Each site was surveyed at two depths, depending on site characteristics (either 5 m and 10 m; or 10 m and 15 m) for a total survey area of 1,600 m². All statistics were standardized to count per 100 m².

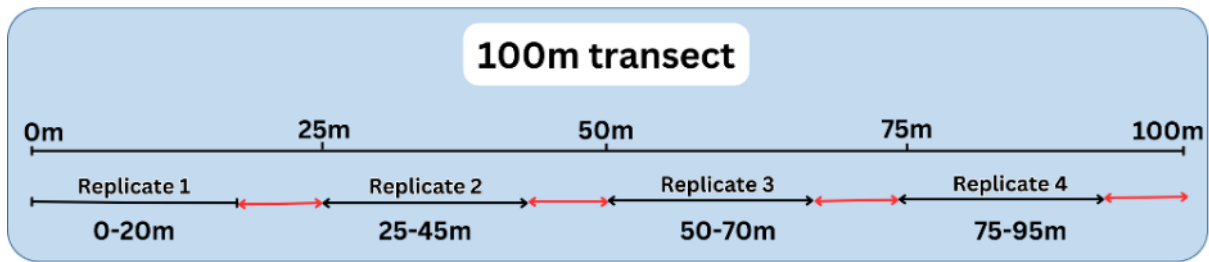


Figure 5.2 Survey methods diagram. Sections in red were not surveyed in line with Maldivian National Coral reef Monitoring framework.

Surveyed indicator fish were recorded by family, separated by ecological or commercially important groups. Commercial species included jacks and trevallies (*Carangidae*), rabbitfish (*Siganidae*), emperor fish (*Lethrinidae*), snappers (*Lutjanidae*) and grouper (*Serranidae*). Ecologically important fish were surgeonfishes (*Acanthuridae*), triggerfishes (*Balistidae*), angelfishes (*Pomacanthidae*), Scaridae (parrotfishes), butterflyfishes (*Chaetodontidae*) and Haemulidae (sweetlips).

Photos were taken every 5 m of the transect and then sorted, labelled and analysed using Reef Cloud to efficiently collate and analyse data using artificial intelligence and human collaboration. The status of the coral reefs in Laamu Atoll was also supported by a review of the scientific literature, papers, theses, and contributions to international symposia published over the past three years. This data and information collection focused on coral cover describing the overall health of the coral reef ecosystem in Laamu Atoll.

All surveyors were trained using the Bell et al. (1984) technique where there are 25 wooden sticks between 0-1 m attached to a 20 m rope laid out in the water. Observers then swam along parallel to the rope keeping a minimum distance of 2 m and estimating the length of each piece of wood. Results were then compared to the true lengths and this training was repeated until estimates between surveyors were no longer significantly different in a paired t-test.

The survey consisted of two main parts: fish surveys by the first team, followed by invertebrate and impact surveys by the second team. Each survey covered four 20 m sections along a 100 m transect, with 5 m gaps between sections. For invertebrate surveys, teams recorded:

- Coral-feeding starfish: *Acanthaster planci* and *Culcita novaeguineae*
- Commercial/ecological species:
 - *Nephropidae* (Lobsters)
 - *Octopoda* (Octopus)
 - *Holothuroidea* (sea cucumber)
 - *Tridacna* (giant clam)
 - *Echinoidea* (sea urchin >5cm)
 - *Lambis* (Spider conch)

Teams also documented impacts including starfish damage, marine debris, fishing line, anchor scars, *Drupella* damage, and disease. Photos were taken every 1 m along the transect, alternating sides, for 80 total images per depth.

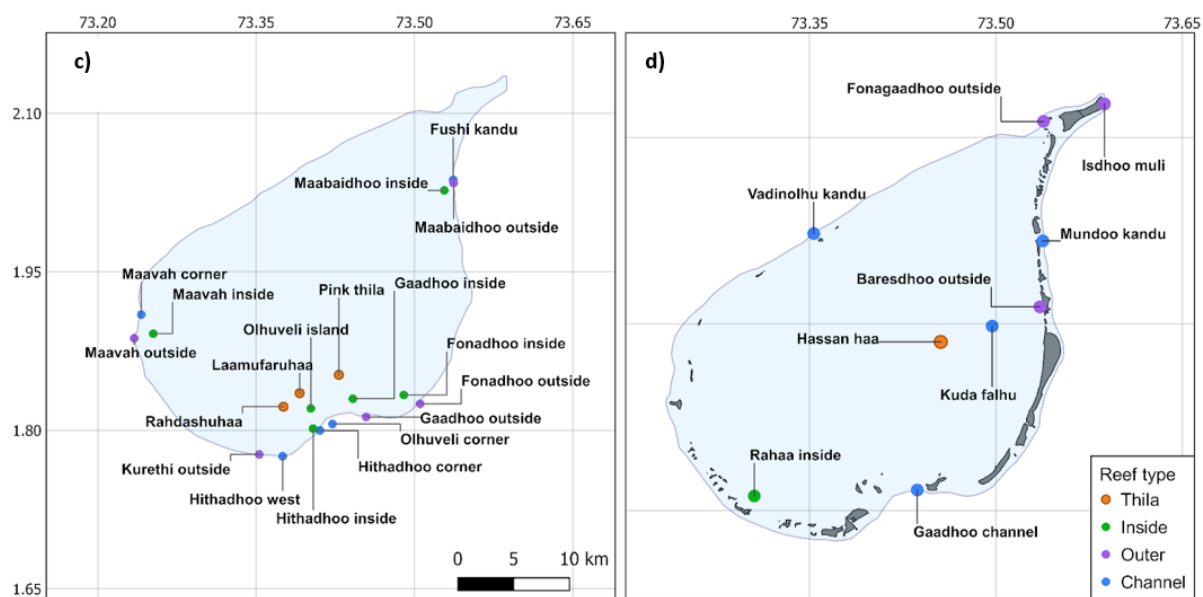


Figure 5.3 Coral reef condition survey sites, adapted from Fischer et al. (2022).

Seagrass

Seagrass condition surveys followed methods described in the Maldives Seagrass Monitoring Network – Monitoring Methods (v1.3, 2020). A 50 m x 50 m area of low variability and even topography was selected for surveys. Within this area, three transects of 50 m were laid in parallel, at least 25m apart and perpendicular to the beach. The survey consisted of recording seagrass variables within 0.5 m x 0.5 m quadrats (Figure 5.5, Figure 5.6). Quadrats were placed every 5 m along the transect line (total eleven per transect line). Photos were taken of each quadrat, along with GPS coordinates and depth. Assessed parameters are presented in Table 5.2.

A Seagrass Ecological Quality Index (SEQI) was calculated, to combine the different seagrass variables into a single indicator to represent seagrass condition in Laamu Atoll. The equation, which accounts for species (S), percent seagrass cover (C), density per m^2 (D), percent macroalgal cover (M) and percent epibenthic cover (E) was as follows:

$$SEQI = \frac{S_{site}}{S_{total}} * 0.2 + C_{site} * 0.2 + D_{site} * 0.2 + (1 - M_{site}) * 0.2 + (1 - E_{site}) * 0.2$$

Epibenthic cover on seagrass was also measured, and represents overgrowth by organisms such as algae, sponges, bryozoans, and other invertebrates that grow on the seagrass leaves (Figure 5.4). This layer plays a crucial role in ecosystem health, serving as an additional habitat and food source for various marine species, including fish and invertebrates. A balanced epibenthic cover supports biodiversity by fostering complex food webs, yet excessive cover, particularly from algae, can indicate nutrient pollution and stress on the ecosystem. Healthy epibenthic communities contribute to seagrass productivity and resilience, enhance nutrient cycling, and serve as indicators of environmental stability and water quality in coastal ecosystems.

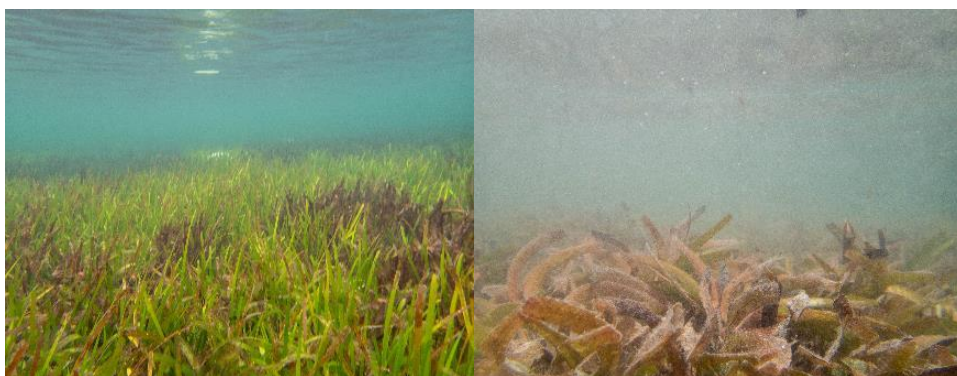


Figure 5.4 Healthy seagrass (left) and seagrass with high macroalgae and epiphyte cover (right) from Laamu Atoll, photographed in March 2023 (UNSW / Rekam Nusantara Foundation).

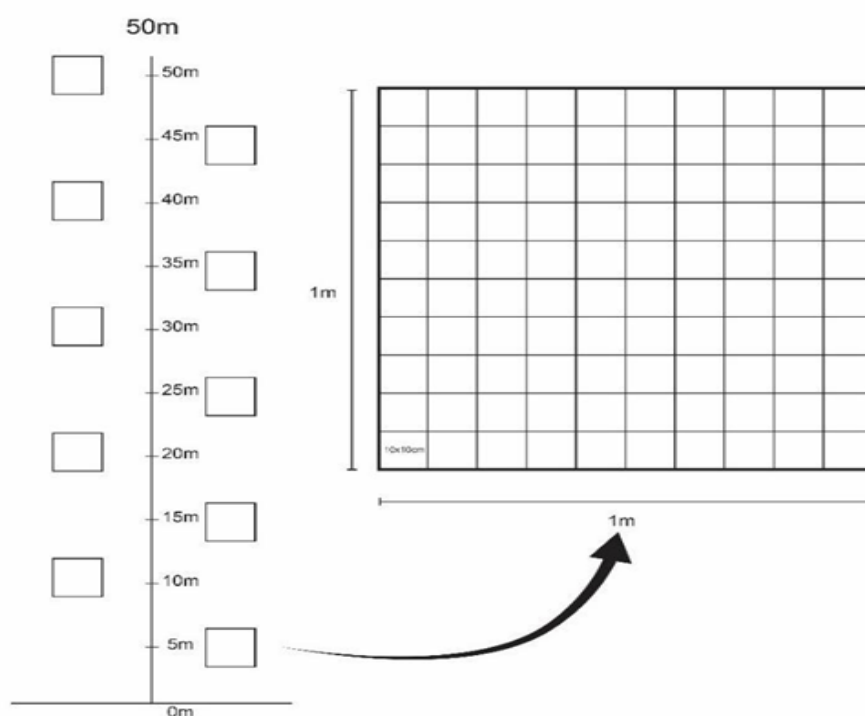


Figure 5.5 Illustration of seagrass data collection transects.

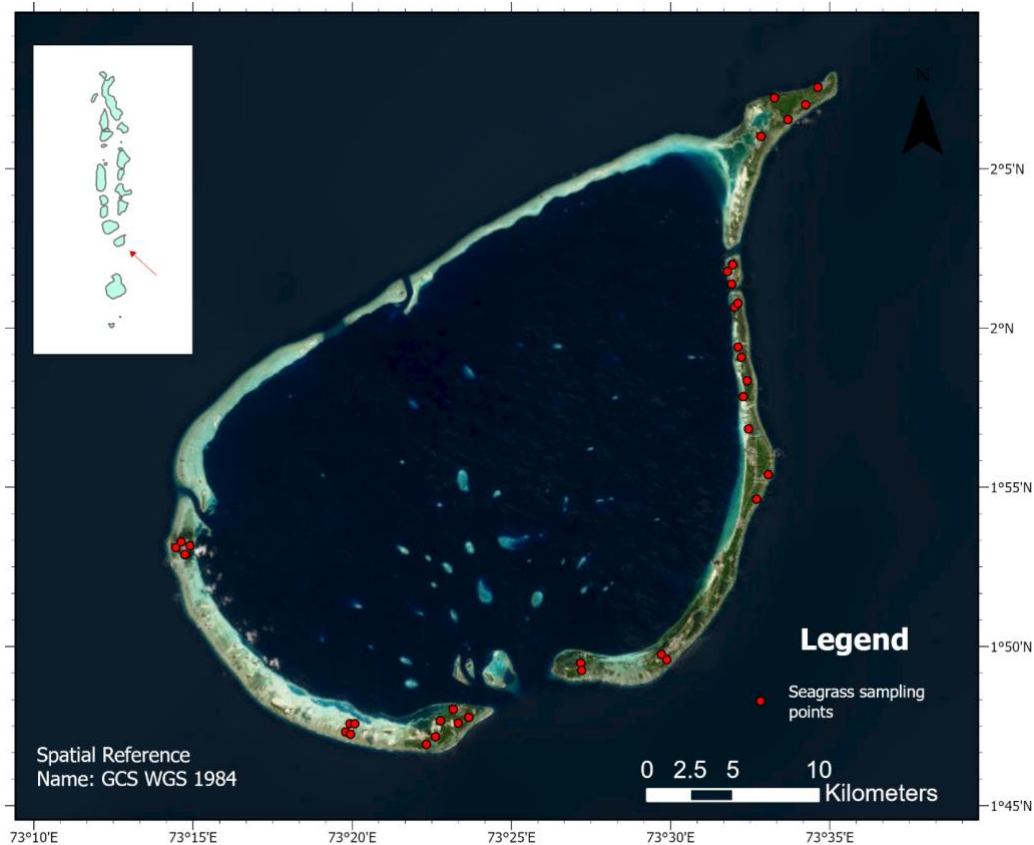


Figure 5.6 Seagrass areas sampled using transects and quadrats.

An assessment of species can reveal the health and disturbance of marine ecosystems, by composition and distribution. The observed seagrass species were *Cymodocea rotundata*, *Halodule uninervis*, *Halodule pinifolia*, *Syringodium isoetifolium*, *Thalassia hemprichii*, and *Thalassodendron ciliatum* (Figure 5.7). Each of these species exhibits unique growth dynamics and ecological functions. For instance, *H. uninervis* and *H. pinifolia* are typically fast-growing pioneer species, often established in disturbed areas and colonizing shallow sandy substrates. They create favourable conditions for other species by stabilizing sediments, thus enabling the establishment of slower-growing species like *Thalassia hemprichii*, which prefers more stable substrates and provides complex habitat structures essential for juvenile fish and invertebrates. For instance, *T. ciliatum* often appears in mature, well-established meadows in deeper waters where it forms dense, large stands. Changes between species may indicate disturbance.

Table 5.2 Parameters measured for seagrass.

Variable	Description	Rationale
Number of species	Number of seagrass species found at the location.	Indicates biodiversity and ecosystem health; helps monitor changes in community composition.
Coverage (%)	Percentage of the seabed covered by seagrass.	Indicates the extent of seagrass meadows; relates to ecosystem services such as carbon sequestration.
Density (blades per m ²)	Number of seagrass individuals per square meter.	Reflects the abundance and health of seagrass meadows; critical for biomass and productivity estimates.
Algae (%)	Percentage of seagrass bed area covered by algae.	Algae coverage can compete with seagrass for resources; an indicator of ecosystem balance.
Epifauna (%)	Percentage of seagrass bed area with epifaunal organisms.	Indicates the presence of associated fauna, contributing to the overall biodiversity of the habitat.
Number of associated benthic	Number of benthic species associated with the seagrass bed.	Reflects the complexity and health of the seagrass ecosystem; important for understanding ecosystem functioning.
Sediment type	The average sediment type, identified through visual inspection.	Identifies potential runoff and an indicator for carbon sequestration into soils.

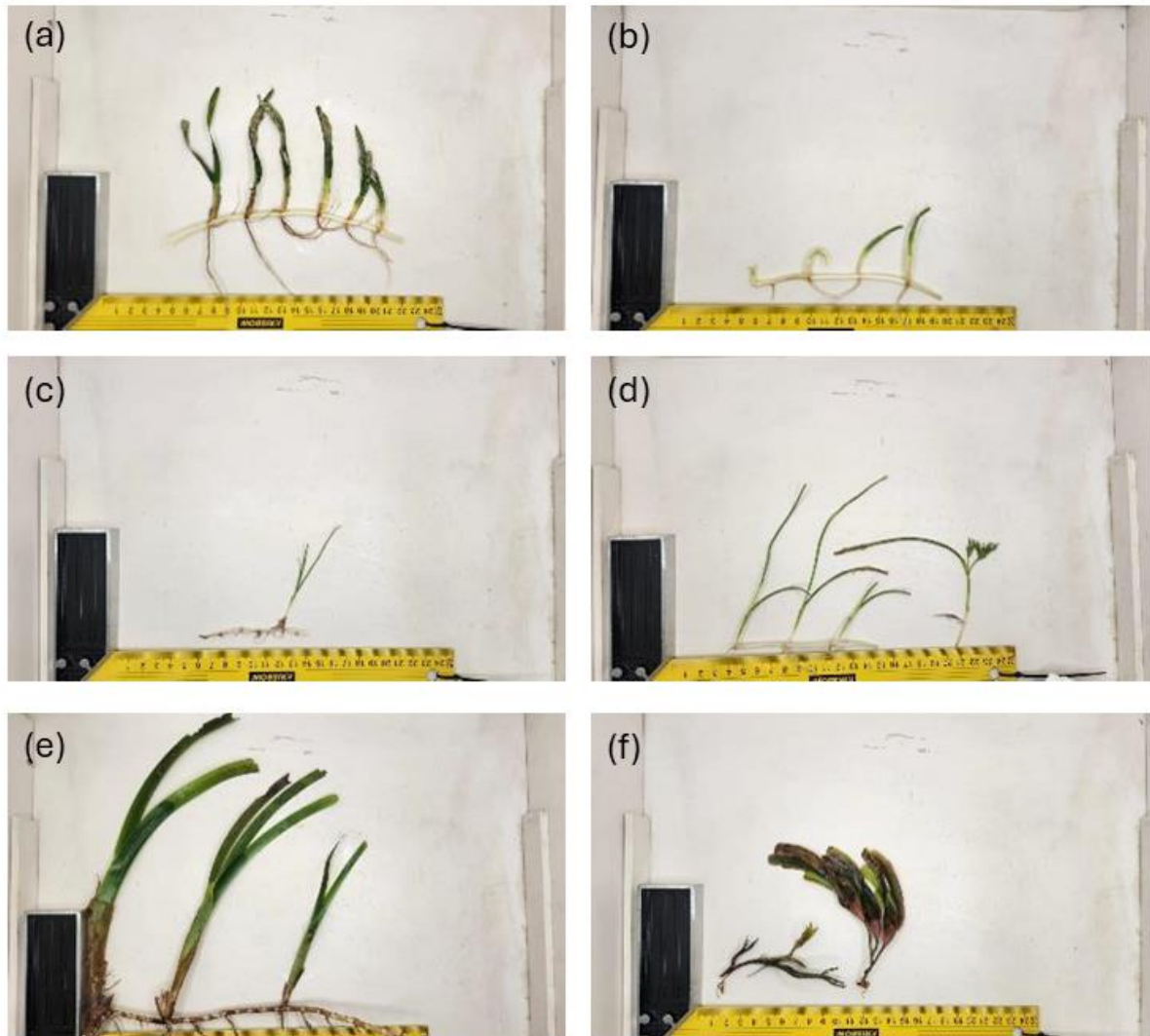


Figure 5.7 Seagrass species found at the Lamuu Atoll observation sites (a) *Cymodocea rotundata*, (b) *Halodule uninervis*, (c) *Halodule pinifolia*, (d) *Syringodium isotifolium*, (e) *Thalassia hemprichii*, and (f) *Thalassodendron ciliatum*.

