THE SEYCHELLES SEAGRASS MAPPING AND CARBON ASSESSMENT

Report submitted to the Government of Seychelles, Ministry of Agriculture, Climate Change and Environment (MACCE), June 2024.

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Cover photography: Mixed species seagrass meadows near Anse aux Pins, Mahé, Seychelles. A remnant patch of *Enhalus acoroides* seagrass can be seen in the foreground, with blades floating on the water surface. *©Jeanne A Mortimer and the 'Seychelles Seagrass Mapping and Carbon Assessment Project'.*

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Partners and collaborators

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Glossary, Units & Abbreviations

Term	Acronym	Definition
Aboveground biomass	AGB	Biomass contained within the plant's living leaves, branches, stems or aerial shoots.
Below ground biomass	BGB	Biomass contained within the plant's living roots and rhizomes.
Blue Carbon / Blue Carbon Ecosystems	BCE	Carbon captured by marine and coastal ecosystems – In Seychelles taken as seagrass and mangrove
Conference of the Parties	COP	The COP is the supreme decision-making body of a Convention – in this context the UNFCCC. All States that are Parties to the Convention are represented at the COP, at which they review the implementation of the Convention and any other legal instruments that the COP adopts and take decisions necessary to promote the effective implementation of the Convention, including institutional and administrative arrangements.
Carbon dioxide equivalent	CO_2e	Unit of measurement used to standardise the climate effects of various greenhouse gases (GHGs). The conversion factor 3.67 is used for organic carbon, which represents the ratio of molecular weight between Carbon Dioxide (CO_2) which has a weight of 44 and Carbon (C) which has a weight of 12 .
Carbon:Nitrogen Elemental analyser	CN analyser	A lab instrument used to measure carbon and nitrogen elemental concentrations in a given sample (such as soil)
Carbon stock (organic)	C_{org}	In the context of Blue Carbon Ecosystems (BCE) The amount of carbon stored within an ecosystem, mainly within living and dead biomass, detritus, soil, or sediments
Exclusive Economic Zone	EEZ	An area of the ocean, generally extending 200 nautical miles beyond a nation's territorial sea, within which a coastal nation has jurisdiction over both living and non-living resources.
Greenhouse gases	GHG	Gases that absorb and emit radiant energy within the thermal infrared range, which can cause the greenhouse effect e.g., carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O)
Hectare	ha	Unit of Area. One hectare is equivalent to 100 m^2, or 0.01 km^2.
Intergovernmental Panel on Climate Change	IPCC	An intergovernmental body of the United Nations. Its job is to advance scientific knowledge about climate change caused by human activities.
Kilotonne	kt	Unit of weight. One kilotonne is equivalent to 1000 tonnes.

Lead	Pb	Elemental symbol for lead, used in the context of this report for lead 210 (^{210}Pb) radioisotope dating
Megagram	Mg	Unit of weight. One Megagram (10^6 grams), is equivalent to one metric tonne.
Nationally Determined Contributions	NDCs	Emission reductions commitments that countries need to submit to the United Nations Framework Convention on Climate Change (UNFCCC) under the Paris Agreement
National Greenhouse Gas Inventory	NGGI	The NGGI Is an Inventory submitted to the United Nations In accordance with the Framework Convention on Climate Change. The gases Included in the Inventory are carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, sulphur hexafluoride, and nitrogen trifluoride.
Nature based Solution	NbS	Nature-based Solutions leverage nature and the power of healthy ecosystems to protect people, optimise infrastructure and safeguard a stable and biodiverse future.
Organic Carbon	C_{Org}	Organic carbon stored within soil or sediment, typically reported in weight per unit area e.g. tonnes per hectare (t ha^{-1}). Carbon may also be found within inorganic material in forms such as calcium carbonate ($CaCO_3$) which forms the bones and skeletons of many marine creatures.
Organic Matter	OM	Living or dead animal and plant material.
Radium	Ra	Elemental symbol for radium, used in the context of this report for radium 226 (^{226}Ra) radioisotope dating
Seychelles' Marine Spatial Plan	SMSP	Seychelles' Marine Spatial Plan (https://seymsp.com/).
Standard Error	SE	A measure of variance around a mean (average) defined as the Standard deviation of its sampling distribution or an estimate of that standard deviation
Teragram	Tg	Unit of Weight one Teragram (10^{12} grams), is equivalent to a megaton.
Tonne	t	Unit of weight. One tonne is equivalent to one Megagram (10^6 grams), as in tC_{Org} = tonnes of Organic Carbon
United Nations Framework Convention on Climate Change	UNFCCC	International environmental treaty to combat "dangerous human interference with the climate system", in part by stabilizing greenhouse gas concentrations in the atmosphere