5.1.2. Mangrove

Sampling was carried out with a transect quadrat plot of 10 x 10 m for mangrove trees, a plot of 5 x 5 m for sampling, and a plot of 1 x 1 m (Figure 5.8). Plots were divided into high and low density, defined before sampling. Other variables included:

- tree height (using a clinometer),
- Diameter at Breast Height (DBH) – diameter of tree at 1.3 m,
- Species Composition, and
- Canopy cover calculated using a ground-based method.

For L. Hithadhoo wetland, all data from the plots were compiled for density zone (high or low), tree height, Diameter at Breast Height (DBH), species composition, and canopy cover. A hemispherical camera was used to capture the image of the sky and vegetation from a fixed position, and the images were then uploaded to an ImageJ to analyse the canopy percentage.

Descriptive statistical analyses were performed to understand the basic characteristics of the mangrove forest. The presence and frequency of different mangrove species across the plots were summarized, and the average canopy cover percentage for each plot and for each density zone was calculated. The species composition within the plots was analysed to determine the relative abundance and diversity of mangrove species. Species richness (the total number of different species present) for each plot was calculated.

ArcGIS Pro software was utilized to map the locations of the plots and visualize the spatial distribution of mangrove characteristics. Remote sensing data were used to overlay and compare pre-sampling density zones with field data.

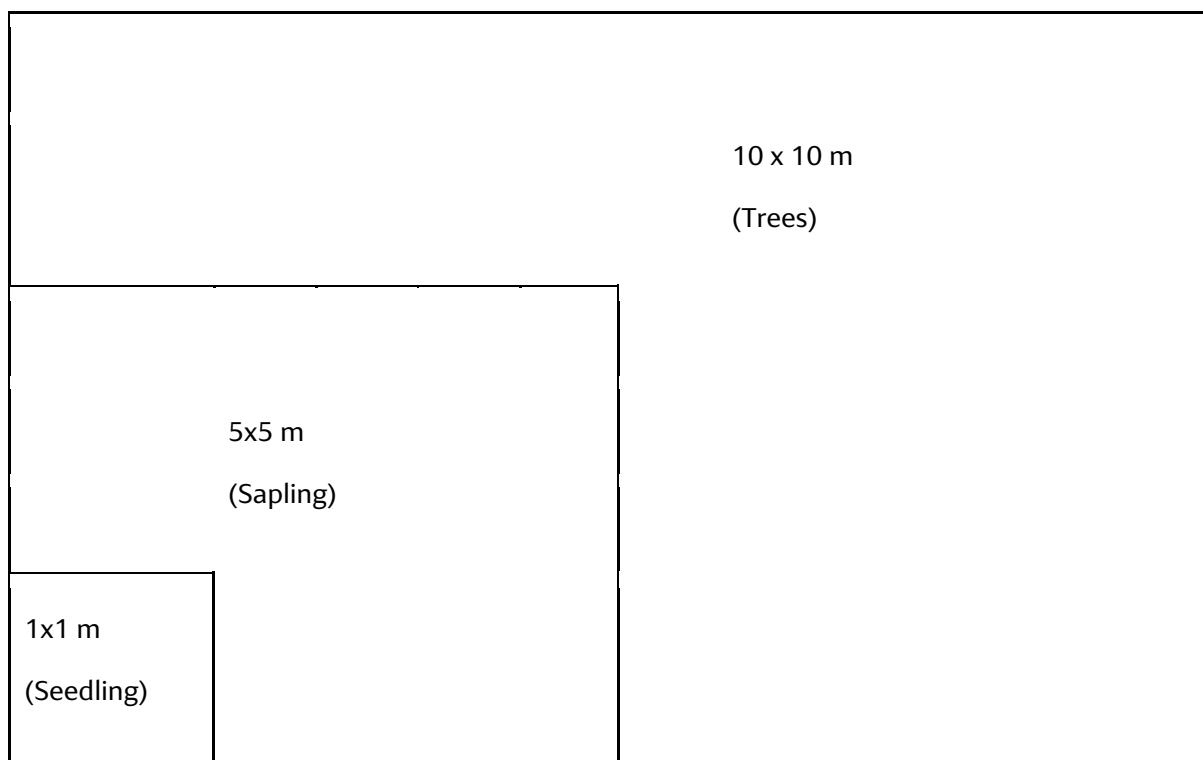


Figure 5.8 Sampling plot of mangrove ecosystem to measure vegetation structure.

Table 5.3 Description of all variables captured for mangroves in the Laamu Atoll, Maldives, including rationale and data sources.

Variable	Description	Rationale
Species	Number of species per plot	Track in community changes
Number of Seedlings	Individuals with circumference < 3.14 cm	Can help monitor recruitment and survival patterns – but are not considered condition account variables
Number of Saplings	Individuals with 3.14 cm < circumference < 12.56 cm	
Number of Trees	Individuals with circumference >12.56 cm	
Average number of trees	Average number of trees per plot (all species)	Number of trees contributes to the species density, relates to carbon sequestration and habitat provisioning.
Species density	Number of individuals per hectare	
Maximum canopy tree height	Average maximum canopy tree height per plot	Tree height relates to carbon sequestration and habitat provisioning. It is used to model biomass and infer functioning of mangrove forests.
Basal-weighted tree height	Tree height weighted by the diameter at chest-height. Average calculated per plot area	
Canopy cover	Percentage of the forest floor that is covered by tree canopy.	Structural property of the ecosystem, which relates habitat provisioning, ecological competition, among others.
Above ground biomass	Biomass contained within the plant's living leaves, branches, stems or aerial shoots.	Needed in carbon accounting, to calculate storage in biomass.
Below ground biomass	Biomass contained within the plant's living roots and rhizomes. May include necromass (litter or detrital materials).	
Carbon stock	Values of total average carbon stocks for each carbon pool (aboveground and belowground). Carbon conversion factors are based on the percent of the biomass that is made of organic carbon.	To estimate the potential blue carbon stock in the mangrove ecosystem.

5.1.3. Statistical modelling of indicators

The compilation of certain indicators requires a combination of multiple data sources, measurement techniques, and statistical modelling. For mangroves, the weight of biological materials above the ground (above ground biomass) is derived from tree height, diameter at breast height (DBH), and species-specific wood density values. Similarly, seagrass requires calculations using shoot density, canopy height) with species composition through multivariate statistical approaches. Stepwise guidance on the calculation of these statistics is described in full within Section 6.

5.2. Condition results

5.2.1. Coral Condition

For benthic analysis, data were available for 28 sites, although timeseries was only available for seven sites.⁶ To provide a consistent comparison over time, statistics were derived from seven sites. The average coral cover for Laamu Atoll changed between 2019 and 2024 (Table 5.4). In 2019, the substrate was dominant (75%), while live coral covered 18% of the reef, with low levels of macroalgae (1%). In 2024, live coral cover was higher in sites at 20%, which reflects variability in areas sampled within sites. While coral remained the same, observed macroalgae increased from 1.4 to 13%.

For coral health indicators, all 28 sites were used. The percentage of dead coral decreased from 4.9% in 2019 to 1.5% in 2024, indicating a positive trend in coral survival (Table 5.5). Coral health statistics, aggregated across 28 surveyed sites (nested within the overall survey areas presented in Annex). However, a coral bleaching event increased bleaching from 0.3% in 2019 to 11% in 2024. Diseased corals were only observed in 2022 (at 0.06%).

For commercially important fish (Table 5.6), there was a significant increase in abundance from 4.20 fish per 100 m² in 2021 to 12.30 fish per 100 m² in 2022, and biomass also increased from 1.40 kg to 4.72 kg per 100 m² over the same period. Ecologically important fish families showed a smaller increase in abundance, rising from 10.65 to 13.12 fish per 100 m². However, their biomass dropped substantially from 3.55 kg in 2021 to 0.76 kg in 2022, indicating that while there were more individuals, they were likely smaller in size or of lower mass, which could reflect changes in the health or age structure of these populations.

Table 5.4 Benthic cover (%), aggregated across 7 surveyed sites (nested within the overall survey areas presented in Annex).

Year	Sponge	Macroalgae	Substrate	Soft Coral	Hard coral	Dead Coral	Other
2019	0.39	1.43	75.22	0.06	17.73	4.28	0.58
2021	4.09	6.78	63.71	0.05	22.93	1.36	1.05
2022	5.96	2.31	56.19	0.07	25.90	1.72	7.03
2024	0.68	13.26	47.75	0.39	19.67	1.45	3.01

⁶ Sites assessed: Fushi Kandu, Fonadhoo Outside, Gaadhoo Inside, Gaadhoo Outside, Hithadhoo Corner, Laamafaru Haa, Maabaidhoo Inside

Table 5.5 Coral health statistics, aggregated across 28 surveyed sites (nested within the overall survey areas presented in Annex).

Year	Metric	Average % (\pm SD)
2019 (n = 19)	Dead	4.90 (12.48)
	Diseased	0.00 (0)
	Bleached	0.34 (2.44)
2021 (n = 6)	Dead	1.11 (4.08)
	Diseased	0.00 (0)
	Bleached	0.04 (0.48)
2022 (n = 13)	Dead	2.6 (6.05)
	Diseased	0.06 (0.53)
	Bleached	0.83 (3.49)
2024 (n = 12)	Dead	1.45 (0.87)
	Diseased	0.00 (0.0)
	Bleached	10.97 (8.81)

Table 5.6 Summary of commercial and ecologically important fish statistics, aggregated by family across sites sampled in Laamu.

Year	Fish families (by importance)*	Metric	Unit	Average
2019 (n = 20 sites)	Commercial	Abundance	(count / 100 m ²)	13.2
		Biomass	(kg / 100 m ²)	-
	Ecological	Abundance	(count / 100 m ²)	9.87
		Biomass	(kg / 100 m ²)	-
2021 (n = 14 sites)	Commercial	Abundance	(count / 100 m ²)	4.20
		Biomass	(kg / 100 m ²)	1.40
	Ecological	Abundance	(count / 100 m ²)	10.65
		Biomass	(kg / 100 m ²)	3.55
2022 (n = 15 sites)	Commercial	Abundance	(count / 100 m ²)	12.30
		Biomass	(kg / 100 m ²)	4.72
	Ecological	Abundance	(count / 100 m ²)	13.12
		Biomass	(kg / 100 m ²)	0.76

* *Commercially important families: Carangidae* (jacks and trevallies), *Lethrinidae* (emperor fishes) *Lutjanidae* (snappers), *Serranidae* (grouper), and *Siganidae* (rabbitfishes); *Ecologically important families: Acanthuridae* (surgeonfishes), *Balistidae* (triggerfishes), *Pomacanthidae* (angelfishes), *Scaridae* (parrotfishes), *Chaetodontidae* (butterflyfishes) and *Haemulidae* (sweetlips).

5.2.2. Seagrass Condition

In August 2023, a total of six seagrass species were observed across 28 sites (Table 5.7), namely *Cymodocea rotundata* (Cr), *Halodule uninervis* (Hu), *Halodule pinifolia* (Hp), *Syringodium isoetifolium* (Si), *Thalassia hemprichii* (Th), and *Thalassodendron ciliatum* (Tc) (see Appendix). The most common species found across all research sites were *Thalassia hemprichii* and *Cymodocea rotundata*. The study site exhibited a high prevalence of this seagrass species, which is present throughout the seagrass ecosystem.

Seagrass cover at Lamuu Atoll sites ranged between 7%–76% (Figure 5.9). The highest value of seagrass cover was found in North-east Dhanbidhoo (76%), while the lowest was found in West Berasdhoo (7%). *Thalassia hemprichii* had the highest value of seagrass cover across all study sites. *T. hemprichii* is a dominant tropical species in the Indo-Pacific region, including Lamuu Atoll. It grows mainly in sandy sediment or coral substrate and can adapt to various aquatic environmental conditions despite being a persistent group of seagrasses (Kilminster et al. 2015). The highest *Thalassia hemprichii* coverage was found in East Fonadhoo with 64%, followed by North Kalhaidhoo (59%) and South-east Kunahandhoo (59%).

The seagrass density in the Laamu Atoll varies from 11 to 844 stands/m². South Maavah had the highest seagrass density, at 844 stands/m². Meanwhile, the lowest seagrass density was in West Berasdhoo, with 11 stands/m². The average seagrass density from 25 sites was 227 stands/m². Variation in seagrass density is driven by topography, physical condition, the activity of coastal communities around the seagrass beds, and seagrass adaptation (see Appendix).

Thalassia hemprichii had the highest average seagrass density across sites, at around 104 stands/m², followed by *Cymodocea rotundata* and *Syringodium isoetifolium* at around 44 stands/m². These seagrass species have a wide coverage area in Laamu Atoll due to their ability to tolerate various water conditions. It is assumed that the observed substrate, which is sandy and away from local settlement activities, contributes to this phenomenon. Multiple factors, including the type of seagrass, substrate conditions, seasons, tides, wave energy strength, the content of organic matter in the sediment, and other environmental factors, influence the density of seagrass stands (Short and Cole, 2001). The observation station recorded a low density of the seagrass species *Halodule pinifolia*, *Thalassodendron ciliatum*, and *Holodule uninervis*. This is due to their ability to adapt to various environmental conditions, preventing one species from being dominant.

The frequency of seagrass is the magnitude of its presence in a community or ecosystem. The more certain species in a sample plot, the greater the frequency of that plant. Species with a high frequency generally have greater adaptability to environmental factors. The highest frequency of seagrass was recorded as 38 in South Maabaidhoo, and the lowest recorded frequency was nine at West Gan 1. Regarding species cover and density, *T. hemprichii* has the highest frequency value compared to other seagrass species. This highly adaptable species can grow and reproduce on sand substrates in coastal and even deep waters (Waycott et al., 2004). In the meantime, *H. pinifolia* seagrass has only been found on the Kalhaidhoo, Maabaidhoo, Berasdhoo, Gan, and Kunahandhoo islands. As a pioneer seagrass, *H. pinifolia* frequently coexists with *C. rotundata*, *T. hemprichii*, and *T. ciliatum*, making it the least common seagrass species (Longstaff & Dennison, 1999).

Table 5.7 List of seagrass species observed in Laamu Atoll, Maldives. Species photos provided in Annex.

Location	Seagrass species*					
	Cr	Hp	Tc	Th	Si	Hu
Kalaidhoo	+	+	+	+		
Dhanbidhoo	+		+	+		
Maabaidhoo	+	+	+	+	+	
Mundoo	+		+	+	+	
Kalhaidhoo	+		+	+	+	+
Berasdhoo	+	+	+	+	+	
Gan	+	+		+	+	
Fonadhoo	+		+	+		
Gaadhoo	+		+	+	+	
Hithadhoo	+		+	+		
Kunahandhoo	+	+	+	+		
Maavah	+			+	+	

*Cr = *Cymodocea rotundata*, Hp = *Halodule pinifolia*, Tc = *Thalassodendron ciliatum*, Th = *Thalassia hemprichii*, Si = *Syringodium isoetifolium*, Hu = *Halodule uninervis*

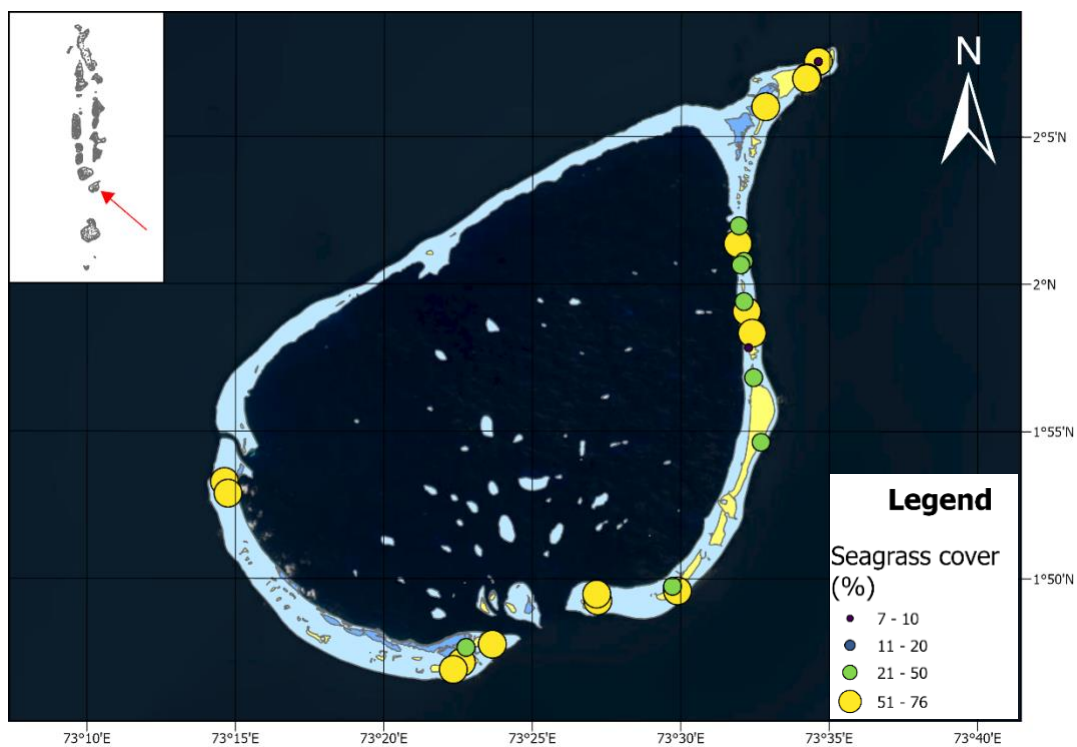


Figure 5.9 Map of seagrass coverage (%) within sampled seagrass meadows of Laamu Atoll, Maldives.

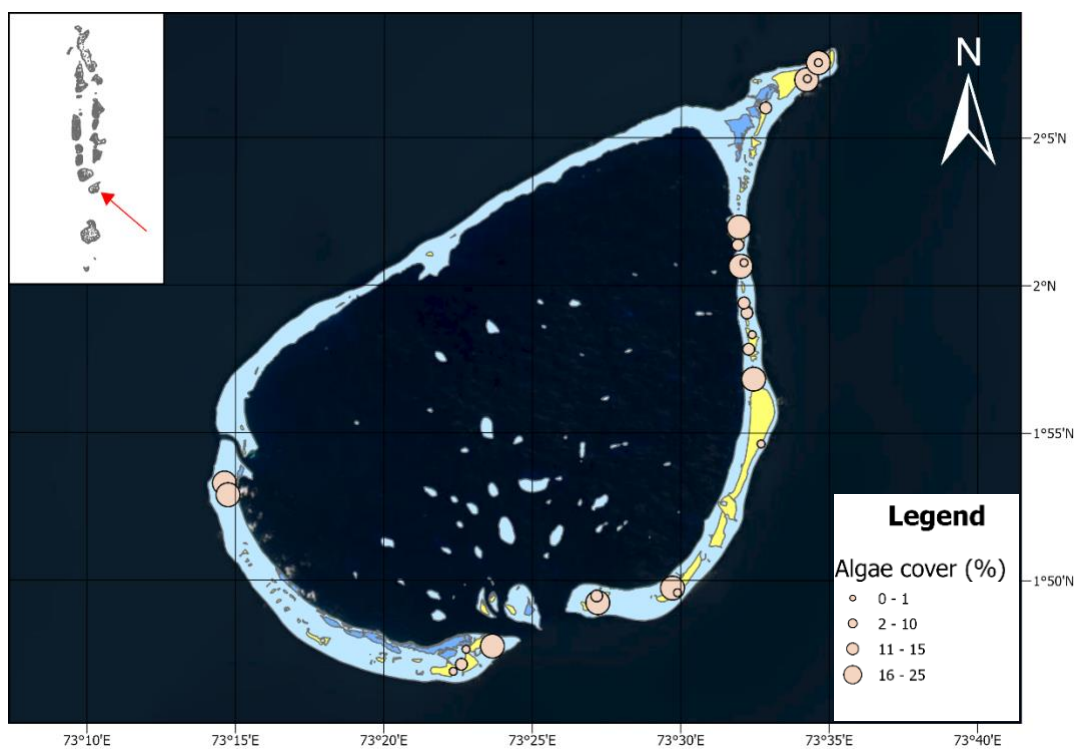


Figure 5.10 Map of average algae coverage (%) within sampled seagrass meadows of Laamu Atoll, Maldives.

This study assessed the health status of seagrass using the Seagrass Ecological Quality Index (SEQI). SEQI is calculated by considering the parameters of the quality of the aquatic environment at each location represented by islands. The seagrass ecosystem in Laamu Atoll is categorised into a medium category, with a range of the SEQI between 0.571 and 0.715 (Figure 5.11). Maavah Island has the highest SEQI value, while Fonadhoo Island has the lowest. The SEQI reflects the balance between seagrass and competing algal and epibenthic cover. In general, seagrass was healthy across Laamu Atoll.

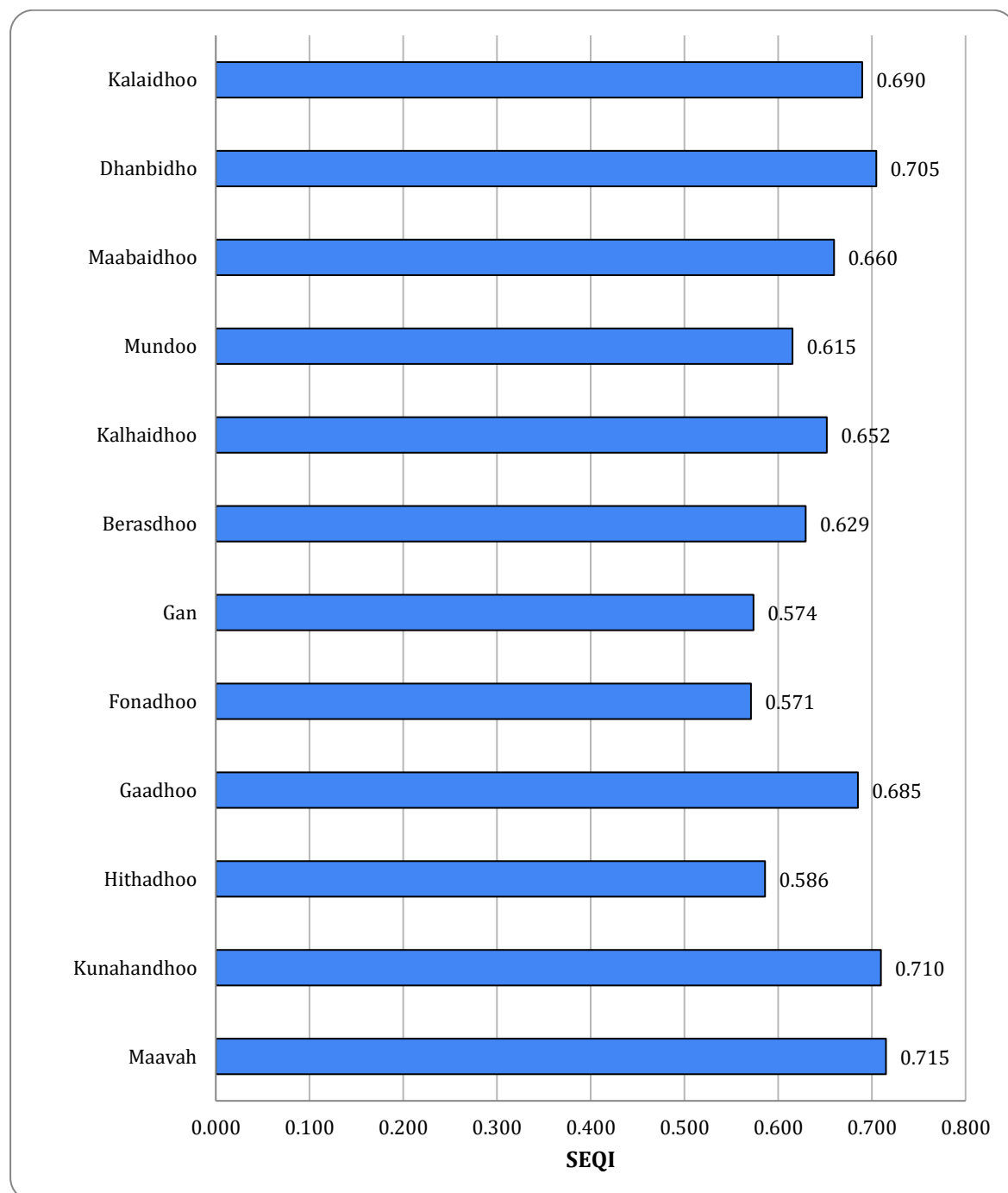


Figure 5.11 Seagrass ecological Index (SEQI) in Laamu Atoll, Maldives.

Table 5.8 Average ecological indicators per seagrass species across Laamu Atoll. Estimated biomass derived from allometric equations by Viera et al. (2018).

Species	Density	Avg. Cover (%)	Avg. Leaf (cm)	Estimated biomass (g)	AGC (gC m ⁻²)	BGC (gC m ⁻²)	Totals (gC m ⁻²)
<i>Cymodocea rotundata</i>	44.48	11	8	7032.40	452.92	1526.93	1979.85
<i>Halodule pinifolia</i>	18.32	2	1	10371.43	661.85	2251.91	2913.76
<i>Thalassodendron ciliatum</i>	15.84	7	3	11053.69	704.23	2400.82	3105.05
<i>Thalassia hemprichii</i>	103.84	29	11	4851.01	315.91	1054.83	1370.74
<i>Syringodium isoetifolium</i>	43.8	4	4	7080.02	456.19	1536.55	1992.74
<i>Holodule uninervis</i>	0.48	0	0	51123.00	3206.63	11114.32	14320.95

5.2.3. Mangrove Condition

Mangroves were identified in several locations in Laamu Atoll, including Maavah, Hithadhoo, Maabaidhoo, and Gan. As the only true mangrove forest (> 50% composition), observations were made using the quadrat plot method in Hithadhoo. In Maavah and Maabaidhoo, due to the small mangrove area, the species and count were noted (Table 5.9). Mangrove affiliated species were also recorded (Table 5.10).

Hithadhoo Island hosts a large, semi-enclosed mangrove at the southern corner of the island. *Rhizophora mucronata* dominates in the centre of the mangrove area and was interspersed with *Ceriops tagal*, while *Lumnitzera racemosa* and *Derris trifoliata* were observed at the edge of the mangrove area. The site was segmented into two plots (high and low density, Figure 5.12). The average tree count, height and basal area were for Hithadhoo were 22.5, 3.7 m and 1051 cm, respectively. The average canopy cover for low- and high-density segments were 72% and 14%, respectively (Table 5.11).

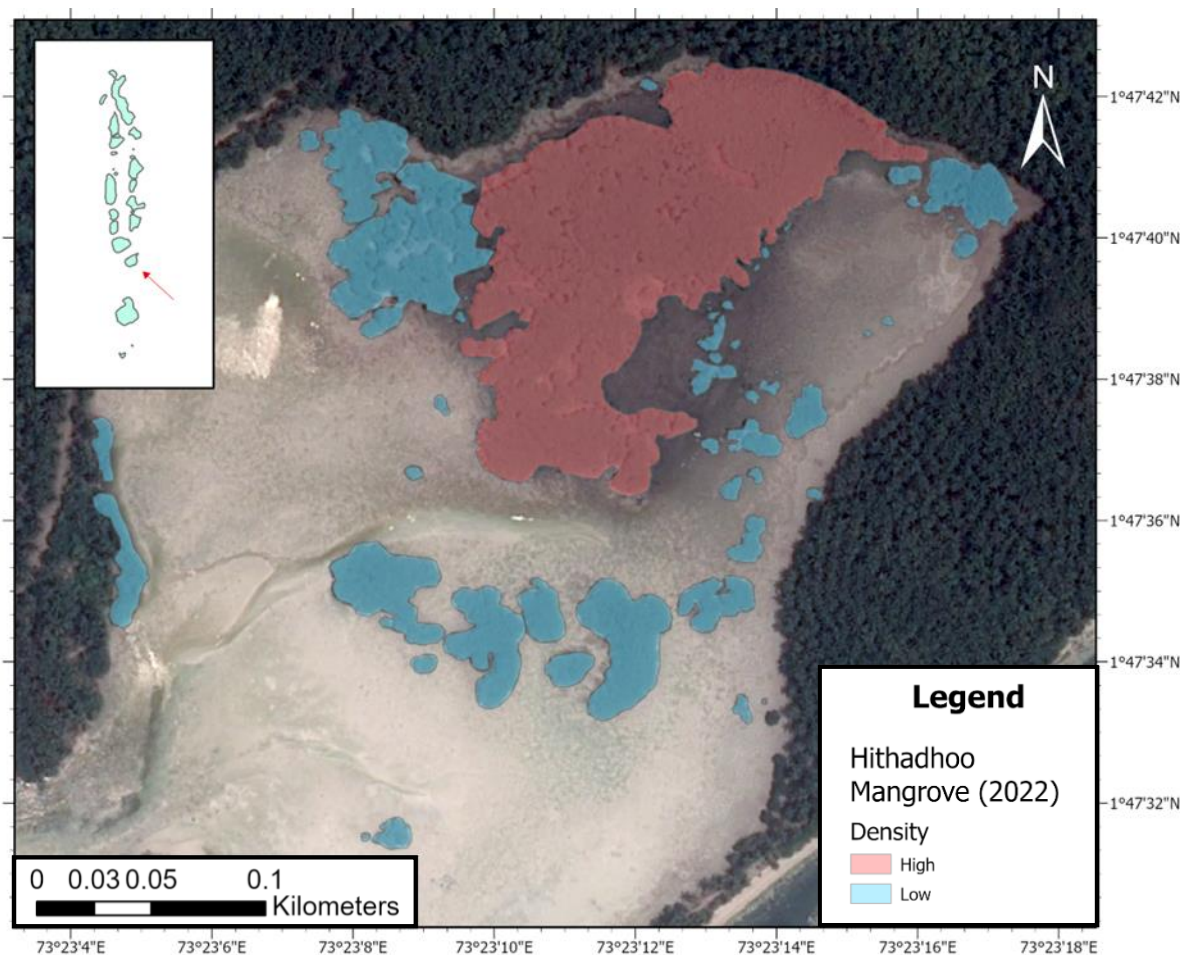


Figure 5.12 Hithadhoo mangrove, showing high- and low-density plots.

Isolated mangrove trees were identified in several areas, including:

- Maabaidhoo Island hosts a large semi-enclosed area that contains transplanted mangroves. The native mangrove-associated *Pemphis acidula* was dominant along the island. Local elicitation indicated that mangroves were planted around 2017, with the propagules originating from Hithadhoo.
- In Maavah, only eight mangrove trees were found remaining, after clearing of the forest into agricultural land. Local people blocked the mangrove area from exchange with the ocean, leading to fresh-water stagnation, which created conditions unsuitable for mangrove forests. The area was replaced with bananas, coconuts, taro, corn, chilli, and other crops. Mangrove associates were present around the periphery of the area.
- Gan's mangroves were found at Boda Fenganda. In this area, *Brugueira gymnorhiza* was dominant. A small brackish water lake surrounding the heavy density of *B. gymnorhiza* has an average height of less than 25 m. Abundant mangrove seedlings and saplings were found under the giant trees of *B. gymnorhiza*.

Table 5.9 General information on mangrove ecosystem in sites survey.

No	Site Name	Genus	Species	Common Name	Divehi Name	Number estimated
1	Hithadhoo	Rhizophora	<i>R. mucronata</i>	Red mangrove	Randoo	See Table X
		Ceriops	<i>C. tagal</i>	Yellow mangrove	Karamana	
		Lumnitzera	<i>L. racemosa</i>	Black mangrove	Burevi	
		Derris	<i>D. trifoliata</i>	Mangrove vine	Thelaviyo	
2	Maavah	Sonneratia	<i>S. caseolaris</i>	Mangrove apple	Kulhavah	1
		Rhizophora	<i>R. mucronata</i>	Red mangrove	Randoo	1
		Brugueira	<i>B. cylindrica</i>	Small-leafed orange mangrove	Kan'doo	4
		Lumnitzera	<i>L. racemosa</i>	Black mangrove	Burevi	2
3	Maabaidhoo	Ceriops	<i>C. tagal</i>	Yellow mangrove	Karamana	5 trees
		Rhizophora	<i>R. mucronata</i>	Red mangrove	Randoo	24 sapling, 54 seedlings
		Phempis	<i>P. acidula</i>	Shrubby coral	Kuredhi	
4	Gan	Brugueira	<i>B. gymnorhiza</i>	Large-leafed orange mangrove	Bodavaki	

Table 5.10 General information of mangrove-associated/coastal vegetation present in Hithadhoo, Maavah, Maabaidhoo, and Gan.

No	Mangrove Association	
	Botanical Name	Divehi Name
1	<i>Scaevola taccada</i>	Magoo
2	<i>Barringtonia asiatica</i>	Kinbi
3	<i>Pandanus sp.</i>	Kashikeyo
4	<i>Hibiscus tilliaceous</i>	Dhiggaa
5	<i>Phempis acidula</i>	Kuredhi
6	<i>Thespesia populnea</i>	Hirundhu

Table 5.11 Estimated valuables for two segments within Hithadhoo mangrove.

Year	Plot	Species	No. Seedling	No. Sapling	No. Trees	Avg tree height (m)	Basal Area (cm ²)	Species density (Ind/Ha)
2023	High Density (n = 2)	R. mucronata	2	8	22	6.0	800	2200
		C. tagal	0	0	2	3	49	200
	Low density (n = 6)	R. mucronata	0	0	5	3.3	208	500
		C. tagal	2	2	16	2.5	1045	1600
2024	High Density (n = 2)	R. mucronata	0	1.5	39	4.9	750	3900
		C. tagal	2	0	6	3.5	57	600
	Low density (n = 6)	R. mucronata	3.7	0	4.2	3.2	208	420
		C. tagal	0	1.5	6	1.4	1045	600

5.2.4. Biophysical Condition

Chlorophyll-a values in Laamu Atoll ranged from 0.001 to >0.19 mg/m³. In the 2017 and 2020 north-east monsoon seasons, the highest chlorophyll-a concentrations were found in the south-east to south-west and northern parts of Laamu Atoll, with the pattern then spreading evenly over the entire region of Laamu Atoll (Table 5.12).

Areas with chlorophyll-a concentrations >0.19 mg/m³ were identified in the shallow waters surrounding the islands in Laamu Atoll. Shallow waters receive nutrients from islands and experience greater sunlight intensity than the deeper waters.

SST in Laamu Atoll varied by season and location. During the northeast and southwest monsoon seasons in 2017 and 2020, SST was approximately 29°C in different parts of the atoll. Ocean currents, solar radiation, and atmospheric conditions drive SST variations.

Table 5.12 Biophysical conditions in 2017 and 2020, compared to reference level.

Variable	Unit	Reference Level	Year	Ecosystem assets					Average
				Coral	Seagrass	Mangrove	Macroalgae	Other Substrate	
Eutrophication	Chlorophyll-a (mg/m3)	-	2017	0.20	0.23	0.24	0.18	0.23	0.22
			2020	0.20	0.23	NA	0.20	0.23	0.21
Temperature	°C	28.0 - 29.7*	2017	31.14	31.29	NA	28.29	30.82	30.38
			2020	28.37	29.31	NA	NA	28.19	28.62

5.3. Condition account

Condition indicators across the three ecosystems were compiled and recorded. The account shows changes in indicators which may represent ecosystem health, which may indicate anthropogenic pressures or natural factors. This may assist in evaluating the effectiveness of conservation measures or policy interventions. As available data were not aligned across all years, an opening and closing accounts was not possible. Instead, the account provides an overview for years with data available.

For coral reefs, the live cover percentage increased significantly from 17.44% in 2019 to 30.14% in 2022, although the increase in 2022 was due to site selection. Bleached and diseased coral remained marginal across the account. The fluctuations in fish biomass may indicate changes in reef functionality, although a longer time series is needed.

For mangroves, marginal changes in tree height and basal area also indicated the influence of plot selection, as ecosystem extent increased. Seagrass live cover decreased marginally from 53.98% in 2023 to 51.29% in 2024, while epibenthic cover increased from 10.51% to 13.42%, indicating a shift in the benthic community composition. These variations could result from seasonal patterns or altered ecological conditions. The data emphasizes the need for established long-term monitoring plots to ensure consistent analysis and accurate interpretations of ecosystem trends. Such plots would allow researchers to disentangle natural variability from anthropogenic impacts, providing a robust basis for evidence-based conservation and management strategies.

Table 5.13 Condition account for mangrove, seagrass and coral reefs of Laamu Atoll. *Difference due to site selection.

Entry	Units	2019	2020	2021	2022	2023	2024
Coral reef							
Live cover	%	17.44	-	22.93	25.90	-	19.67
Bleached	%	0.34	-	0.04	0.83	-	10.97
Diseased	%	0	-	0	0.6	-	0
Fish biomass (commercial families)	Kg / 100 m ²	-	-	1.4	4.72	-	-
Fish biomass (ecological families)	Kg / 100 m ²	-	-	3.55	0.76	-	-
Mangrove							
Average tree height*	m	-	-	-	-	4.5	4.05
Basal area*	cm	-	-	-	-	529	479
Above ground biomass	Mg	-	-	-	-	168.90	168.45
Below ground biomass	Mg	-	-	-	-	185.47	184.66
Seagrass							
Live cover	%	-	-	-	-	53.98	51.29
Epibenthic cover	%	-	-	-	-	10.51	13.42

*Dominant mangrove species - *Rhizophora mucronata*

6. Ecosystem service accounts

Each ecosystem asset supplies one or more ecosystem services that benefit economic and other human activities. Ecosystem services accounts record the flows of ecosystem services supplied by ecosystem types and used by economic units during an accounting period. In ecosystem accounting, ecosystem services are considered revealed transactions or exchange, and, thus, recording supply as equal to use.

In many cases, ecosystem services will contribute to benefits in combination with other inputs such as labour and produced capital. SNA benefits can be seen as resulting from a joint production process involving ecosystems and various other inputs including produced assets and labour. Ecosystem accounting aims to **isolate and record** the ecosystem's contribution to the benefits received. The SEEA EA distinguishes between:

- **final ecosystem services** (where the user of the service is an economic unit), and
- **Intermediate services** are those ecosystem services in which the user of the ecosystem services is an ecosystem asset and where there is a connection to the supply of final ecosystem services.

In some cases, the ecosystem services will be an indirect contribution to benefits, for example, where the nursery population services supplied by seagrass meadows are an input to the supply of fish biomass provisioning services, which in turn contribute to the benefit of marketed fish. In this case, the nursery population service is treated as intermediate while the biomass provisioning service is final.

Key considerations include:

- Use of final ecosystem services is attributed to economic units (business, government, households) or non-resident economic units (exports).
- For any single transaction of an ecosystem service (i.e., where there is a supply-use pair) the magnitude of the flow will be the same for both supply and use in terms of quantity and monetary value.
- The relationship between the supply of ecosystem services and the use of ecosystem services will not always be from one ecosystem asset to one economic unit or user. In some cases, ecosystem services will be supplied through a combination of ecosystem assets, and, in other cases, one ecosystem service will be used by different economic units.

6.1. Wild fish provisioning

According to the SEEA-EA (2021) definition "Wild fish and other natural aquatic biomass provisioning services are the ecosystem contributions to the growth of fish and other aquatic biomass that are caught in uncultivated production contexts by economic units for various uses, primarily food production. This is a final ecosystem service." Wild fish and other natural aquatic products provisioning service is supplied by marine ecosystems in the Maldives, particularly coral reefs. According to MBS (2019), 7.4% of all Maldivians primary activity was agriculture, forestry and fishing (13428 jobs).

The ecosystem service is expressed in gross tonnes of fish harvested. The economic benefits from these services are the catch of aquatic products, including finfish and shellfish (e.g., lobster). These benefits result from a joint production process, where the role of the ecosystem in supplying the biomass intersects with the activity (and associated human inputs like labour and fishing vessels) of people and economic units. The beneficiaries are the local fisheries industry, which is one of the main economic activities in Laamu Atoll alongside tourism and agriculture.