Executive summary

Project Background

During the 2021 United Nations Climate Change Conference (COP26), Glasgow, United Kingdom, Seychelles committed within the Nationally Determined Contribution (NDC) to map the full extent of the blue carbon seagrass and mangrove ecosystems within its waters and measuring their carbon stock values, with the goal of including these ecosystems within the Seychelles' National Green House Gas inventory (NGGI) by 2025. *The Seychelles Seagrass Mapping and Carbon Assessment Project* was initiated to deliver the seagrass components of this commitment with the following aims:

1. To assess the distribution and extent of seagrass habitats.
2. To quantify how much carbon is stored in associated below-ground sediments.
3. To assess the rate at which carbon accumulates.
4. To build scientific capacity to support future surveys and a blueprint for further development of seagrass mapping and blue carbon research regionally.

Conclusions and Recommendations

1. **Seagrass is a nationally important blue carbon ecosystem for Seychelles. It covers nearly 160,000 ha in area and stores 18.9 million tonnes organic carbon - equivalent to 69 million tonnes of $C0_2$.** Managing and accounting for Blue Carbon can go some way to offsetting carbon emissions from other sources in Seychelles, **while delivering additional benefits to local economies**.

2. Seychelles has considerable seagrass carbon stores. **The integrity of these stores requires that the seagrass ecosystem remains healthy and intact, and the underlying sediments where most carbon is stored remain undisturbed.**

3. **Establishing seabed protection through the Seychelles Marine Spatial Plan and aligned management is an important first step to delivering the commitment to protect seagrass as outlined in the Seychelles' NDC**.

4. **Spatial protection measures must be supported through robust commitments to regulation and licencing of specific activities which directly or indirectly impact the seabed**. For example, establishing development and planning processes and safeguards specific to seagrass, and a **requirement for Environmental Impact Assessment (EIA)** in areas where seagrass habitat is known or is likely to occur. Accounting for any loss or gain associated with any extraction or seabed alteration will **facilitate the commitment to include seagrass ecosystems within the Seychelles NGGI by 2025**.

Summary: Seychelles Seagrass Habitat and Species Diversity

ECOLOGICAL IMPORTANCE OF SEAGRASS IN SEYCHELLES

Seagrasses are marine plants with leaves, roots, and flowers.

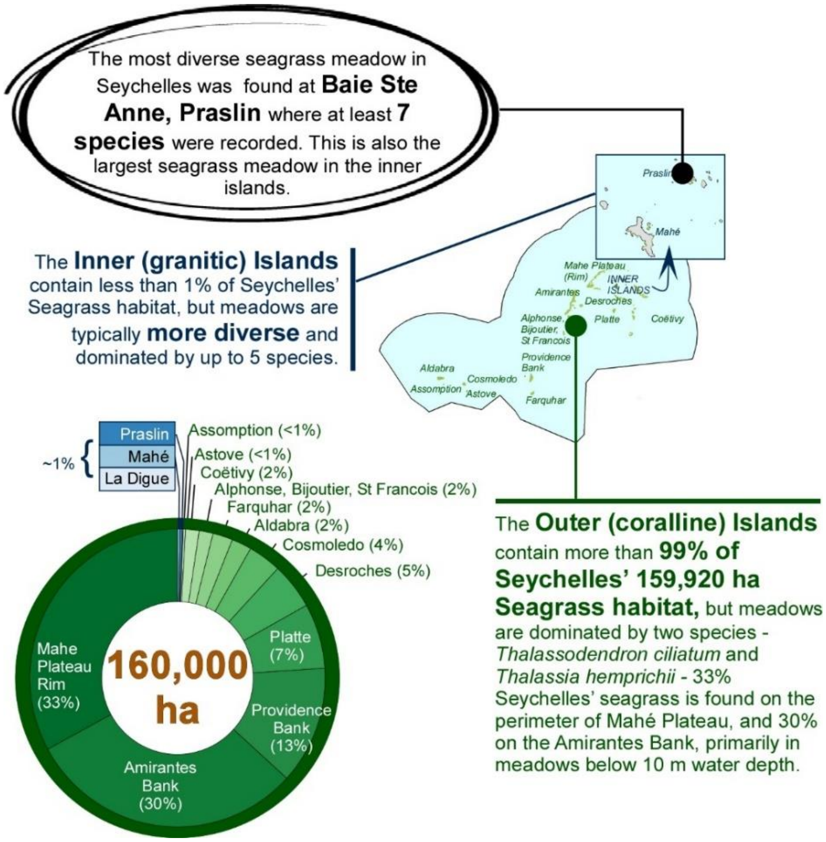
Approximately 12 seagrass species occur in Seychelles with the **highest species diversity** in the **Inner (granitic) islands**, particularly at Baie Ste Anne (Praslin), Ste Anne Marine Park, and Au Cap (Mahé).