6.1.1. Physical value

A variety of data sources and approaches are available to quantify the physical stocks and flows associated with the provisioning service of fisheries biomass in the Maldives. Each approach has its own uncertainties and different costs associated with data collection and maintenance. Data collection of reef fisheries remains problematic, as the reef fishers are not obliged to report their catches. Whilst the total catch of reef fisheries is low compared to the tuna fisheries, it has a substantial value for the local economy and food security. Reef catches, particularly at the household or subsistence level are not collected. Data was sourced from:

- Catch statistics from the Ministry of Fisheries and Ocean Resources, and
- Survey data of catch landed within Laamu Atoll, as surveyed by Maldives Resilient Reefs and reported in Thomas (2022).

The Maldives Bureau of Statistics reports that catch of "other marine fish" (which includes reef fish) has decreased from 6611 (2013) to 194 (2023) metric tonnes (Table 6.1). From the Maldives Statistical Yearbook 2024, there were approximately 3453 fishing trips from Laamu Atoll in 2023, with an average of 44 vessels engaged per month. These reported landings and trips were recorded for catch sold at market or to other firms. These numbers are recognized to be under-reported and may represent the export market of reef fish.

The national statistics were compared with a study by Thomas (2022), who analysed landing data from the artisanal fleet for Laamu atoll between November 2021 and Jan 2022. A resource use survey of Laamu Atoll in 2021 estimated the artisanal fleet to be composed of 228 dinghies (not associated with the tuna industry), with an estimated 499 fishers targeting reef fish (Rees et al., 2021). Most vessels ran on <50 horse-power motors (63%), although 18% of boats possessed <100 HP motors (from a sample of 101 boat owners).

Table 6.1 Reported fish landed in the Maldives for “Other marine fish” between 2013 and 2023, as a percentage of total fish catch. Adapted from MBS (2024).

	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Total catch ('000 metric tons)	130	129	127	129	143	151	135	149	145	155	161
Other marine fish (including reef fish, '000 metric tons)	6.61	7.14	4.42	3.22	2.49	2.83	2.04	1.70	1.45	0.45	0.19
% of total	5.09	5.53	3.48	2.49	1.74	1.87	1.51	1.14	1.00	0.29	0.12

Assuming a linear relationship, the biomass and fishing trips were standardized to 365 days and rounded to the nearest whole number. To estimate the composition of the catch, the percentage of reported catch over a sample of 357 trips was used to disaggregate total catch, using statistics in Table 6.2.

Table 6.2 Landed catch normalized to annual landings for the artisanal fishing fleet of Laamu Atoll, based on data from Thomas (2022).

Port	Biomass (kg)	Fishing trips (#)	Days sampling (#)	Biomass (kg yr ⁻¹)	Fishing trips (# yr ⁻¹)
Maavah	4812.78	77	58	30,287	485
Gan	4581.50	42	93	17,981	165
Maabaidhoo	1574.89	78	94	6,115	303
Maamendhoo	1145.37	137	93	4,495	538
Dhanbidhoo	319.38	68	95	1,227	261
Fonadhoo	198.24	38	94	770	148
Hithadhoo	88.11	16	91	353	64
Grand total	-	-	-	61,228	1964

Table 6.3 Reef fish species landed by the artisanal fishing fleet of Laamu atoll, based on Thomas (2022). Estimated percentage of reported catch determined from a sample of 357 trips (~18% of trips). Local names from Maldives Reef Fishery Management Plan (2020).

Species	Common name	Local name	% reported catch	Estimated catch (kg yr ⁻¹)
<i>Caranx ignobilis</i>	Giant trevally	Muda han'dhi	16	9796
<i>Lutjanus bohar</i>	Red snapper	Raiymas	14	8572
<i>Lutjanus gibbus</i>	Humpback snapper	Ginimas	6	3674
<i>Caranx sexfasciatus</i>	Bigeye trevally	Haluvimas	3	1837
<i>Lethrinus sp.</i>	Emperor species (not specified)	-	3	1837
<i>Lethrinus conchyliaius</i>	Redaxil emperor	Thun raiy filolhu	2	1225
<i>Sphyræna barracuda</i>	Great barracuda	Tholhi ge baavai' thah	2	1225

6.1.2. Monetary value

To estimate the monetary value of fish provisioning on Laamu atoll, **the market price of catch landed (i.e., output value) alone cannot be used**, as the value is based on:

- The value of the fish (i.e., ecosystem service), in addition to
- Operating costs, intermediate consumption, compensation of employees, consumption of fixed capital, return on fixed assets, taxes and subsidies.

There are two recommended methods for the monetary value of the service, namely (1) a market-based quota system and (2) resource rent. The Ministry of Fisheries and Ocean Resources has identified the need for a licensing system, as outlined by the Reef Fisheries Management Plan (2020). The system will require licenses for commercial fishing vessels, processing facilities, and third-party traders handling reef fish. While this licensing framework is primarily designed for fishery management, data collection, and ensuring sustainable practices, it could eventually support the development of a market-based quota system that would provide direct price observations for valuing ecosystem services. However, until such market mechanisms are fully established and generating reliable price data, the **resource rent method remains necessary** for valuing reef fish provisioning services in ecosystem accounts.

Resource Rent calculations

i. Gross Output Value

The total gross output value for catch and price data was estimated, using the physical ecosystem service values for 2021. Landing prices are limited for the reef fishery per species, and a significant amount of the landed catch is consumed or gifted. A value of MVR 40 was used, based on the range of first sale prices tourism industry outside of Male' (MVR 35 – 40).⁷ The total annual revenue was estimated by multiplying catch volumes by price.

Table 6.4. Estimated price per species landed in Laamu Atoll.

Species	Common name	Local name	Reported catch (%)	Estimated catch (kg yr ⁻¹)	Price (MVR kg ⁻¹)
<i>Caranx ignobilis</i>	Giant trevally	Muda han'dhi	16	9796	391,840
<i>Lutjanus bohar</i>	Red snapper	Raiymas	14	8572	342,880
<i>Lutjanus gibbus</i>	Humpback snapper	Ginimas	6	3674	146,960
<i>Caranx sexfasciatus</i>	Bigeye trevally	Haluvimas	3	1837	73,480
<i>Lethrinus sp.</i>	Emperor species (not specified)	-	3	1837	73,480
<i>Lethrinus conchyliatus</i>	Redaxil emperor	Thun raiy filolhu	2	1225	49,000
<i>Sphyrna barracuda</i>	Great barracuda	Tholhi ge baavai' thah	2	1225	49,000
Grand total			46	28166	1,126,640

⁷ Maldives Resilient Reefs (2024) Understanding tourist resort seafood sourcing practices in the Maldives, pg 17

ii. Operational expenses

Operational expenses were calculated from consumables (considered items replaced within 1 year), fuel costs, maintenance and repairs. From consultation, bait is free (or caught during trips), while ice and storage costs are not associated with reef fish (immediate sale or consumption). The list of consumables for reef fishing was sourced from surveys with fishers. The unit costs were identified by fishers or found online (Table 6.12). For fuel costs, data from the fisheries surveys were used, accounting for 234 trips, averaging 3.85 hours. Average diesel price from 2021 used.

Table 6.5. Items consumed and replaced (within 1 year), estimated from advertised prices online. Quantities consumed estimated from surveys.

Article	Unit cost (MVR)	Quantity per year	Cost (MVR)
Gillnet (monofilament, for bait fish)	120	2	240
Fish handling gear	75	12	900
Float buoys set	80	12	960
Rope (mooring and line)	200	2	400
Hook + sinker set	35	18	630
Reel / line	63	8	504
Total per boat			3,634
Total per fleet (84 boats)			305,256

Table 6.6. The estimated fuel price across trips in Laamu Atoll, from fisheries landing surveys.

Trips	Diesel (litres)	Cost (MVR)
Price per trip	20.59	269.68
All trips (n = 1964)	40431.65	529,654.54

The hull maintenance estimate of MVR 13,000 per year reflects a schedule of anti-fouling applications and minor fibreglass patch-ups performed twice a year. This assumes haul-outs coincide with peak marine-growth seasons and small repairs are consolidated into a single annual service or addressed by the boat owner.

Annual engine maintenance was assumed as one comprehensive service (oil and filter change, spark-plug check, lower-unit inspection and impeller replacement). This one-stop service was assumed to include labour and parts, and extra for gasket and small-parts replacement. Gear repair remains explicitly excludes consumable costs (nets, lines, hooks, floats, ice, fuel and bait), covering only the labour and miscellaneous spare parts (e.g., worn reels, damaged rod guides, and broken winch-blocks).

Table 6.7. Estimates of annual boat maintenance and repairs.

Article	Estimated annual cost (MVR)
Hull maintenance	13,000
Engine maintenance	12,000
Gear repair	9,000
Total per boat	34,000
Total per fleet	2,856,000

iii. Labour costs

The cost of crew must be estimated. From local consultation, the most common form is either individual ownership or profit sharing, with the vessel owner distributing the profits to the crew. Reef fishing vessels typically have 2 – 6 people per dinghy. The labour costs were calculated using the assumption of crew numbers as direct wages, accounting for sharing arrangements.

Fishing as a primary and secondary activity of employment varied between 2% and 5% on L. Gan and L. Fonadhoo (Agricultural Survey, 2019), although from local consultation, few reef fishers live on these islands.

From consultation, persons involved in reef fishing only did so for approximately 33% of their available time per year and were involved in other income-generating activities. Thus, wages were calculated with publicly available statistics from 2012 and adjusted for inflation to 2019 to match catch data. An average annual income from fishing of MVR 18,527 was used (representing 33% of activity). From the survey by MRR (2019), there were 499 people involved in the reef fishery, although only 12% were focused on reef fishing (as opposed to targeting pelagic fish), a total compensation value of MVR 1,848,995 was estimated.

Table 6.8. Estimated price per species landed in Laamu Atoll.

	Monthly income (MVR per capita)		Annual income (MVR per capita)	
	Lower bound	Upper bound	Lower bound	Upper bound
2012	1309	1583	15712	19000
2019 (inflation adjusted)	1397	1691	16765	20289
Standardization to salary	4234	5123	50803	61482

iv. Capital costs

The capital cost was determined by combining fixed capital costs and return on fixed capital. Fixed capital costs included the depreciation of vessels and fishing gear, plus a return on fixed capital investment using market interest rates. All fishing vessels within Laamu Atoll were between 6 – 8.5 m, with 50 Hp engine were considered. Larger vessels tended to either host recreational fishing trips or target pelagic fish (c.f. reef fish). Unpowered boats were omitted from analysis. Shore fishing was also omitted, as data was limited. Return on fixed capital was assumed at 4%, leading to an estimated MVR 166,400 for boats and engine, while gear costs were estimated at MVR 552 per boat, and MVR 35328 total.

Table 6.9. Estimated annual depreciation of the Laamu reef fishing fleet. Fleet size estimated from MRR (2022). Depreciation calculated as average over the first 5 years.

Engine (Hp)	Cost (vessel and engine, MVR)	Annual depreciation (%)	Annual Depreciation (first 5 years, MVR)	Fleet size (#)	Annual Fleet Depreciation (average across first 5 years, MVR)
50	65000	6.2	3535.13	64	226248.32

v. Resource Rent

Resource rent was calculated by subtracting all costs against the Gross Output Value.

Table 6.10. Resource rent calculation for reef fishery in Laamu Atoll.

Component	Value (MVR)	Calculation Notes
Total revenue	1,126,640	Sum of (catch volume × first-sale price) for all species
Intermediate costs	2,938,231	Sum of fuel, maintenance, gear, etc.
Gross operating surplus	-1,811,591	Revenue - intermediate costs
Compensation of employees	1,109,397	Number of workers × Alternative wage rate × Days worked
Consumption of fixed capital	513,608	Annual depreciation of vessels and gear
Return on fixed capital	201,728	Value of vessels and gear × return rate
Resource Rent of sector	-3,636,324	Final calculation

The results of the economic analysis suggest a deeply negative resource rent, indicating that the reef fishery appears economically unviable. However, this outcome is likely not a true reflection of the underlying ecosystem service provided by the reef fishery. The fishery is still delivering significant food supplies and livelihoods even while showing no net profit in economic terms. In the reef fishery example, the ecosystem is still producing fish and fishers are harvesting them.

The large discrepancy between revenue and intermediate costs indicates a **significant underreporting of catch volumes**. In small-scale fisheries dominated by vessels under 10 meters, landings often go unrecorded due to informal sales, inadequate monitoring infrastructure, and limited incentives for fishers to report accurately. As a result, the estimated revenue fails to capture the full value of the service provided by the fishery.

Addressing this issue requires targeted improvements in data collection, especially at the community and landing-site level, where most small-scale fishery transactions occur. Policy responses should aim to enhance monitoring systems, support fisher cooperatives, and integrate participatory reporting methods that make it easier and more beneficial for fishers to report catch volumes.

After significant and careful analysis, **we determine that this service is data deficient and cannot be included in the accounts at this time**. If converted to physical values (a highly inaccurate proxy), the negative rent is equivalent to **90 tonnes** of unreported reef fish catch.

6.2. Fisheries nursery service

According to SEEA EA (UN, 2021) definition, “Nursery population and habitat maintenance services are the ecosystem contributions necessary for sustaining populations of species that economic units ultimately use or enjoy, either through the maintenance of habitats (e.g., for nurseries or migration) or the protection of natural gene pools. This service is an intermediate service and may input to a number of different final ecosystem services including biomass provision and recreation-related services. The focus here is on valuation of nursery services that supporting the supply of biomass provisioning services.”

Coral reefs and seagrass meadows provide nursery habitat services that support both commercial and subsistence fisheries for pelagic and reef species in the Maldives. In tropical settings, 37% of commercial species were estimated to move between nursery habitats and coral reefs (Honda et al., 2013).

Nursery habitats provide a range of benefits to juvenile fish, including:

- **Increased survival:** Protection from predators and harsh environmental conditions contributes to higher survival rates for young fish.
- **Enhanced growth:** Abundant food resources and favourable conditions promote faster growth rates.
- **Successful recruitment:** Increased survival and growth in nursery habitats result in a larger number of juveniles reaching adulthood and joining the reproductive population.

To model the ecosystem service, a productivity change method was conducted which estimated the enhancement in density of relevant juvenile fish species. This was then compared to local fisheries information of within Laamu Atoll separately for coral reef and seagrass ecosystems. The evaluation of nursery services relies on two primary categories of metrics. The metrics needed included the enhancement of juveniles, density of observed juveniles in Laamu Atoll, total area of nursery habitat, and connectivity to adult fishing grounds (i.e., export).

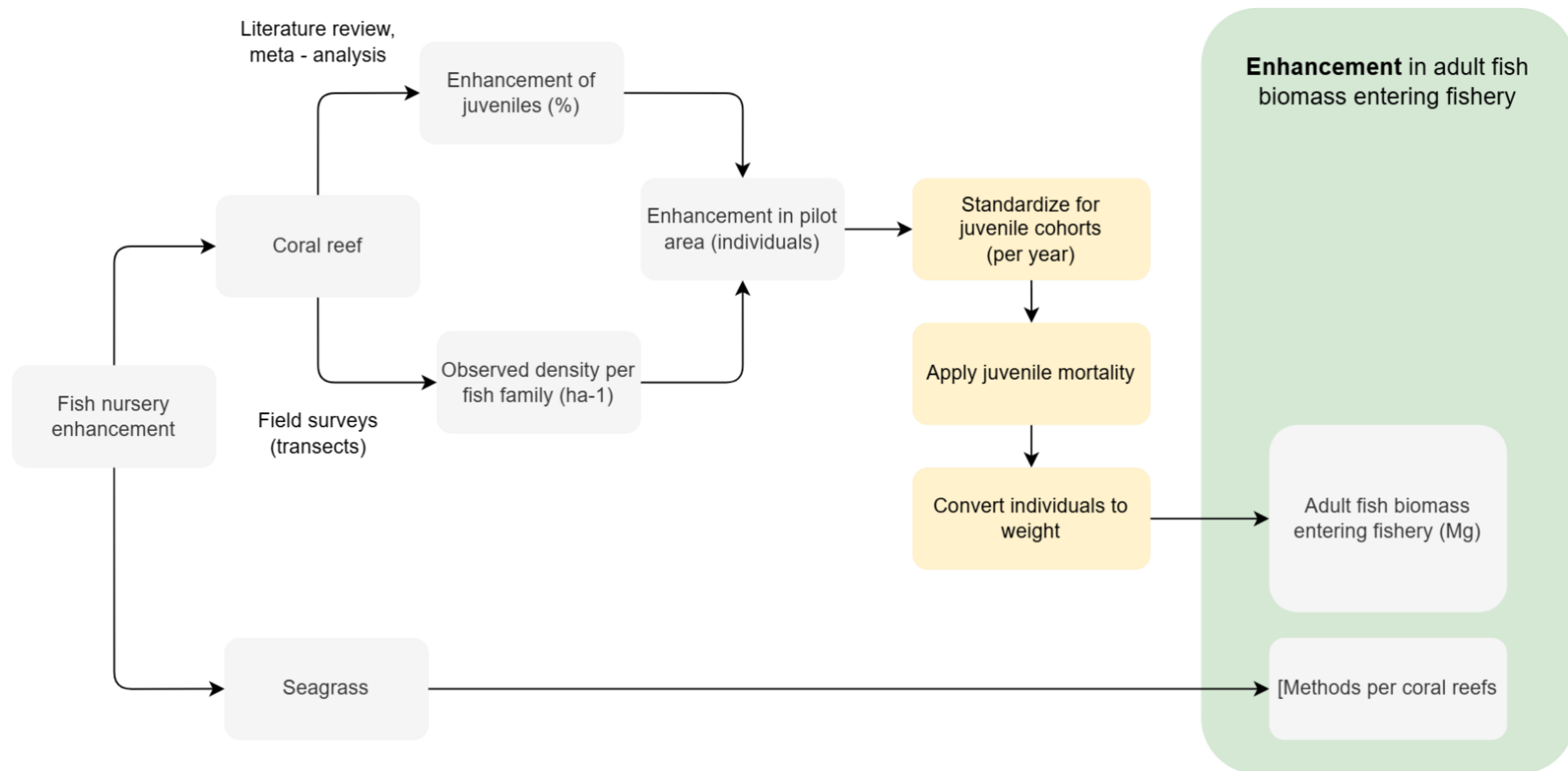


Figure 6.1 Calculation of fisheries enhancement from coral reef and seagrass for a defined period. Yellow boxes indicate assumptions either derived from the literature or expert knowledge.

6.2.1. Density enhancement

Estimating the juvenile nursery services provided by coral reefs is challenging due to the complex and dynamic use of reef habitats by various species throughout their development. Many species transition between different reef sub-habitats, such as starting in shallow back reef areas and later moving to deeper fore reef zones as they mature. Compounding these challenges, coral reefs frequently serve as habitats for both juveniles and adults, leading researchers to underestimate or their critical nursery function.

Relevant fish families identified from Section 8.1 were extracted from a meta-analysis by Lefcheck et al., (2019), which provided estimates of increased fish density relative to unstructured sandy substrate. The following was performed:

1. Relevant fish species from tropical studies were extracted,
2. Data was filtered for habitat categories of interest (seagrass, coral reef and unstructured habitats)
3. The cleaned data was grouped by habitat type, and pooled means are calculated for each habitat using a weighted average of the response means, where weights are based on the sample sizes.
4. Log Response Ratios (LRRs) were calculated from the pooled means per habitat for habitat comparisons (seagrass vs. unstructured; coral reef vs. unstructured).
5. Back-transformation: To improve interpretability, the LRR values are back-transformed to the original scale using e^{LRR} .

The LRR provides a proportional difference between habitats on a logarithmic scale, with positive values indicating a higher response in the first habitat, and negative values indicate a lower response). The LRR was then back transformed to convert the logarithmic ratios into fold-change values, representing the proportional increase or decrease in the response variable, with resulting numbers presented in Table 6.11.

Table 6.11 The change in response (density) between coral and seagrass, against unstructured habitats, based on relevant data filtered from a metanalysis by Lefcheck et al., (2019).