Seagrass provides important ecological services on behalf of fisheries, biodiversity, water quality, tourism, and coastal protection including:

- erosion protection;
- important fish habitat;
- nursery grounds for juvenile fishes;
- food and habitat for endangered species e.g. sea turtles and dugong; and
- sequestration (capture) and storage of carbon.

WHERE DO SEAGRASSES OCCUR IN SEYCHELLES?

A total of **159,920 ha (1,599 km²)** of **seagrass were mapped** across the 1.36 million km² of Seychelles' Exclusive Economic Zone (EEZ) using a combination of satellite imagery and ground truth from eight locations.


The most diverse seagrass meadow in Seychelles was found at **Baie Ste Anne, Praslin** where at least **7 species** were recorded. This is also the largest seagrass meadow in the inner islands.

The **Inner (granitic) Islands** contain less than 1% of Seychelles' Seagrass habitat, but meadows are typically **more diverse** and dominated by up to 5 species.

The **Outer (coralline) Islands** contain more than **99% of Seychelles' 159,920 ha Seagrass habitat,** but meadows are dominated by two species - *Thalassodendron ciliatum* and *Thalassia hemprichii* - 33% Seychelles' seagrass is found on the perimeter of Mahé Plateau, and 30% on the Amirantes Bank, primarily in meadows below 10 m water depth.

Distribution of the total 159,920 ha (1,599 km²) seagrass habitat in Seychelles

Location	% of total	km²
Mahé Plateau Rim (including Bird & Denis islands)	32.9	527
Amirantes Bank	30.3	485
Providence Bank	12.8	205
Platte Reef	7.1	113
Desroches atoll	5.0	80
Cosmoledo atoll	3.6	58
Aldabra atoll	2.2	35
Farquhar atoll	2.2	35
Alphonse & St Francois atolls	1.5	24
Coëtivy	1.5	24
Inner (granitic) Islands (*See following table)	*** 0.6**	*** 9**
Astove atoll	0.3	4
Assomption	0.1	1

*Distribution of the 9 km² seagrass habitat in the Inner (granitic) Islands:

Praslin	0.30	4.80
Mahé	0.14	2.25
Ste Anne Marine Park	0.08	1.27
La Digue	0.02	0.26
Curieuse	0.02	0.25
Other granitic islands (including Silhouette)	<0.01	0.02

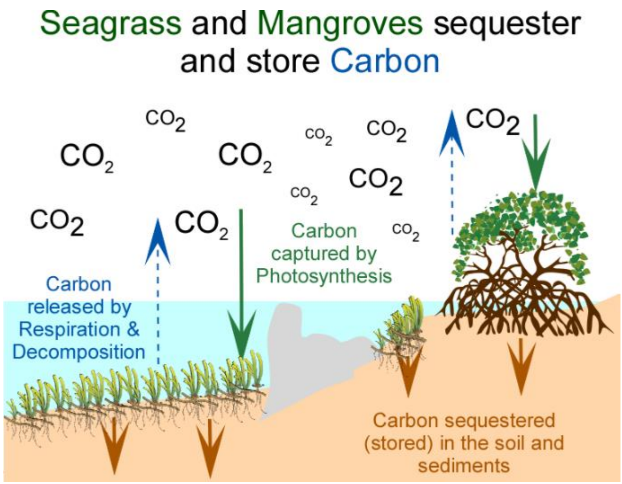
Carbon Storage

WHAT IS A BLUE CARBON ECOSYSTEM?

Blue Carbon Ecosystems (BCEs) include coastal ecosystems such as seagrass, mangroves and tidal marshes that sequester (capture) and store large amounts of carbon.

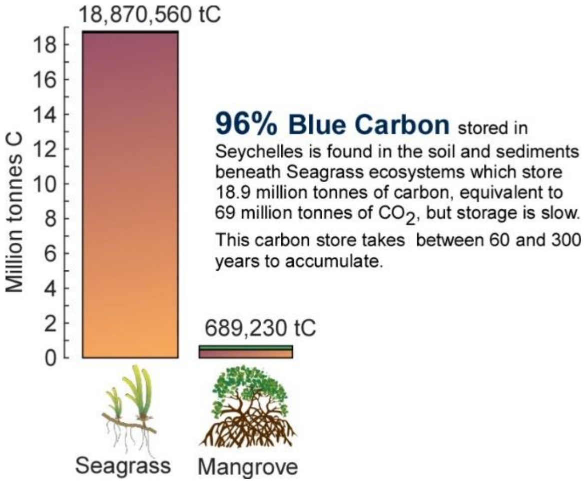
In Seychelles, seagrass and mangroves are important BCEs.

Carbon that is released into the environment by respiration, decomposition, and human pollution from fossil fuels is captured by photosynthesis of the seagrass and mangroves and stored in the soil and sediments. They may also capture and store organic carbon entering the marine environment from terrestrial sources.



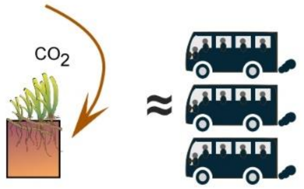
HOW MUCH CARBON DO BLUE CARBON ECOSYSTEMS STORE IN SEYCHELLES?

Estimating the amount of carbon that seagrass stores within both plant tissues and the associated sediments, is key to understanding its role in climate change and how managing blue carbon ecosystems such as seagrass might help to address it. In addition to mapping seagrass, sediment cores and vegetation samples were collected. These were analysed using loss on ignition (LOI) and elemental analysis to determine the organic carbon content. Combined with habitat mapping, these values can be used to estimate the total carbon stored – the carbon stock. Further radio isotope analysis was conducted to establish rates of carbon sequestration (i.e. how fast or slow carbon is being stored) allowing comparison to other sources of carbon emission from the Seychelles economy.



In Seychelles, two blue carbon ecosystems are recognized by the Intergovernmental Panel on Climate Change (IPCC) - (1) seagrass, and (2) mangroves. **96% of the total organic carbon stored within blue carbon ecosystems in Seychelles is found beneath seagrass meadows**. The above ground vegetation carbon pools are relatively small and, in most cases, represent less than 1% of the total seagrass carbon pool. While seagrass ecosystems store approximately a third the organic carbon <u>per hectare</u> of mangroves, seagrass **accounts for more than 98% of Seychelles BCE total**.

ANNUAL SEQUESTRATION



~510,000 tCO$_2$e is sequestered annually beneath Seychelles' Seagrass. This, is **equivalent to the annual emmisions from Seychelles' Energy sector** as a whole*, and more than **three times the annual emmisions from the Transport sector.**

*based median observed sequestration rates, and 2018 emissions (Seychelles Government, 2023)

On average, the seagrass meadows of Seychelles store **118 tonnes of organic carbon per hectare**: the **vast majority within the below ground sediment**. The **estimated total stock of organic carbon** (assessed to a maximum depth of 1.2 m) in the seagrass meadows of Seychelles is **18.9 million tonnes** equivalent to **~69 million tonnes of C0$_2$ (tCO$_2$e)**.

These carbon stores while large, are vulnerable to loss if sediments are disturbed. The **accumulation rate for organic carbon is slow and ranged** from 0.35-2.51 tonnes per hectare per year, with a median accumulation rate of **0.87 tonnes organic carbon per hectare per year**. Given rates of carbon accumulation this suggests the **sediment cores** analysed **represent between 60 and 300 years of net carbon accumulation**.

Each year an estimated **510,000 tCO$_2$e is sequestered by seagrass; nearly the same as the annual emissions from across Seychelles' energy sector**, and **nearly three times the transport sector** (Government of Seychelles 2023). The total carbon stored

therefore **approximates to 120 years of current carbon emissions from the energy sector** and 420 years of emissions from the transport sector.

The above estimates indicate the importance of seagrass habitat and their potential for CO_2 mitigation within Seychelles' national carbon accounting yet should be treated with a degree of caution. Accumulation rates and the total carbon measured in different environments are highly variable. **Sequestration rates should not be used to justify continuation or increased emissions** under 'business-as-usual' but may help Seychelles achieve its net-zero emission target by 2050 or before.