Coral reef vs unstructured		Seagrass vs unstructured	
Log Response Ratio	Fold change	Log Response Ratio	Fold change
0.27	31%	0.12	13%

6.2.1. Observed density

Empirical data was available through Maldives Resilient Reefs, which sampled Hithadhoo, Gaadhoo and Maabaidhoo seagrass. The distribution of coral reefs and seagrass meadows was achieved throughout the extent accounts, using the estimate of 4220 ha of seagrass on Laamu Atoll in 2020 (Table 4.2). The total abundance of juveniles within seagrass was estimated for Laamu Atoll and combined with the estimated enhancement of seagrass

Table 6.12 Juvenile abundance estimates for seagrass meadows of Laamu atoll. Enhancement was estimated at 13%.

Family	Common Name	Abundance ha ⁻¹	Total abundance	Estimated enhancement
Carangidae	Travellys	2.24	7881.74	906.75
Lethrinidae	Emperors	326.63	1146792.45	131931.87
Lutjanidae	Snappers	91.59	321574.79	36995.33
Serranidae	Groupers	43.33	152117.49	17500.24
Siganidae	Rabbitfishes	69.59	244333.79	28109.20

Data for juvenile density on Laamu Atoll was unavailable. A literature review was conducted to extract the density of juvenile fish in tropical coral reefs. The total abundance was estimated using the Extent accounts for Laamu Atoll in 2020 (Table 4.2).

Table 6.13 Juvenile fish enhancement for coral reef species caught on Laamu Atoll, using estimates from literature. Enhancement was estimated at 31%.

Family	Common Name	Abundance ha ⁻¹	Total abundance	Estimated enhancement (individuals)	Publication
Lethrinidae	Emperors	41.11	275108.12	65101.92	Lee & Lin (2015)
Lutjanidae	Snappers	209.68	1403178.56	332049.89	Tupper (2007)
Serranidae	Groupers	160.98	1077278.16	254928.42	Evans et al., (2014)

6.2.2. Export to fishery

The final step is to assess the export of juvenile fish to fishery areas. Several assumptions were performed to simplify estimates, as very few studies provide quantitative estimates of survival and connectivity between nursery systems and fisheries.

1. The estimated juvenile phase per family was identified through the literature. The length of the juvenile phase was used to standardize enhancement to 12 months.
2. The average adult weight per family was estimated through FishBase⁸, using species found on Laamu Atoll,
3. Predation, competition and environmental factors can lead to juvenile mortality of 85 – 99%. Due to the lack of data for Laamu Atoll, a conservative estimate of 95% mortality was assumed.

⁸ FishBase: <https://www.fishbase.org/au/v4>

Table 6.14 Estimate of additional adults entering the fishery due to enhancement from coral reef and seagrass. Mg = Metric ton.

Family	Estimated juvenile phase (months)	Estimated weight (kg)	Seagrass			Coral reef		
			Annual enhancement (Individuals)	Export to fishery (Individuals)	Export to fishery (Mg)	Annual enhancement (Individuals)	Export to fishery (Individuals)	Export to fishery (Mg)
Carangidae	7.5 (3 – 12)	15	1450.80	72.54	1.09	-	-	-
Lethrinidae	12 (6 – 18)	3	131931.87	6596.59	19.79	65101.92	3255.10	9.77
Lutjanidae	15 (6 – 24)	5	29596.26	1479.81	7.40	265639.91	13282.00	66.41
Serranidae	24 (12 – 36)	20	8750.12	437.51	8.75	127464.21	6373.21	127.46
Siganidae	4.5 (3 – 6)	1	74957.87	3747.89	3.75	-	-	-

6.3. Carbon sequestration

Global climate regulation services are related to the contribution of an ecosystem in regulating the chemical composition of the atmosphere and oceans. Of specific interest are the sequestration and capture of carbon and other greenhouse gases (e.g. methane) from the atmosphere into long-term storage. Under the SEEA EA, this is considered a final ecosystem service, where all society could be considered beneficiaries in mitigating the damage caused by climate change.

Global climate regulation services (specifically for carbon) are considered a single service consisting of two components,

- (i) carbon sequestration from the atmosphere into biomass and soils, and
- (ii) carbon retention in long-term storage.

Accounting for carbon sequestration consists of:

1. In physical terms, estimating the gain of carbon entering carbon pools⁹ during the accounting period,
2. performing economic valuation by multiplying this by a suitable carbon price, and
3. turning the economic value into an annual service flow by multiplying the value by a suitable rate of return (to create an annuity).

The SEEA EA frames this component to differentiate the retained carbon stocks that provide a value to society in avoided damages arising from higher levels of carbon in the atmosphere. Thus, in physical terms, the amount stored is a “proxy” for the service flow provided; in monetary units, the service flow is the annual annuity, with higher annuity flows reflecting higher levels of ecosystem service provision. The scope of measurement of carbon retention service is limited to biocarbon in ecosystems (excluding subsoil assets such as oil and gas) and restricted to long-lived biomass (e.g., excluding carbon stored in croplands).¹⁰

Carbon sequestration is measured by the net carbon balance per ecosystem, which accounts for changes to carbon stocks (e.g. land-use change, timber harvest, unmanaged removal) for a given accounting period. The logic for calculation was developed per Figure 6.2.

Notes that data was insufficient to estimate the annual rate of retention of carbon within seagrass meadows into long term storage. This requires coring of these ecosystems and subsequent lab analysis of carbon isotopes and estimation of rate of burial.

⁹ Carbon pool: a reservoir that stores carbon for a certain amount of time. These reservoirs can be living organisms or organic matter in various stages of decomposition (e.g., living biomass, organic matter, soil carbon etc.).

¹⁰ IPCC (2003) Good Practice Guidance for Land Use, Land-Use Change and Forestry, Chapter 3: https://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf_files/Chp3/Chp3_3_Cropland.pdf

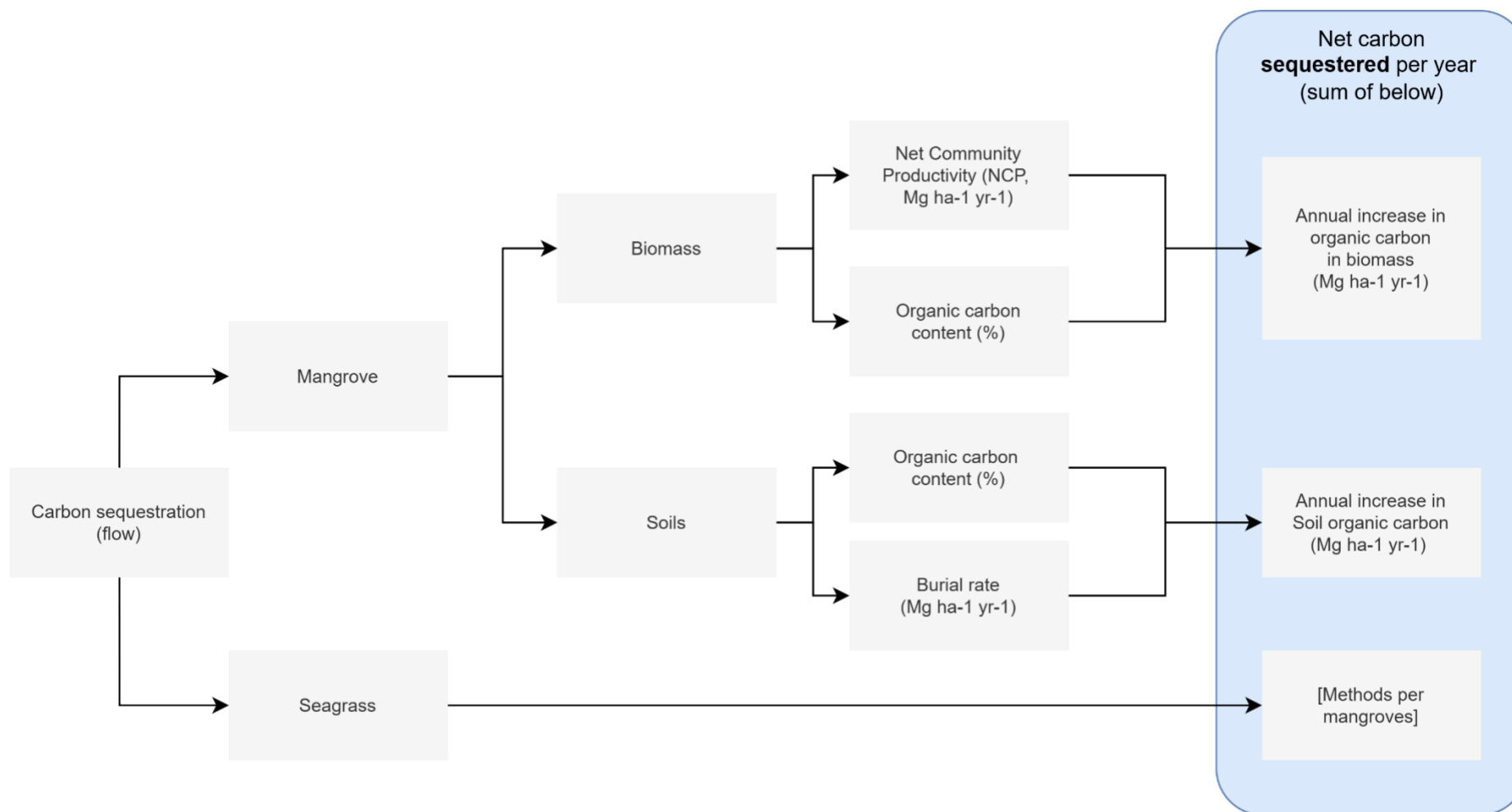


Figure 6.2 Calculation of sequestered carbon into biomass and soils for a defined period.

NCP = the balance between the total amount of organic material produced by photosynthesis (gross primary production) and the total amount of organic material consumed by respiration within a community. * Note carbon retention into long-term storage was not estimated for mangrove and seagrass.

6.3.1. Carbon sequestration

Carbon sequestration in mangrove and seagrass ecosystems was determined by reviewing the scientific literature to determine the amount of carbon sequestered in (i) the biomass, and (ii) adjacent soils for a defined period. Table 6.15 provides the factors for estimating these variables.

Table 6.15 Variables per ecosystem to estimate annual sequestration for mangrove and seagrass.

Variable	Units	Mangrove	Seagrass	Source(s)
Net Community productivity (NCP)	Mg ha ⁻¹ yr ⁻¹	17.23	4.44	Kamruzzaman et al., 2017, Ganguly et al. (2017)
Carbon content (Dry weight)	%	42	35	Kathireasan et al., (2013); Fourqurean et al. (2012)
Organic carbon seq. rate to soils	Mg C ha ⁻¹ year ⁻¹	1.231	0.0945	Yamano et al., 2020; Miyajima et al. (2021)

Table 6.16 Calculation of annual sequestration for mangroves. High resolution satellite was used for ecosystem service calculations.

Year	Mangrove area	Net Community Productivity	Carbon seq. in biomass	Organic Carbon seq. into soil	Total carbon seq.
Units	ha	Mg	Mg C	Mg C	Mg C
2014	2.77	47.72	20.04	3.41	23.45
2016	2.83	48.78	20.49	3.48	23.97
2017	2.84	48.95	20.56	3.50	24.06
2019	2.85	49.03	20.59	3.50	24.09
2020	2.90	50.03	21.01	3.57	24.59
2022	2.93	50.40	21.17	3.60	24.77
2023	2.92	50.31	21.13	3.59	24.72
2024	2.91	50.22	21.09	3.59	24.68

Table 6.17 Calculation of annual sequestration, using an average seagrass cover of 53.98% on Laamu Atoll. *2017 and 2018 uses Sentinel data, while 2018 onwards uses Planet data for mapping sources, which increased accuracy over time.

Year	Seagrass meadow extent	Seagrass area	Net Community Productivity	Carbon seq. in biomass	Organic Carbon seq. into soil	Total carbon seq.
Units	ha	ha	Mg y ⁻¹	Mg C y ⁻¹	Mg C y ⁻¹	Mg C y ⁻¹
2017*	4257.43	2298.16	10203.83	3571.34	217.20	3788.54
2018*	4049.78	2182.47	9690.17	3391.56	206.27	3597.82
2019	3583.61	1931.32	8575.06	3001.27	182.53	3183.80
2020	3894.86	2098.94	9319.29	3261.75	198.37	3460.12
2021	3628.47	1956.00	8684.64	3039.62	184.86	3224.49
2022	3473.50	1872.36	8313.28	2909.65	176.96	3086.60
2023	3511.98	1892.43	8402.39	2940.84	178.85	3119.69
2024	3831.21	2064.96	9168.42	3208.95	195.16	3404.11

6.3.2. Monetary valuation

For carbon sequestration, monetary valuation is to measure the economic value of removing and storing carbon dioxide from the atmosphere, thus averting the damages associated with climate change. The following methods could be used:

- 1. Social Cost of Carbon (SCC) / Avoided damage method:** This is central metric represents the estimated economic damages caused by emitting an additional tonne of carbon dioxide into the atmosphere.

In case of carbon retention, it is recommended to apply a SCC, as this aligns with the framing of avoided damages. It considers future costs related to factors such as:

- Agricultural losses due to climate change,
- Losses from coastal flooding and sea-level rise,
- Increased healthcare expenditures due to heat-related illnesses,
- Damage to infrastructure.

The values are based on the discounted costs from adding one tonne of CO₂ over the long term and are sensitive to the discount rate adopted. The value of USD 51 per Mg CO₂ is used by the US government, although a more recent calculation given further data suggests an updated value of USD 185 per Mg CO₂ (Rennert et al., 2022).

- 2. Market-based pricing:** Carbon markets, where carbon credits are traded, provide a price signal for carbon. One credit represents one tonne of CO₂ removed or avoided.

Market prices for carbon credits can be used as a basis for estimating the economic value of sequestration services. For the carbon sequestration component, the use of a compliance market price where available is recommended. In countries with existing markets, the recommendation is to use these prices as “best available estimates”.

In the absence of market-based pricing in the Maldives, SCC was used for years with both mangrove and seagrass data. Given the vulnerability of the Maldives to climate change impacts the updated value of USD 185 per Mg CO₂ was used. Calculated values were adjusted for inflation via the average annual Consumer Price Index (CPI) reported by the World Bank.

Table 6.18 Monetary value of carbon sequestration by mangrove and seagrass for given years. Inflation adjusted to 2024.

Year	Mangrove total seq.	Seagrass total seq.	Total seq.	Monetary value*	Monetary value (Inflation adjusted) [#]	Exchange rate ⁺	Monetary value	Monetary value (Inflation adjusted)
Unit	Mg C	Mg C	Mg C	USD	USD	-	MVR	MVR
2017	24.1	3788.5	3812.6	705331	746789	15.40	10862091	11500549
2019	24.1	3183.8	3207.9	593460	627717	15.40	9139290	9666837
2020	24.6	3460.1	3484.7	644671	691566	15.41	9934387	10657028
2022	24.8	3086.6	3111.4	575604	600589	15.39	8858546	9243060
2023	24.7	3119.7	3144.4	581708	589852	15.40	8958306	9083722
2024	24.68	3404.1	3428.8	634326	634326	15.40	9768622	9768622

*Monetary value estimated using Social Cost of Carbon (at USD 185).

[#]Inflation, consumer prices (annual %) from reported IMF statistics.

⁺Exchange rate from Maldives Monetary Authority, from July each year.

6.4. Coastal protection

The very existence of the islands of the Maldives is fundamentally dependent on coral reef ecosystems and the coastal protection they provide. Coral reefs not only provide continued protection to islands but were also responsible for their formation, as reef-building corals created the structural foundation upon which islands developed through the accumulation of coral sand and debris. All Laamu Atoll's coastline should be considered protected by coral reefs, except where additional protection has been constructed (e.g., seawall and sheet pile).

Coral reefs act as a natural breakwater system where the complex three-dimensional structure of coral and reef framework creates friction that dissipates wave energy as waves move across the reef flat. The shallow reef crest causes waves to break offshore, with studies showing that reef crests can reduce wave energy by 75-95% before waves reach the shoreline. Further, the reef slope from deep to shallow water reduces wave energy through a combination of wave refraction, friction, and breaking, making coral reefs particularly effective at dissipating both normal wave conditions and extreme wave events from storms or tsunamis.

While this makes the absolute value of coral reefs to the Maldives immeasurable, as without them, there would be no homes or infrastructure to protect, pragmatic decision-making requires understanding specific spatial dependencies between infrastructure and their adjacent protective reefs. By examining these spatial relationships and estimating the replacement costs of protection through artificial structures like seawalls, we can provide decision-makers with practical metrics for prioritizing reef conservation and management efforts, acknowledging that these valuation methods do not represent a perfect substitute for all the services and values that coral reefs provide to the Maldives.

6.4.1. Physical value of protection

While detailed hydrodynamic models like SWAN (Simulating WAVes Nearshore) or XBeach can provide precise estimates of wave attenuation by coral reefs, these models require extensive data inputs that may not be readily available across all Maldivian atolls, including high-resolution bathymetric surveys, continuous wave monitoring data, and detailed reef structural assessments.

Instead, a simplified spatial modelling approach was employed to estimate coastal protection services based on readily available remote sensing data. For coral reefs in the Maldives, protection zones were defined as extending up to 100 m inland from the coastline, as coral reefs are adjacent to all coastlines across the atoll. Shorelines with existing protection were removed from analysis (e.g., quaywalls around harbours, seawalls).

The length of 100 m was chosen, as previous studies by David et al. (2021) identified shoreline retreats of 0.26 m and 1.3 m between 2017 and 2019. Given the potential increase in erosion due to loss of the coral structure, an estimated 2 m / yr erosion rate was assumed, considering the service life of a quaywall or sheet piling is 20 – 30 years. This spatial model allows for rapid assessment of protection zones across multiple islands and provides a practical compromise between accuracy and feasibility for national-scale natural capital accounting.

Physical values: number of buildings and length of shoreline protected

The following methods developed through consultation with the Ministry of Climate Change, Environment and Energy, Maldives Bureau of Statistics and local representatives from Laamu Atoll and island councils.

For Laamu Atoll, there are three main beneficiaries of coastal protection, namely:

- Households – through protection of homes and infrastructure,
- Tourism sector – through protection to infrastructure, and
- Industry – particularly the protection of land for the agricultural sector.

The present analysis focused on islands designated as residential or tourism only. Information was not available on the type and market value of the building and number of residents per building. Data were not available to map cropland, which could also be considered for protection.

For residential islands, census blocks maintained by Maldives Bureau of Statistics were used to identify areas requiring protection. Blocks within 100 m of the shore were considered under protection and the adjacent coastline providing protection was measured. For tourism islands, building footprints were used, sourced from the Google Research Open Buildings¹¹ project (v3). The datasets used are listed in Table 6.19. The overarching process is provided in Figure 6.3, followed by an illustrative example (Figure 6.4, Figure 6.5).

Table 6.19 Data sources to calculate coastal protection.

Type of data	Data type	Date(s) of collection	Source
Boundaries of islands in Laamu Atoll	Polygon	2024	MLSA One Map (https://onemap.mv/)
Census boundaries	Polygon	Nov, 2024	Maldives Bureau of Statistics
Building boundaries	Polygon	2021	Google Open Buildings https://sites.research.google/gr/open-buildings/
Buffer of coastline (100 m)	Polygon	-	Generated by consultants
Buildings / Census blocks within buffer	Polygon	-	Generated by consultants
Protected coastline	Polyline	-	Generated by consultants
Quaywall and sheetpile estimates	-	September, 2024	Local consultation with MTCC

¹¹ Available: W. Sirko, S. Kashubin, M. Ritter, A. Annkah, Y.S.E. Bouchareb, Y. Dauphin, D. Keysers, M. Neumann, M. Cisse, J.A. Quinn. *Continental-scale building detection from high resolution satellite imagery*. [arXiv:2107.12283](https://arxiv.org/abs/2107.12283), 2021.

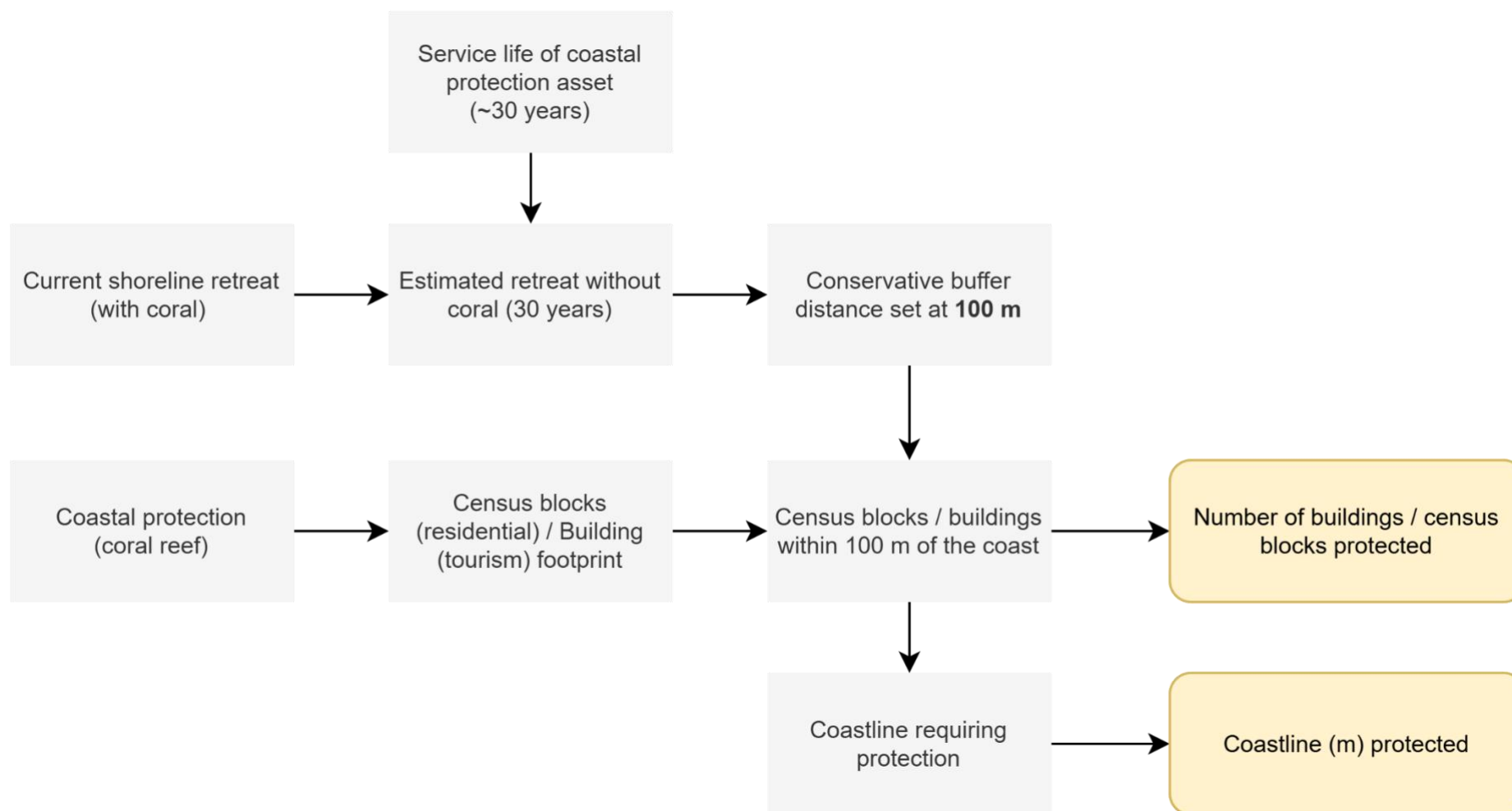


Figure 6.3 Calculation of coastal protection of buildings from coral reefs by number of census blocks / buildings and coastline (m) protected. Census blocks, as defined by Maldives Bureau of Statistics, were used for residential islands. Building footprints were used for tourism islands. Agricultural, mixed use and uninhabited islands were excluded from analysis.

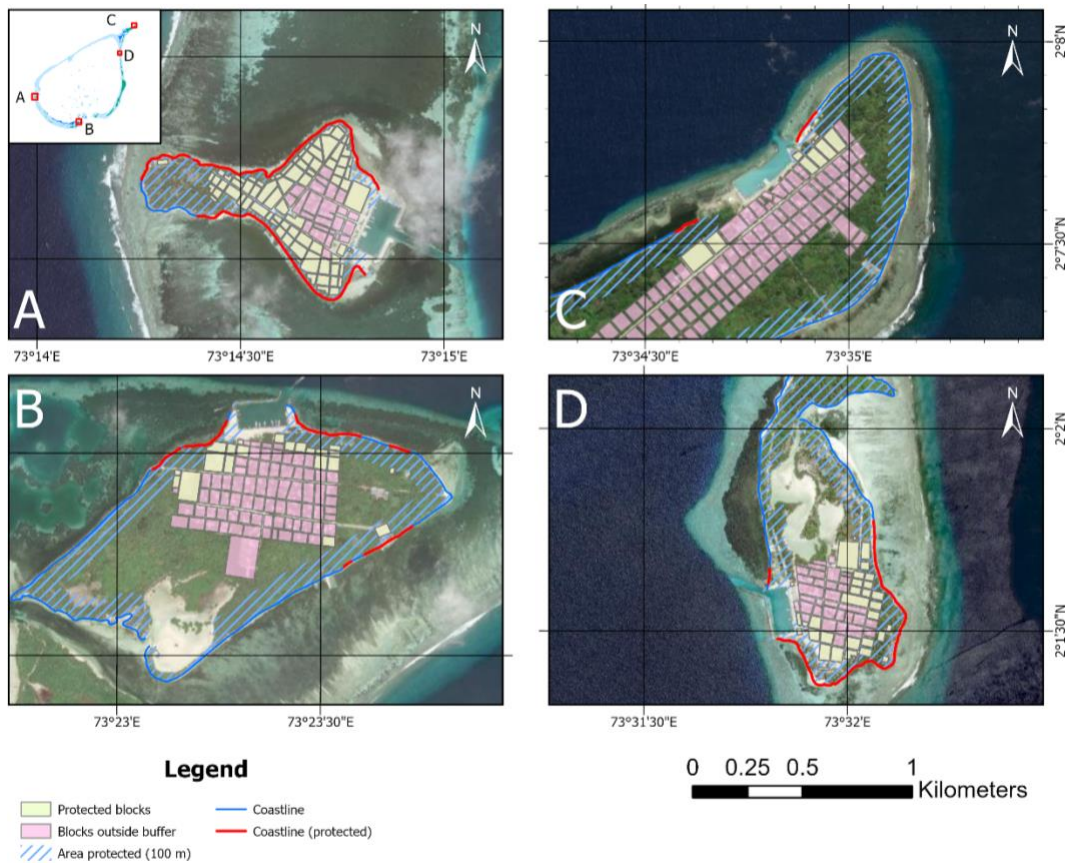


Figure 6.4 Census blocks and length of coastline identified as protected within residential islands, showing (A) Maavah, (B) Hithadhoo, (C) Isdhoo and (D) Maabaidhoo.

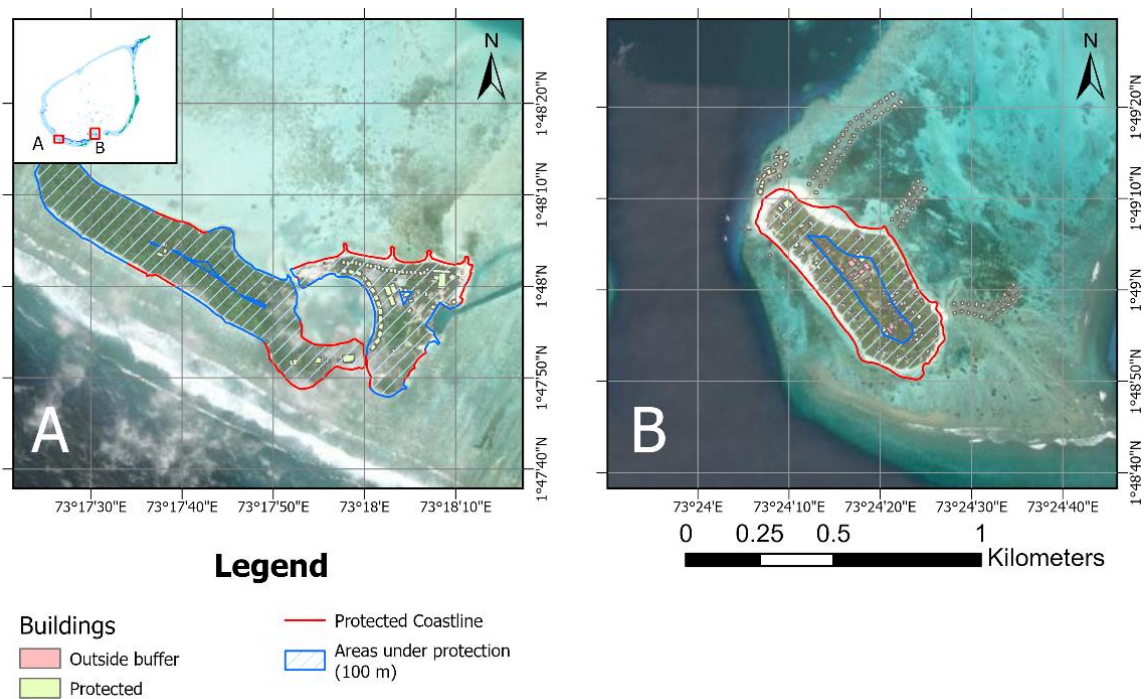


Figure 6.5 Buildings and length of coastline identified as protected within tourist islands, showing (A) Fares, and (B) Olhuvelhi.

6.4.2. Monetary valuation

The **replacement cost** of the service provided by coral reefs is a recommended valuation technique in the UN SEEA EA (paragraphs 9.50-9.51). A model that estimates the value of coastal protection provided by coral reefs was estimated by estimating the cost to build and maintain infrastructure that would provide the same service. The total replacement cost is estimated as the per meter cost of protection construction, multiplied by the length of coastline with buildings that received coastal protection services.

The service replacement cost is estimated as the estimated annual capital depreciation of seawall infrastructure that would provide a similar service. To simplify valuation, a straight-line depreciation model has been assumed, which is calculated as:

$$\text{Annual depreciation} = \frac{\text{Cost} - \text{Salvage value}}{\text{Service life (years)}}$$

Where *Cost* is the initial cost of construction, *Salvage value* is the value of infrastructure materials at end of life, and *Service life* is the years of functionality before replacement.

The following parameters were used for the cost and maintenance of coastal protection assets over their service life, based on informal consultation in 2024 with experts from Maldives Transport & Contracting Company (MTCC), with the mean value used for simplification.

Table 6.20 Cost estimates of by coastal protection type per meter.

	Cost (MVR/m)	Service life	Annual depreciation (MVR/m)
Quaywall	60,000	20-30	2500 (±500)
Sheet pile	170,000	20-30	6,800 (±1700)

We assumed the universal use of sheet pile as the high estimate, and quay wall (similar to seawall construction) as the low estimate. The mean service life of 25 years was used, and it was assumed that there was no salvage value. We recognize that cheaper alternatives may be used, although these methods may not be designed for a long service life with current practices. The USD to Rufiyaa value was set at 15.4 (October 2024), per the Maldivian Monetary Authority. Calculated values were adjusted for inflation via the average annual Consumer Price Index (CPI) reported by the World Bank.

Table 6.21 Physical and monetary value of protection provided by coral reefs for residential and tourism islands. Coastal length protected only accounts for areas with adjacent built assets. #Census blocks were used for residential islands, while buildings were used for tourist islands.

Island type	Island	Physical value		Monetary value (Annual depreciation)		Monetary value (Annual depreciation)	
		Buildings / blocks protected#	Coast length Protected (m)	Quaywall (MVR)	Sheetpile (MVR)	Quaywall (USD)	Sheetpile (USD)
Residential	Dhan'bidhoo	43	2192	5479867	14905238	355836	967873
	Fonadhoo	153	7421	18553490	50465492	1204772	3276980
	Gan	93	7528	18820134	51190765	1222087	3324076
	Hithadhoo	21	1132	2830960	7700212	183829	500014
	Isdhoo	12	636	1589952	4324669	103244	280823
	Kalaidhoo	40	2262	5654438	15380071	367171	998706
	Kunahandhoo	12	650	1624751	4419322	105503	286969
	Maabaidhoo	37	1488	3721066	10121300	241628	657227
	Maamendhoo	69	2111	5278154	14356580	342737	932245
	Maavah	81	2557	6393331	17389860	415151	1129212
	Mundoo	38	1967	4918462	13378216	319381	868715
Tourism	Fares	83	1208	3019033	8211769	196041	533232
	Olhuveli	96	1988	4970371	13519408	322751	877884
Total		778	33142	82854008	225362901	5380130	14633955

6.5. Sediment nourishment

The Maldivian islands are dependent on natural sediment production from surrounding coral reef ecosystems for their physical maintenance and survival. These low-lying coral islands are formed entirely from carbonate sediments, where 50–70%, of sediments are derived directly from the skeletal remains of corals and coralline algae. The remains of these reef organisms are broken down by wave action and biological processes (consumption and release by parrot fish). The calculation of sediment nourishment from coral and seagrass is provided in Figure 6.6.

6.5.1. Coral reef

Ainési et al. 2024 indicates that Maldivian reefs deliver approximately 0.049 cubic meters of sediment per meter of shoreline annually, which maintains beach volumes and island elevations in the face of rising sea levels and other erosional forces.

Table 6.22 Average delivery of sediment ($\text{m}^3 \text{ m}^{-1} \text{ y}^{-1}$), as reported by Ainési et al. 2024.

Island	Average delivery ($\text{m}^3 \text{ m}^{-1} \text{ y}^{-1}$)
Baavanadhoo	0.0391
Boduhini	0.0252
Dhakandhoo	0.0222
Galamadhoo	0.0182
Hulhudhoo	0.0162
Kan	0.0675
Kon	0.0593
Mainadhoo	0.0596
Thiladhoo	0.0550
Vadhoo	0.1295
Average	0.0492

The economic value of this natural beach nourishment process was estimated using **replacement cost**, by comparing natural replenishment to the price of artificial beach replenishment costs in the Maldives. To calculate this, we multiplied the natural annual sediment delivery rate to the entire shoreline length of residential, industrial, tourism and institutional islands and the local cost of beach sand replenishment per cubic meter. We also embedded potential transport costs, as local reefs would no longer be able to provide sediment and erosion issues would worsen.

Sand nourishment per cubic meter was estimated between MVR 30 – 45 in 2005 (Live & Learn, 2006). Using the average, after adjusting for inflation using the consumer price index, the average value per cubic meter was MVR 73.77. However, this estimate does not account for additional costs such as environmental protection measures (silt curtains, settling ponds), particle size sorting and removal of organics. To account for additional costs (including transport), a conservative increase of 40% per cubic meter was applied (MVR 103.28)

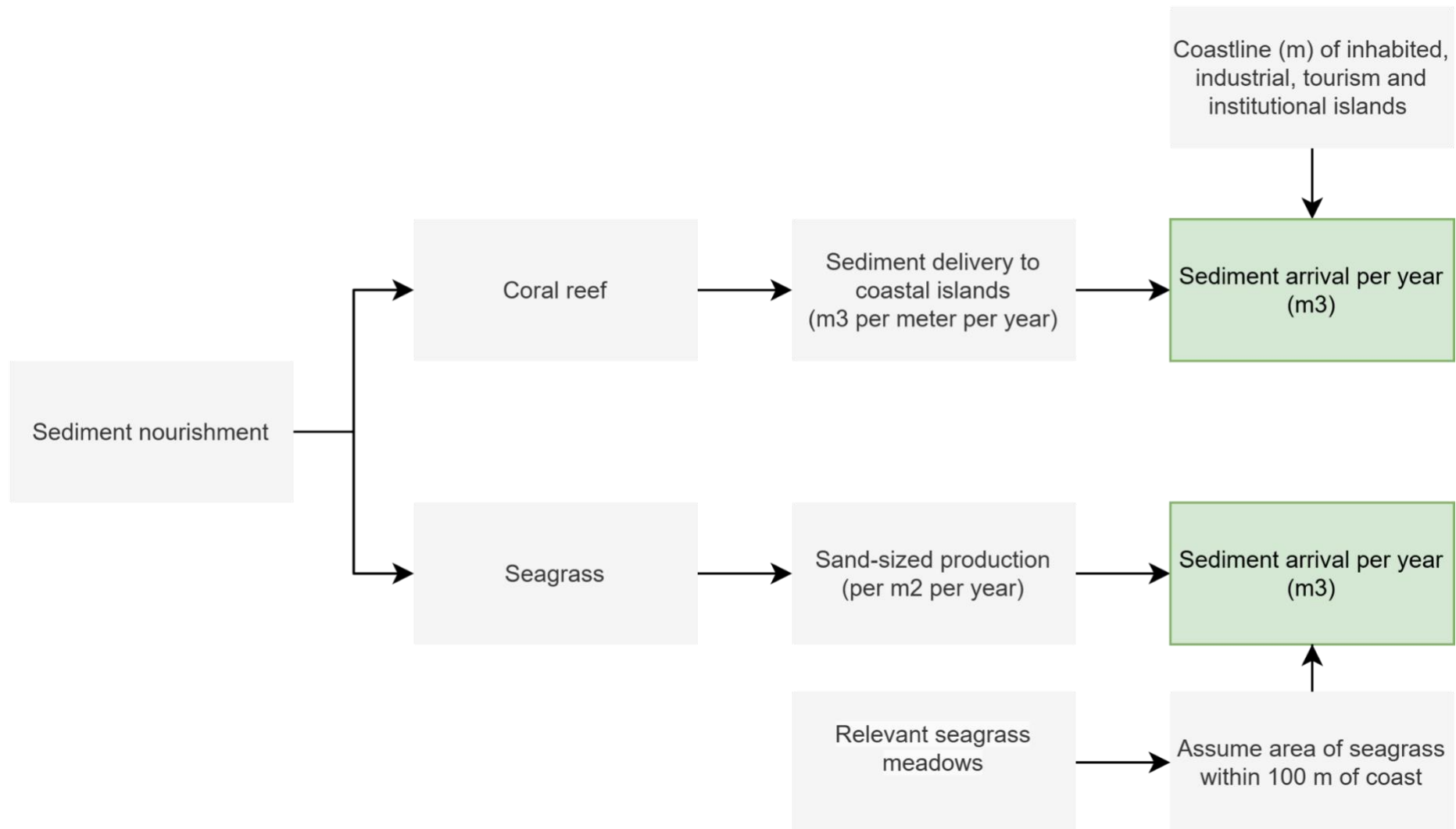


Figure 6.6 Calculation of coastal nourishment from sediments produced by coral and seagrass ecosystems per year.

6.5.2. Seagrass

Seagrass play a less recognized role in sediment production around the islands of the Maldives. These ecosystems contribute to sediment generation by providing habitats for carbonate-producing organisms (“epibiotic organisms” such as benthic foraminifera and crustose coralline algae) that live on seagrass leaves and eventually add to the sediment pool as they dislodge or when the leaves die. This process primarily produces sand- and gravel-sized sediments, which are ideal for island formation due to their stability on reef platforms, unlike finer sediments that are more easily washed away.

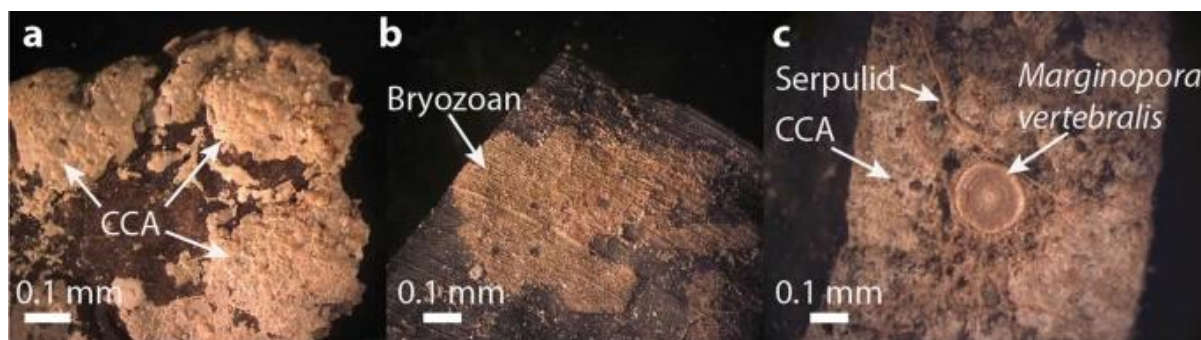


Figure 6.7 Seagrass epibionts in the Maldives, adapted from East et al. (2023).