Seagrass meadows below 10 m water depth typically store more carbon as the sediment layer above bedrock is usually thicker. While sediment cores from shallow water environments are typically shorter, the concentration of organic carbon is often higher.

Seagrass Carbon and the Seychelles Marine Spatial Plan

In its 2021 NDC, **Seychelles committed to protect its BCEs**; to protect at least 50% of its seagrass and mangrove ecosystems by 2025, and 100% of seagrass and mangrove ecosystems by 2030.

Effective spatial management is an important step towards protecting seagrass. The Seychelles Marine Spatial Plan (SMSP) addresses the 30% Marine Protected Area (MPA) commitment made in 2021 and identifies **three types of Zone: (1)** High Biodiversity Protection Zone Biodiversity Protection Zone; **(2)** Medium Biodiversity Protection and Sustainable Use Zone; and **(3)** Multiple Use Zones. **The mapped distribution of seagrass habitat / associated carbon stores was compared to the distribution of these three zones**, existing protected areas, and other spatial management measures.

A total of 99.5 % seagrass habitat is found within Zones 1 or 2 (designated MPAs), or a pre-SMSP protected area. Approximately 2.3 % of seagrass habitat is found within the existing (pre SMSP) protected areas. Approximately 7% of seagrass habitat is found in Zone 1 – High Biodiversity Zones. The majority (90%) of seagrass habitat falls within Zone 2 - Medium Biodiversity Protection and Sustainable Use Zone and gazetted as sustainable use MPAs. Less than 0.5% mapped seagrass was found within Zone 3 - Multiple Use Zones, principally abutting the granitic inner islands of Mahé, Praslin, and La Digue.

The effectiveness of Seagrass Protection will depend on the types of restrictions applied to potentially damaging activities and/or the location of these activities. Given the length of time carbon stores take to accumulate, and the potential for large scale emissions following damage or disturbance to the habitat and sediments, **extraction and seabed alteration are likely to be incompatible with sustainable management and maintenance of seagrass and its carbon sequestration capacity**. Any such activity should therefore be sited away from seagrass wherever possible and/or mitigated.

Another concern is that seagrass meadows characterized by the **highest levels of species diversity (e.g. Baie Ste Anne, Praslin and Au Cap region of Mahé) occur in Zone 3** and **do not occur within an existing protected area.**

Introduction

Seagrass ecosystems provide many important benefits to coastal communities (Nordlund et al. 2016). They protect the shoreline from erosion and provide areas for recreation and fishing that are of cultural value. Seagrass improves the quality of the water chemistry for coral reefs by adding oxygen and removing carbon dioxide, thereby reducing acidity on localized scales which can damage organisms with calcareous skeletons of corals, molluscs and other invertebrates. Seagrass meadows provide habitats for invertebrates and fish, including fishes of economic importance. They provide nursery habitat for juvenile fishes, and food and habitat for endangered species such as sea turtles and dugong. The leafy blades of seagrass meadows form a dense canopy that slows currents and encourages suspended material to settle downwards, thereby stabilizing sediments. Dense networks of rhizomes and roots help anchor seagrasses into the sediment, and store carbon in the woody material and sediments. For this reason, seagrass, as well as the coastal habitats of mangrove and saltmarsh, are often referred to as 'blue carbon' ecosystems. Yet, to fulfil their critical roles for both climate change mitigation and adaptation, blue carbon ecosystems need to be maintained in a healthy and functional state. Globally, these ecosystems are in critical need of protection, with approximately 50% lost in the past 100 years.

In the inner islands of Seychelles, especially near Mahé, many coastal ecosystems have been degraded or destroyed due to human activities such as coastal landfill projects, and remain threatened by coastal development, pollution, warming sea temperatures and ocean acidification induced by climate change (Republic of Seychelles 2021). Yet many other areas continue to host significant seagrass meadows (Figure 1).

Figure 1: Research scientists from Island Conservation Society and the University of Oxford surveying a seagrass meadow (Thalassodendron ciliatum) at Desroches Atoll, Amirantes.