We calculate the contribution of seagrass ecosystems to sediment generation by estimating:

1. Rates of **sand sized** epibiotic sediment produced per m^2 of seagrass,
2. Annual amount generated per residential, industrial, institutional and tourism island on Laamu atoll, and
3. Assume the amount transported to island coastlines.

Table 6.23 provides the factors from Faathihutta island, Huvadhoo Atoll, were used from East et al. (2023), which aligned with the seagrass cover and species composition collected for Laamu Atoll. Table 6.24 provides the total seagrass coverage % on Laamu Atoll by study species of *Thalassodendron ciliatum* (*T. cillicatum*, “**Tc**”) and *Thalassia hemprichii* (*T. hemprichii*, “**Th**”). This number will be an underestimation since only 2 of the 6 species present on Laamu are calculated. The other species, however, have less potential for epibenthos.

Table 6.23 Factors from East et al. (2023) to estimate sand-sized CaCO_3 production from seagrass.

	Variable	Site Z1a
Zone characteristics	Area (km^2)	0.421
	% Seagrass cover	$61 \pm 3\%$
	% <i>T. ciliatum</i>	$91 \pm 3\%$
	% <i>T. hemprichii</i>	$9 \pm 3\%$
	Leaf density (m^{-2})	$1,937 \pm 98$
Rate sand-sized CaCO_3 production (kg m^{-2} per year), \pm cumulative error	<i>T. ciliatum</i>	0.27 ± 0.05
	<i>T. hemprichii</i>	0.07 ± 0.03
	Total	0.34 ± 0.06

Table 6.24 Percentage cover (%) of all seagrass and percentage of seagrass per Th and Tc species for the 2023 and 2024 sampling campaigns, averaged per island sampled.

Island	2023			2024			Average		
	Seagrass	Th	Tc	Seagrass	Th	Tc	Seagrass	Th	Tc
Berasdhoo	37.02	5.80	22.46	-	-	-	37.02	22.46	5.80
Dhanbidhoo	59.44	0.94	41.88	45.37	4.91	31.11	52.41	36.50	2.92
Fonadhoo	57.35	0.86	56.50	49.35	0.75	55.69	53.35	56.09	0.80
Gaadhoo	72.87	14.05	42.38	-	-	-	72.87	42.38	14.05
Gan	29.07	0.00	19.31	-	-	-	29.07	19.31	0.00
Hithadhoo	52.43	7.83	42.36	67.41	12.59	57.72	59.92	50.04	10.21
Kalaidhoo	69.75	14.26	43.66	85.74	50.74	41.67	77.75	42.66	32.50
Kalhaidhoo	54.52	13.48	17.56	73.33	0.00	43.06	63.93	30.31	6.74
Kunahandhoo	73.04	13.69	59.35	-	-	-	73.04	59.35	13.69
Maabaidhoo	52.14	0.32	20.47	48.80	7.69	44.78	50.47	32.62	4.00
Maavah	60.47	0.00	2.08	39.78	0.05	8.93	50.12	5.50	0.02
Mundoo	45.60	15.93	16.56	50.56	12.22	37.44	48.08	27.00	14.07
Average	55.31	7.26	32.05	57.54	11.12	40.05	56.20	35.25	8.80

To estimate the sediment from seagrass, a conservative approach was taken assuming seagrass within 100 m of the island was contributing to the sediment budget each year. The following were calculated:

- **Coverage of seagrass, by species:** The seagrass cover (%) was used to identify the full coverage of seagrass (as opposed to extent) and then estimated for both Th and Tc species,
- **Sand-sized calcium carbonate production (CaCO₃ production):** Coverage per species was multiplied by production per species at 0.7 and 2.7 Mg Ha⁻¹ per year for Th and Tc, respectively.
- **Cubic meter:** Volume was estimated assuming a density of calcium carbonate is equal to 2711 kg/m³; at 25.2°C.
- **Monetary valuation:** Aligned with coral sediments, a replacement cost of MVR 103.28 m⁻³ was used, with conversion to USD at 15.4 (October 2024).

Table 6.25 Estimates of calcium carbonate production per island, from Th and Tc seagrass. *Volume estimated assuming a density of calcium carbonate is equal to 2711 kg/m³; at 25.2°C. Mg = megagram (1000 kg)

	Meadow extent	Cover (m ²)			CaCO ₃ production (Mg)			Volume* (m ³)
Island	Area (m ²)	All seagrass	Th	Tc	Th	Tc	Total	
Baresdhoo	436847.33	161720.88	36322.51	2106.71	2.54	0.57	3.11	1.15
Bodufinolhu	86709.19	55433.19	16801.80	1132.44	1.18	0.31	1.48	0.55
Boduhuraa	69111.45	18950.36	10221.82	4398.45	0.72	1.19	1.90	0.70
Dhan'bidhoo	512419.90	268559.27	98024.13	2862.30	6.86	0.77	7.63	2.82
Fares	2012.55	551.84	297.66	128.08	0.02	0.03	0.06	0.02
Fonadhoo	1526532.03	814404.84	456799.67	3654.40	31.98	0.99	32.96	12.16
Gaadhoo	689938.39	502758.10	213068.88	29936.18	14.91	8.08	23.00	8.48
Gan	758377.80	220460.43	42570.91	0.00	2.98	0.00	2.98	1.10
Guraidhoo	645.50	323.52	17.79	0.00	0.00	0.00	0.00	0.00
Haiythoshi	31526.38	18890.61	9452.86	965.14	0.66	0.26	0.92	0.34
Hithadhoo	864595.15	552735.68	167534.18	11291.80	11.73	3.05	14.78	5.45
Isdhoo	151688.44	96974.42	29392.95	1981.08	2.06	0.53	2.59	0.96
Kadhdhoo	473758.64	252750.23	141767.61	1134.14	9.92	0.31	10.23	3.77
Kalaidhoo	276804.55	176961.15	53636.92	3615.13	3.75	0.98	4.73	1.74
Kandaru	94866.60	47879.17	15618.19	624.73	1.09	0.17	1.26	0.47
Kudafushi	112601.37	30875.30	16654.13	7166.27	1.17	1.93	3.10	1.14
Kunahandhoo	316665.40	231292.41	137272.04	18792.54	9.61	5.07	14.68	5.42
Maabaidhoo	452067.85	228158.64	74425.35	2977.01	5.21	0.80	6.01	2.22
Maamendhoo	32390.40	20707.18	6276.35	423.03	0.44	0.11	0.55	0.20
Maandhoo	237160.52	68942.56	13312.81	0.00	0.93	0.00	0.93	0.34
Maavah	494889.87	248038.80	13642.13	2.73	0.95	0.00	0.96	0.35
Mahakanfushi	55841.88	16233.23	3134.64	0.00	0.22	0.00	0.22	0.08
Mendhoo	292234.77	186825.69	56626.87	3816.65	3.96	1.03	4.99	1.84
Mundoo	390489.35	187747.28	50691.77	7132.33	3.55	1.93	5.47	2.02
Grand Total	8360175.31	4408174.79	1663563.99	104141.16	116.45	28.12	144.57	53.33

Table 6.26 Natural nourishment from coral reefs per island on Laamu Atoll, in physical and monetary terms. *Relevant seagrass meadows for annual flow were estimated within 100 m of residential and tourism islands. #For islands unsampled by field campaigns, adjacent sampled islands were used.

Island type	Island	Coastline (m)	Natural nourishment from coral			Natural nourishment from seagrass		
			Physical (m ³ y ⁻¹)	Monetary (MVR y ⁻¹)	Monetary (USD y ⁻¹)	Physical (m ³ y ⁻¹)	Monetary (MVR y ⁻¹)	Monetary (USD y ⁻¹)
Residential	Dhan'bidhoo	5364.93	263.81	27244.85	1769.15	2.82	290.84	18.89
	Fonadhoo	12101.3	595.05	61454.28	3990.54	12.16	1255.72	81.54
	Gaadhoo	5105.85	251.07	25929.12	1683.71	8.48	876.10	56.89
	Gan	18372.36	903.41	93300.76	6058.49	1.10	113.52	7.37
	Hithadhoo	7375.09	362.65	37453.08	2432.02	5.45	562.90	36.55
	Isdhoo [#]	6674.28	328.19	33894.16	2200.92	0.96	98.76	6.41
	Kalaidhoo	7873.78	387.17	39985.56	2596.47	1.74	180.22	11.70
	Kunahandhoo	6525.78	320.89	33140.02	2151.95	2.22	559.35	36.32
	Maabaidhoo	7568.63	372.17	38435.91	2495.84	0.20	229.09	14.88
	Maamendhoo [#]	3075.39	151.22	15617.84	1014.15	0.34	21.09	1.37
	Maavah	4110.5	202.12	20874.44	1355.48	0.08	36.41	2.36
	Mundoo	3597.7	176.91	18270.25	1186.38	53.33	208.54	13.54
Tourism	Fares [#]	2289.16	112.56	11625.08	754.88	0.02	2.11	0.14
	Olhuveli [#]	1988.14	97.76	10096.42	655.61	<0.01	<0.01	<0.01
Grand Total		92022.89	4524.98	467321.8	30345.59	88.9	4434.65	287.96

6.6. Recreational value

Recreation-related services, according to the SEEA, are the ecosystem contributions, through the biophysical characteristics and qualities of ecosystems that enable people to use and enjoy the environment (as opposed to built infrastructure) through interactions with the environment. This includes services to both locals and non-locals (i.e. visitors, including tourists)¹² and may include:

- Direct interaction (e.g., diving, snorkelling, kayaking through an ecosystem),
- The ecosystem enables a recreational activity (e.g., attracting birds for birdwatching),
- Motivation for visit – visit chosen specifically due to an area of the island / atoll, which incorporates spend on food and beverages.

Measurement approaches for recreational-based services have previously been conducted in the Maldives using:

- benefit-transfer methods applying values estimated elsewhere to the study site,
- visitor counts and time-use surveys to quantify physical use and intensity,
- travel-cost models that infer value from expenditures on transport and time costs,
- contingent valuation and choice experiments (i.e., willingness to pay)

While these methods, such as willingness to pay, can cover a range of non-use and preservation values, they are subject to bias and require careful design that often cannot be repeated regularly and over time. Therefore, we use **direct expenditure analysis**, which sums actual payments for activities such as snorkeling, or diving.

The method provides a conservative, transparent estimate of the economic contribution of recreation to local economies, grounded in observed spending. To align with the SEEA, and for robust policy and investment decisions, a market-based approach that leverages actual expenditure data offers **the most defensible and straightforward foundation** for measuring the service, avoiding the speculative assumptions of willingness-to-pay surveys.

Longitudinal monitoring that links ecosystem health and tourism expenditure enables an understanding of dependencies. Coral cover, fish biomass or water clarity alongside time-series data on bookings for dive trips, excursion revenues, and visitor counts, could provide correlations between environmental degradation (driven by climate change, bleaching events, or pollution) and downturns in nature-tourism spending. Decision-makers can leverage these insights to prioritize conservation investments where economic returns are highest, to design adaptive management strategies. Thus, the direct expenditure approach, underpinned by surveys and continuous monitoring supports both sustainable tourism and ecosystem management.

¹² A distinction is made between recreation that involves a trip to a site some distance from home and recreation close to home. In the terminology of tourism statistics, this is the distinction between visitors (who travel outside of their usual environment) and non-visitors. Visitors can further be separated into those undertaking single day trips and those who stay overnight outside of their usual environment.

6.6.1. Coral reefs

Coral reefs provide significant recreational ecosystem services that directly support tourism activities in the Maldives through a diverse range of activities and experiences. To capture the nature-related spend, a survey instrument was deployed across Laamu Atoll, on-site at Rahaa and Six Senses Resort, and guest houses. To link to the tourism sector, which targets overseas visitors, only tourists over 18 years of age (with nationalities other than Maldivian) were analyzed.

The survey provided data at the individual visitor level, including:

- Socio-demographic data on the respondent (age, gender, nationality, residence),
- Trip characteristics (nights stayed, people in group, type of group),
- Spend on accommodation, food and beverages, transport to and within Laamu,
- Activities and experiences undertaken during the stay (both number of times and spend), and
- Sustainability views.

Physical ecosystem service estimate

The physical service was measured by the **number of nights stayed** by tourists to Laamu Atoll, where they partook in coral-related activities during the day Table 6.27. For each response, the proportion of nights stayed at the accommodation where the tourists participated in coral-related activities (ϕ) was estimated by estimating days with coral activities performed (N_{eco}) against the total nights at the accommodation (N_{total}) (Eqn. 1).

$$\phi = \frac{N_{eco}}{N_{total}} \quad (1)$$

Table 6.27. Full activities, identifying those that were explicitly coral-related and also their average price during the sampling period.

Type	Activity	Average cost per person per unit
Coral related	Snorkelling	77.86
	Diving	109.31
	Whale Shark encounter (reef)	90.00
	Shark Feeding	0.00
	Reef fishing	151.25
Non-coral related	Swimming	30.08
	Canoeing	33.33
	Picnic	37.38
	Photography	0.00
	Surfing	218.75
	Private island experience	550.00
	Guided tours	0.00
	Cetacean cruise	150.00
	Turtle watching	30.08

The proportion was then multiplied by a conservative estimate of tourists to Laamu atoll each year. This was estimated by applying Laamu's share of total tourism infrastructure (by number of beds, ~0.75%) in the Maldives, with the number of tourists arriving in 2024 (2,047,435).¹³ The proportion of visitors across Maldives for guest houses (23%) and resorts (69%) was assumed (Table 6.28).¹⁴

Table 6.28. Estimated visitors and coral-related nights to Laamu Atoll. # Using average stay length from survey (5.8 nights).

Type	Visitors to Laamu Atoll	Visitors motivated by coral-reef activities	Estimated nights [#]	% coral-related activity days	Coral-related nights
Guest house	3,532	2,355	20,485.6	86	17,559.1
Resort	10,595	7,063	61,451.0	55	33,876.8
All	15,356	10,237	89,064.8	60	53,250.4

Monetary ecosystem service estimate

The direct nature-based expenditure was calculated by summing, for each individual, the product of participation count (n_i) and unit price (p_i) for all coral-related activities. Free coral-related experiences (i.e., shark feeding) were recorded but did not contribute direct revenue (Eqn. 2).

$$S_{\text{direct}} = \sum_{i \in A} n_i p_i \quad (2)$$

Accommodation, food and beverage spend have intermediate costs to the resort / guest house that should be isolated before estimating the nature-related component (e.g., labour, supplies, utilities, maintenance, repairs, cost of sales and other expenses). Industry benchmarks for the Maldives were consulted, which were estimated at 30 – 35% of the average nightly rate – which are higher than average due to import and transport costs. An assumed 32% was assigned to the direct input costs for accommodation, food and beverage.

This proportion of coral-reef related nights (Eqn. 1) was then applied to the individual's total accommodation and food & beverage spend, corrected for inputs and standardized per night to estimate coral-attributed lodging (S_I) and F&B expenditures ($S_{F\&B}$, Eq. 3).

$$S_I^{\text{coral}} = S_I \times \phi, \quad S_{F\&B}^{\text{coral}} = S_{F\&B} \times \phi \quad (3)$$

Total nature-dependent spend per person was obtained by summing direct nature activity spend, nature-attributed accommodation spends, and nature-attributed F&B spend. The share of total trip expenditure attributable to ecosystems was then computed as the quotient of total nature-dependent spend and overall trip spend (Eqn. 4).

$$\Psi = \frac{S_{\text{direct}} + S_I^{\text{coral}} + S_{F\&B}^{\text{coral}}}{S_{\text{total}}} \quad (4)$$

¹³ Ministry of Tourism and Environment (2025) Baseline Report on Tourism Development Practices in Laamu Atoll Prepared by Enhancing National Development through Environmentally Resilient Islands (ENDhERI) Project.

¹⁴ Ministry of Tourism and Environment (2024) Tourism Yearbook 2024.

All calculations were performed at the individual level in a R (v4.3), with results aggregated to produce summary statistics of mean and total ecosystem-dependent tourism expenditure.

Extrapolation to spend per year

Additional extrapolation to the atoll level was performed by integrating individual-level nature expenditure estimates with aggregate visitor statistics. Annual visitor counts were obtained from the Ministry of Tourism and Environment, disaggregated by gender and nationality. The total coral-related spend (S_{annual}) was estimated by multiplying the corresponding number of annual visitor nights (N_k), with the proportion spent by visitors from guest houses and resorts (\bar{S}_k , Eqn. 5).

$$S_{\text{annual}} = \sum_k N_k \bar{S}_k \quad (5)$$

Table 6.29. Estimated spend per category, extrapolated using a conservative estimate of visitor numbers (n = 15,355) staying 5.8 nights. The proportion in guest houses was 23% and 77% in resorts. Errors due to rounding.

Type	Activity spend (USD millions)	Accom. (USD millions)	Food and Beverage spend (USD millions)	Transport spend (USD millions)
Guest house	1.50	1.79	0.51	1.12
Resort	5.86	44.37	6.93	6.11
All	7.37	46.55	7.49	7.25

Table 6.30. Estimated coral-related spend per category. Errors due to rounding.

Type	Coral activity spend (USD millions)	Coral-related accommodation spend (USD millions)	Coral-related Food and Beverage spend (USD millions)	Coral-related Transport spend (USD millions)
Guest house	3.76	1.03	0.29	0.97
Resort	2.99	15.60	2.44	3.25
All	4.37	18.66	3.00	4.40

Table 6.31. Estimated total spend and coral-related spend. Conversion to Rufiyaa of 15.41 (MMA, 2024). Errors due to rounding.

Type	Total spend (USD millions)	Total coral-related spend (USD millions)	Total spend (MVR millions)	Total coral-related spend (MVR millions)
Guest house	4.92	3.61	75.77	55.65
Resort	63.27	24.28	974.98	374.11
All	68.66	30.43	1058.04	468.93

Quality assurance check

To ensure our survey-based estimates (USD 46.55 M accommodation, USD 7.5 M food & beverage, USD 7.25 M transport) were robust, we conducted an external validation by comparing identified proportions with official industry releases and international statistical datasets to compare total receipts and category shares, and consulting independent travel industry reports and case studies to confirm that the proportions of spend broadly align with published benchmarks. A comparison of Laamu Atoll's survey-derived spend distribution against broader patterns, based on the 2017 Tourism Satellite Account and 2024 Tourism Yearbook for the Maldives¹⁵:

- The survey identified Laamu's visitors allocate roughly 68% of their total spend to accommodation, 11 % to food & beverage, 10 % to transport, and 11 % to activities.
- This is similar to the 70 % of expenditures to accommodation and food services (79% Laamu) combined and around 20 % to transport and recreation (21% Laamu).

¹⁵ Tourism Satellite Account and Tourism Input Output Indicators of The Maldives: https://statisticsmaldives.gov.mv/nbs/wp-content/uploads/2021/09/TSA_Tourism_InputOutput_Indicators-ofTheMaldives2017-1.pdf

6.6.2. Mangroves

The Hithadhoo mangrove represents a unique ecological site in Laamu Atoll, and an emerging ecotourism destination in Laamu Atoll, where the Hithadhoo council has launched the "Hithadhoo Mangrove Adventures" initiative to showcase the saltwater mangrove system to visitors. Located on the southwest side of Hithadhoo, the site offers tourists an alternative experience to traditional reef-based activities in the Maldives. Visitors can explore the mangrove's waterways while learning about its biodiversity, including various mangrove species and the marine life that uses these waters as a nursery ground. The initiative demonstrates how local councils can develop nature-based tourism experiences that both educate visitors and create economic opportunities for their communities.

The economic value of mangrove tourism at Hithadhoo can be calculated based on kayaking activities, which is currently the primary tourist offering. With an average of 10 tourists per month paying \$20 per kayak rental, the site generates approximately \$200 in monthly revenue, translating to an annual revenue of \$2,400. While there is no entrance fee required for accessing the mangrove areas, and the operation is not yet supporting formal employment in the local community, the site offers additional activities including birdwatching, photography, swimming in nearby areas, and visits to heritage sites. The tour offers additional drone / standard photography packages which could add further value to the activities. This suggests potential for growth in both revenue and local employment opportunities through expanded ecotourism services.

Table 6.32 Calculation of additional revenue generated from mangrove-related tourism activities.

	Avg. tourists (month)	Unit cost (USD, per kayak tour)	Revenue per month	Annual revenue (USD)
Calculation	10	20	200	2,400



Figure 6.8 Hithadhoo Mangrove Adventures advertisement. Source: Hithadhoo Council.

6.6.3. Seagrass (gleaning)

Gleaning in Laamu Atoll represents a traditional small-scale fishery that predominantly involves collecting invertebrates from the littoral zone using simple tools or no tools at all. This social-ecological activity occurs primarily across reef flats and seagrass meadows, with patterns of use varying between islands based on their geographic features and accessibility.

Unlike many other regions where gleaning is crucial for subsistence, in Laamu Atoll it serves primarily as a social and recreational activity that brings communities together, from young children to elderly community members and accommodates people with disabilities. With 92.6% of participants rating it as highly enjoyable, gleaning serves as a valued social platform where friends and family members gather in groups averaging 4-5 people to collect marine resources. Women typically glean in the evening hours between 4-6 pm, staying close to their home islands, while men may venture further and glean for longer periods. Rather than being driven by economic necessity, as tuna remains the primary protein source in Maldivian diet, gleaning in Laamu provides an opportunity for community bonding, recreation, and supplementary income through the collection of various species, particularly gastropods, octopus, and lobsters.

The decline of seagrass meadows poses a threat to gleaning activities in Laamu Atoll, with 47.6% of participants citing seagrass die-off as a major concern (McGowan, 2023). This ecological change has been particularly severe in Maabaidhoo, where extensive areas of former seagrass habitat have been transformed into rocky shores, with seagrass now limited to the island's exposed side. The loss of seagrass habitat has significant implications for gleaning practices, as these areas serve as critical feeding grounds for many targeted invertebrate species, particularly gastropods which move into the seagrass at night to graze.

A study from McGowan (2023) identified the following statistics for gleaning occurrence:

- Average days per month: 7.9 ± 3.9 days
- Average trip duration: 2.7 ± 1.5 hours
- Men's average trip duration: 3.5 ± 1.8 hours
- Women's average trip duration: 2 ± 0.55 hours
- Average group size: 4.5 ± 1.8 people

A previous study by Rees et al. (2021) identified 227 gleaners on Laamu Atoll. Considering a population of 16,805 (in October 2020), the number of gleaners was approximately 1.35% of the total population. Under the assumption of forty (40) groups performing gleaning per week (1% of population), statistics could be generated for annual participation in the fishery (Table 6.33).

Table 6.33 Number of hours spent gleaning within Laamu Atoll.

Ecosystem	Factor	Units	2023
Seagrass	Participants in gleaning across trips	# participating (cumulative)	1440
	Gleaning effort	Hours	3960

6.7. Supply and use tables

Ecosystem service accounts are structured in supply and use tables, which record the flows of ecosystem services to sectors of the economy, household and government. These tables are extensions of the traditional supply and use tables found in the System of National Accounts (SNA), adapted to include non-market services provided by ecosystems (e.g., coastal protection, recreation). The supply table records the provision of services per ecosystem, while the use table identifies the beneficiaries, including industries, households, and governments. Table 6.34 provides definitions for each beneficiary type.

Table 6.34 Beneficiaries as defined by UN System of National Accounts (SNA) and UN System of Environmental Economic Accounting.

Beneficiary	Description	Example
Economic sectors	Industries and enterprises that derive direct or indirect benefits from ecosystem services in their production processes or outputs	The fisheries industry benefits from the provisioning service of fish stocks
Households	Individuals or groups of people living together who consume ecosystem services directly for their well-being and livelihoods	A family living near the shoreline is protected from storm surge and wave energy from coral reefs
Government	Benefits from ecosystem services in its role as a steward of public goods and as an entity responsible for providing public services	Governments benefit from regulating services such as coastal protection provided by coral reefs, which mitigates the need for expensive infrastructure investments

6.7.1. Physical value tables

The tables are first presented in physical values in non-monetary units such as tons, cubic meters, or hectares. These tables quantify the physical supply of services provided by ecosystems (e.g., the carbon sequestered by mangroves, or the number of recreational visits to a park) and their corresponding use by beneficiaries, including industries, households, and governments. They are particularly valuable for tracking changes in ecosystem health and performance over time.

Table 6.35 Ecosystem service supply table, in physical values.

Ecosystem service	Year (data)	Units	Economic units	Households	Government	Ecosystems			Total supply
						Coral reef	Seagrass	Mangrove	
Final ecosystem services									
Wild fish provisioning (reef fish)	2022	Tonnes landed (Mg)				28.17			28.17
Global climate regulation (Carbon sequestration)	2020	Carbon sequestered (MgC)					3460.1	24.6	3484.7
Coastal protection	2023	Coastline protected (m)				33,142			33,142
Recreational value	2023	Visitor nights / Participants (#)				53,250	1440 (gleaning)	120	
Intermediate ecosystem services									
Nursery and habitat maintenance service*	2020	Tonnes of enhancement (Mg)				203.64	40.78		244.42
Sediment production	2023	Natural sediment nourishment (m³)				4524.98	88.9		4613.88

Table 6.36 Ecosystem service supply table, in physical values.

Ecosystem service	Year (data)	Units	Economic units (ISIC code)			Households	Government	Ecosystem	Total use
			Marine fishing (0311)	Short-term accommodation activities (5510)	Others				
Wild fish provisioning (reef fish)	2022	Tonnes landed (Mg)	28.17						28.17
Global climate regulation (Carbon sequestration)	2020	Carbon sequestered (MgC)					3484.7		3484.7
Coastal protection	2023	Coastline protected (m)		3196			29,946		33,142
Recreational value	2023	Visitor nights / Participants (#)		53,250					53,250
Nursery and habitat maintenance service*	2020	Tonnes of enhancement (Mg)	244.42						244.42
Sediment production	2023	Natural sediment nourishment (m ³)		210.34			4,403.54		4613.88

6.7.2. Monetary value tables

The tables are then presented in monetary values to express the value of ecosystem services in economic terms, enabling their integration into national accounts and policy frameworks.

Monetary tables allow for the comparison of ecosystem services with other economic sectors, highlighting their contribution to GDP and overall societal well-being. These tables quantify the economic benefits derived from ecosystem services, whether through the market prices and non-market valuation techniques described throughout this Section. They are essential for cost-benefit analyses, investment decisions, and policy-making processes that aim to balance economic development with environmental sustainability.

Table 6.37 Ecosystem service supply table, in monetary values (MVR, millions) over multiple years due to differing data source dates.. NV = Not valued, data insufficient to perform monetary valuation of service.

*Quaywall replacement cost

Ecosystem service	Year (data)	Economic units	Households	Government	Ecosystems			Total supply
					Coral reef	Seagrass	Mangrove	
Wild fish provisioning (reef fish)	2022				NV	-	-	NV
Global climate regulation (Carbon sequestration)	2020				-	10.58	0.08	10.66
Coastal protection*	2023				82.85	-	-	82.85
Recreational value	2025				640.91	NV	0.00	640.91
Nursery and habitat maintenance service	2020				NV	NV	-	NV
Sediment production	2023				0.47	<0.01	-	0.47

Table 6.38 Ecosystem service use table, in monetary values (MVR millions) over multiple years due to differing data source dates. NV = Not valued, data insufficient to perform monetary valuation of service.

Ecosystem service	Year (data)	Economic units (ISIC code)			Households	Government	Ecosystem	Total use
		Marine fishing (0311)	Short-term accommodation activities (5510)	Others				
Wild fish provisioning (reef fish)	2022	NV						NV
Global climate regulation (Carbon sequestration)	2020					10.66		10.66
Coastal protection	2023		7.99			74.86		82.85
Recreational value	2025		640.91					640.91
Nursery and habitat maintenance service	2020	NV						NV
Sediment production	2023		0.02			0.45		0.47

7. Asset account

Ecosystem Asset Accounts provide a framework for valuing ecosystems as assets by calculating the economic worth of the services they offer over time, using the net present value (NPV) approach. This approach aggregates the future flows of ecosystem services, discounting them to represent their current economic value. To implement this, assumptions are made about future income flows, the discount rate, and the expected lifespan of the ecosystem assets. The SEEA EA encompasses all ecosystems, regardless of ownership, integrating the biophysical environment within its extended asset boundary.

In the current valuation, **only the carbon stock** of the ecosystem has been assessed, representing a partial view of the asset's full value. Calculating the comprehensive asset value across all ecosystem services would require additional data, particularly for tourism and fisheries services, which contribute significantly to the Maldives' economy and biodiversity. Further analysis and data collection are needed to capture these values.

Carbon sequestration and carbon stock in ecosystems represent two distinct concepts in carbon accounting. **Carbon sequestration** (flow) refers to the rate of capturing and storing carbon dioxide from the atmosphere into biomass, soils, and other ecosystem components. On the other hand, **carbon stock** refers to the total amount of carbon stored in an ecosystem's biomass, soils, and sediments at a given point in time.

As a measure of the accumulated carbon held in an ecosystem, carbon stock is considered an **asset** or a static quantity, representing the existing carbon reserves that provide long-term storage. Estimating the carbon retention of ecosystems requires an understanding of how much carbon is stored within soils that will remain undisturbed over time. To estimate the service, carbon sequestration should first be measured to understand the total amount of carbon currently stored in the ecosystem (i.e., aboveground, and belowground biomass, and soil organic carbon).

The **Social Cost of Carbon (SCC)** provides a globally recognized measure of the economic damages associated with carbon emissions, integrating the **NPV approach** within its calculation. SCC estimates the monetized damages of emitting one additional ton of CO₂ today, discounting future climate-related impacts to a single present-day value. The SCC value used in this report, USD 185 per ton CO₂, is based on a 2% near-term discount rate, which aligns with the recommended approach in Rennert et al. (2022) study, where discount rates are dynamically linked to economic growth and long-term risk-free interest rate trends.

While SEEA EA typically applies discount rates between 3-5%, the **lower 2% discount rate in SCC is particularly relevant for the Maldives** due to the country's **acute vulnerability to climate risks**. Given that climate-related damages will disproportionately affect the Maldives, applying a higher discount rate would significantly undervalue future climate damages and the long-term benefits of carbon sequestration. Therefore, using the SCC framework ensures that carbon-related ecosystem assets are valued in a manner consistent with both international climate policy standards and the Maldives' national priorities for climate resilience.

7.1. Mangrove carbon

The two dominant species on L. Hithadhoo are *Rhizophora mucronata* (*R. mucronata*) and *Ceriops tagal* (*C. tagal*). To estimate aboveground (AGB) and belowground (BGB) biomass (as dry weight), the following allometric equations were used based on Wartman et al. (2022).

The calculations for the carbon account are presented in Table 7.2. The calculations made use of the average value for species density (between a high density and low-density plot). This result was obtained due to the contribution from each species varying significantly between sites, given a massive change in diameter at breast height (DBH) calculated from the average basal area, and species density (Table 7.3). Aside from tree biomass, estimates from Macreadie et al. (2024) were used which provided organic carbon content on mangrove soils at 393 ± 29 tonnes ha^{-1} .

Table 7.1 Stepwise process to estimate the physical value of carbon sequestration.

Component	Description
Aboveground biomass	<ul style="list-style-type: none"> Tree diameter at breast height (DBH): Measured using a diameter tape at ~1.3 meters above the ground for trees. Tree height: Measured using a clinometer or laser rangefinder. Vegetation cover: Measured using quadrat sampling or remote sensing techniques depending on the scale and complexity of the ecosystem.
Below-ground biomass	<ul style="list-style-type: none"> Root diameter and depth: Measured through destructive sampling (not recommended for large-scale studies) or using root coring techniques. Soil samples: Collected for laboratory analysis of organic carbon content.
Carbon composition	<ul style="list-style-type: none"> Input the measured data (e.g., DBH, height, soil organic carbon content) into an equation that models the amount of biomass within the system (i.e., allometric model equation).¹⁶ The choice of the model should align with the species present and relevant to the study area. The aboveground and belowground biomass per sample area can then be estimated, which could be scaled to the accounting area.

¹⁶ Allometric model: a mathematical model or equation used to estimate and predict various attributes of trees and forests, such as biomass, volume, and growth, based on measurable tree characteristics like diameter at breast height (DBH), height, and wood density. For a comparison by mangrove species see: <https://iopscience.iop.org/article/10.1088/1748-9326/ac31ee>

Table 7.2 Allometric equations used to estimate AGB, BGB, and carbon content of mangroves for L. Hithadhoo in 2023. DBH = diameter at breast height, WD = Wood density, assumed at 0.85.

Tree species	AGB (Kg Dry Weight)	BGB (Kg Dry Weight)	Conversion factors (Biomass to C)		Carbon (Mg ha ⁻¹)			Literature source
			AGB	BGB	AGB	BGB	Total	
<i>R. mucronata</i>	$0.25128 \text{ DBH}^{2.26026}$	$1.42040 \text{ DBH}^{1.68979}$	0.47	0.39	13.14	20.24	33.37	Wartman et al. 2022
<i>C. tagal</i>	$0.189 \text{ DBH}^{2.34}$	$0.199(\text{WD}^{0.899}) (\text{DBH}^{2.22})$			8.52	5.06	13.58	Gillerot et al. 2018, Wartman et al. 2022

Table 7.3 Carbon account for mangrove biomass in 2023 according to stratification.

Site	Species	Avg. tree height (m)	Basal area (cm ²)	Average basal area	Species density (tree ha ⁻¹)	AGB (Kg DW tree ⁻¹)	BGB (Kg DW tree ⁻¹)	Total biomass per area (Mg ha ⁻¹)	Carbon (Mg C Ha ⁻¹)
High density	<i>R. mucronata</i>	3.6	800	36.36	2200	19.16	36.28	121.97	50.94
	<i>C. tagal</i>	3	49	24.5	200	10.58	7.83	3.68	1.61
Low density	<i>R. mucronata</i>	3.3	208	41.6	500	22.31	40.65	31.48	13.17
	<i>C. tagal</i>	2.5	1045	65.31	1600	33.32	23.25	90.51	39.57

Table 7.4 Carbon stocks for mangrove biomass in 2023 according to stratification, estimated from Macredie et al. (2024).

Site	Species	Carbon in biomass (Mg C)	Carbon in soils* (Mg C)	Total stock (Mg C)
High density (Area = 0.83 ha)	<i>R. mucronata</i>	42.28	326.19	369.81
	<i>C. tagal</i>	1.34		
Low density (Area = 2.05)	<i>R. mucronata</i>	27.00	805.65	913.77
	<i>C. tagal</i>	81.12		

Table 7.5 Carbon accounts for seagrass per site in late 2023 (August).

Site	Coverage (%)	Density (blades m ⁻²)	Biomass (kg m ⁻²)	AGC (g C m ⁻²)	BGC (g C m ⁻²)	Totals C (g C m ⁻²)
Kalaidhoo	66.39	235.00	3392.13	30.31	73.51	103.82
Dhanbidhoo	76.00	234.00	3398.47	31.61	76.45	108.06
Maabaidhoo	48.50	278.50	3148.96	27.89	68.05	95.94
Mundoo	40.50	188.50	3736.06	26.81	65.60	92.41
Kalhaidhoo	49.00	51.50	6595.21	27.96	68.20	96.16
Berasdhoo	35.50	50.50	6652.09	26.14	64.08	90.21
Gan	29.33	195.33	3678.24	25.30	62.19	87.49
Fonadhoo	50.50	193.50	3693.46	28.16	68.66	96.82
Gaadhoo	68.00	217.50	3509.08	30.53	74.00	104.53
Hithadhoo	53.50	162.00	3992.39	28.57	69.57	98.14
Kunahandhoo	69.00	298.50	3054.74	30.66	74.31	104.97
Maavah	61.50	630.50	2201.60	29.65	72.02	101.67
Average	53.98	227.94	3921.04	28.63	69.72	98.35

7.2. Seagrass carbon

Multiple campaigns to measure seagrass ecosystems were conducted in Laamu, namely February - April and August 2023. Biomass is the best predictor for estimating carbon content of seagrass, although these metrics were not available for February-April. To estimate seagrass carbon stock, and provide a comparison of potential changes in inferences, data from the February – April trip used allometric equations for above and below ground carbon values, based on coverage – see equations (1) and (2) (Wahyudi et al. 2020).

$$\text{Above Ground Carbon (AGC)} = 21.337810 + 0.13514[\text{Coverage}] \quad (1)$$

$$\text{Below Ground Carbon (BGC)} = 53.2301 + 0.3055[\text{Coverage}] \quad (2)$$

These resulted in the estimates for 2023 per site (Table 7.6). Considering 4,128.77 ha of seagrass in Laamu atoll, and a carbon stock of 1.02-ton C/ha, a total of 4209.34 tonnes of carbon are present at site. Similar to the mangroves study, it should also be considered how soils also contain high levels of carbon content. For instance, a study on soil cores from seagrass at Laamu atoll found seagrasses contain an average of 167 tonnes ha⁻¹ and are the primary contributor of organic material in sediments of three islands of the Maldives (Macreadie et al. 2024).

Table 7.6 Carbon stock estimates for seagrass between 2019 and 2024, using coverage and total C factors from 2023. Only high-resolution seagrass data is presented (omitting 2017 and 2018).

Year	Seagrass meadow extent (ha)	Seagrass area (ha)	Carbon stock in biomass (Mg C)	Carbon stock in soils (Mg C)
2019	3583.61	1931.32	189954.26	322530.44
2020	3894.86	2098.94	206452.51	350522.98
2021	3628.47	1956.00	192353.12	326652
2022	3473.50	1872.36	184146.51	312684.12
2023	3511.98	1892.43	186143.11	316035.81
2024	3831.21	2064.96	203130.70	344848.32

7.3. Monetary valuation

The SCC, applied here at a rate of USD185 per tonne of CO₂ (per Rennert et al., 2022), offers a metric for estimating the economic value of carbon stocks in the Maldives. Using the SCC aligns with the concept of avoided damages, capturing the **long-term** (as opposed to annual) economic costs of agricultural losses, health expenditures, coastal flooding, and infrastructure damage. However, this estimate may be conservative, as the Maldives is particularly vulnerable to climate impacts like sea-level rise and extreme weather.

7.3.1. Social Cost of Carbon

The SCC is calculated by comparing two different scenarios that run from 2020 to 2300, a timespan chosen because carbon dioxide remains in the atmosphere for hundreds of years. The first scenario shows a baseline future, while the second scenario adds a small pulse of extra CO₂ emissions in 2020. By comparing these two scenarios, researchers can determine how much additional damage that extra pulse of emissions causes across four key areas: agriculture, energy costs, human mortality, and sea-level rise. This difference in damages between the two scenarios represents the harm caused by each additional ton of CO₂ emissions.

Once researchers calculate these yearly damages, they convert all future damages into present-day dollars through discounting, which accounts for the fact that people generally value present costs and benefits more than future values. To address the many uncertainties in predicting the future, the researchers ran this calculation 10,000 times, each time using different possible scenarios for things like population growth, economic development, and climate sensitivity.

Rennert et al., 2022 produced a final estimate that each ton of CO₂ emitted today causes about USD 185 in damages (with a range from USD 44 to 413), though this value depends significantly on the discount on future damages. For USD 185, a 2% discount rate was used.

Table 7.7 Carbon stock value in monetary terms for Laamu Atoll, for 2023 to align with field data. Assuming a stable mangrove carbon stock on Hithadhoo of 1280 Mg C. An SCC price of USD 185 was used and adjusted for inflation to 2024.

Year	Total carbon stock (Mg C)	Monetary value of carbon asset (USD)	Monetary value of carbon asset (MVR)
2023	503,459	94,443,859	1,454,435,426

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