Three parameters are important for an understanding of the potential of seagrass as a nature-based solution (NbS) that can address climate change through mitigation and/or adaptation. These are: (1) the distribution and extent of seagrass habitats (2) how much carbon is stored in associated below-ground sediments, and (3) the rate at which carbon accumulates. Because seagrass habitats are submerged, they are inherently more challenging to study than terrestrial environments. It follows that to reliably estimate the extent of seagrass habitat, and to quantify the amount of stored carbon within these habitats, most of which can be found within the underlying sediments, remains challenging.

Seagrass Habitats in Seychelles

The Blue Economy sectors of Seychelles, particularly tourism and fisheries, rely on the natural capital and services provided by rich coastal ecosystems that include terrestrial vegetation, freshwater wetlands, mangrove forests, coral reefs and seagrass meadows (Republic of Seychelles 2021). Most of these coastal ecosystems occur on or adjacent to land masses, while coral reefs and seagrass habitats can be found at water depths ranging from 0 to approximately 30 metres, either located adjacent to land or situated on submerged plateaus far from shore. Approximately 21,340 km^2 (2.1 million of ha, or 1.5%) of the Exclusive Economic Zone (EEZ) of Seychelles comprises waters less than 30 metres deep (GEBCO, 2020 data).

These coastal ecosystems can be grouped into two geographically distinct regions in Seychelles (Figure 2) commonly referred to as: 1) 'The Inner Islands' – comprising high granitic islands situated on the Mahé Plateau, where most of the human population resides and places high environmental pressure on coastal ecosystems; and 2) 'The Outer Islands' – low lying coralline atolls and submerged banks, more remote and less accessible, with few people. Note, within this report seagrass associated with Denis and Bird Island, as well as the outer rim of the Mahe Plateau is analysed as part of the 'outer islands' due to the similar coralline habitats.

Seychelles is a country with extensive seagrass habitats, yet many historical maps of seagrass lack field validation and there are no *in-situ* estimates of the carbon stock held in these ecosystems. Previous work, as well as that of this study, indicates that the abundance and extent of seagrass meadows in the outer islands are greater than those of the inner islands. In contrast, species diversity is higher in the inner islands, both in terms of species richness and species evenness.

Approximately 12 seagrass species occur in Seychelles, and all but one of them can be found in both the inner and outer islands (Figure 3, Table 1). That exception is *Enhalus acoroides* which has been documented only in the inner islands. While *Enhalus acoroides* is still dominant at some sites in the inner islands (such as the nearshore of Baie Sainte Anne, Praslin), at most locations (especially adjacent to Mahé), *Enhalus acoroides* has been extirpated from its previous range and/or reduced to small patches and fragments by coastal landfill projects. Other genera that are abundant in the inner islands include: *Oceana serrulata*, *Thalassia hemprichii, Syringodium isoetifolium*, *Halodule* uninervis, *Thalassodendron ciliatum*, and *Halophila* spp. (3-5 species). (Figure 2). In contrast, while all but *Enhalus acoroides* do occur in the outer islands, only *Thalassodendron ciliatum* and to a lesser extent*Thalassia hemprichii* are clearly dominant there. A more detailed assessment of seagrass species abundance and distribution is underway as a secondary outcome of the project but is outside the consideration of this report.

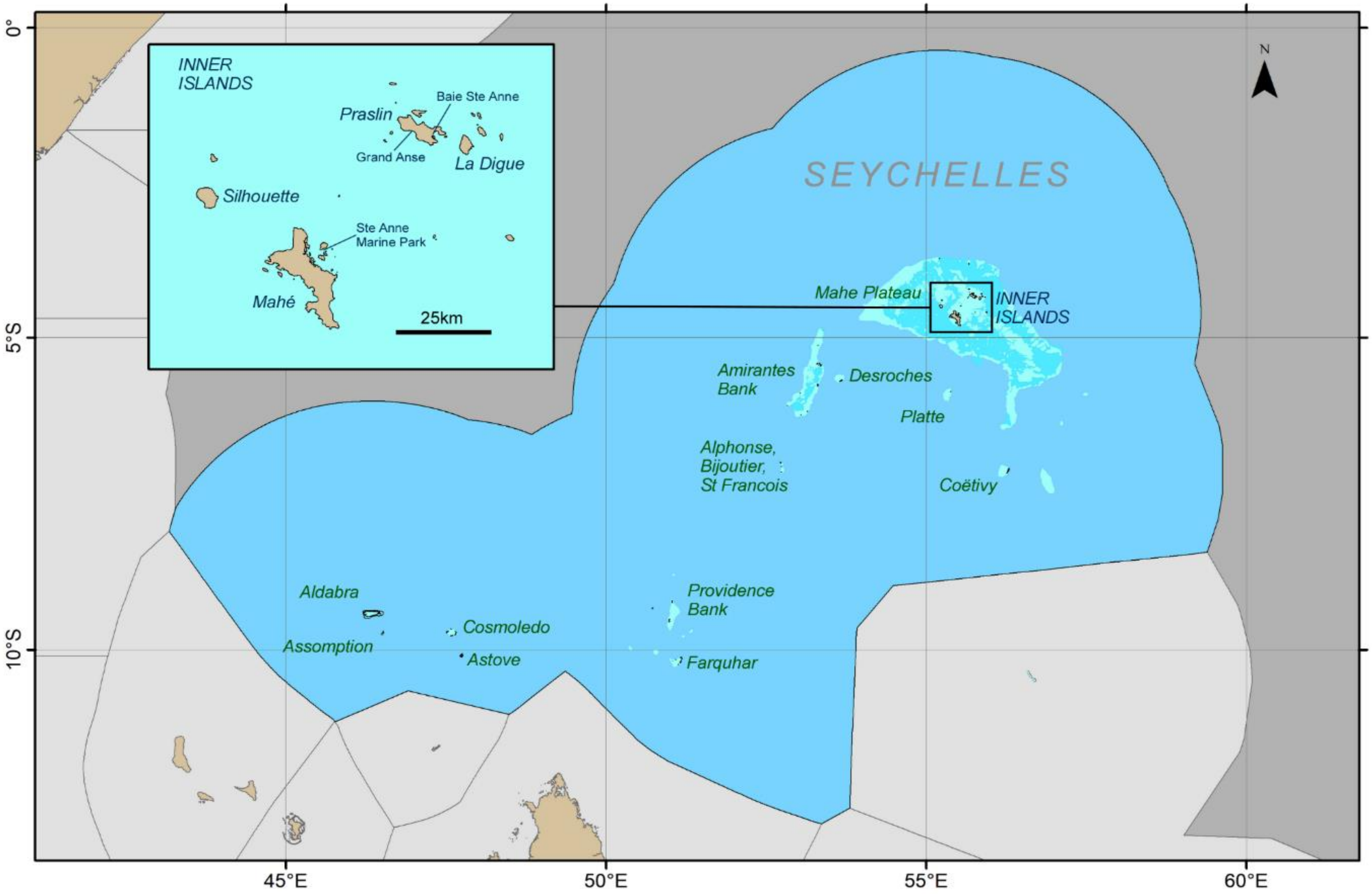


Figure 2: The Seychelles Islands in the Western Indian Ocean. The boundary of the Exclusive Economic Zone is shown in dark blue, with shallower plateaus, banks, islands and atolls shown in lighter shades. Inner (granitic) islands including the largest islands of Mahé, Praslin and La Digue are shown in the inset figure.

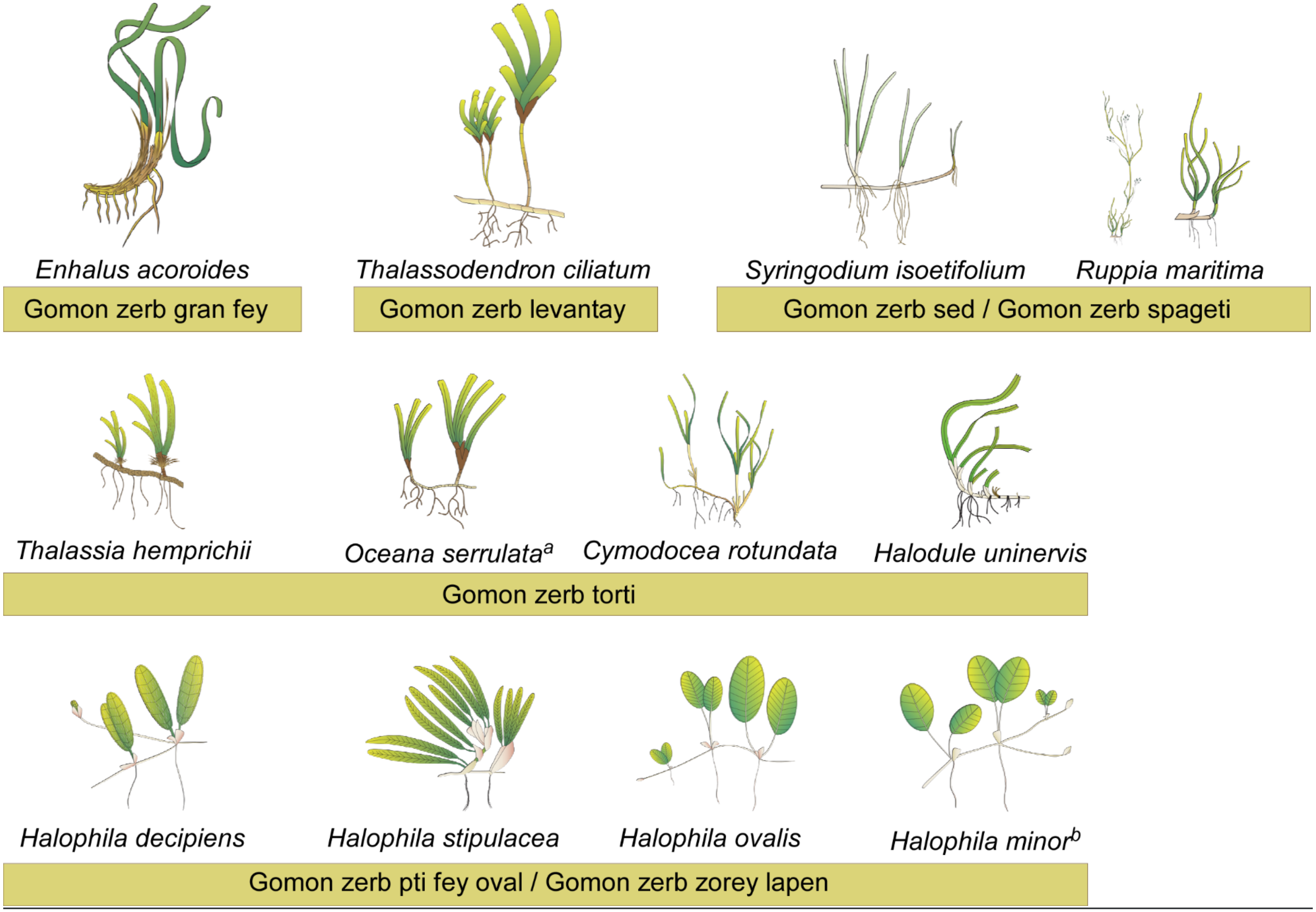


Figure 3: Seagrass species of Seychelles, showing scientific and main creole names. See Table 1 for distribution: [a] Formerly Cymodocea serrulata; [b]Taxonomy under revision. May be part of Halophila ovalis species complex. Seagrass graphics sourced from the Integration and Application Network (ian.umces.edu/media-library).

*Table 1: Comparison of the occurrence and distribution of twelve seagrass species in the Inner Islands and Outer Islands of Seychelles indicating whether the species has been reported to occur, and if so whether it tends to dominate meadows or only occur sparsely amongst other more dominant species. *Taxonomy under revision - may be part of Halophila ovalis species complex.*

			Inner Islands		Outer Islands	
Family	Species	Creole Name	Reported	Dominant	Reported	Dominant
Hydrocharitaceae	*Enhalus acoroides*	Gomon zerb gran fey	Yes	Yes		
	*Halophila ovalis (complex)**	Gomon zerb pti fey oval	Yes		Yes	
	Halophila decipiens		Yes		Yes	
	Halophila stipulacea		Yes		Yes	
	*Halophila minor**		Yes		Yes	
	Thalassia hemprichii	Gomon zerb torti	Yes	Yes	Yes	Yes
Cymodoceaceae	*Oceana serrulata*		Yes	Yes	Yes	
	Cymodocea rotundata		Yes		Yes	
	Halodule uninervis		Yes		Yes	
	Syringodium isoetifolium	Gomon zerb sed	Yes	Yes	Yes	
	Ruppia maritima				Yes	
	Thalassodendron ciliatum	Gomon zerb levantay	Yes	Yes	Yes	Yes

The Seychelles NDC

Nationally Determined Contributions (NDCs) are central to the Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC). They represent the efforts of each country to reduce emissions and adapt to the impacts of climate change. The Seychelles included the following commitments and targets specific to seagrass and other Blue Carbon ecosystems within the most recently updated NDC presented at the Glasgow 2021 COP (Republic of Seychelles 2021):

- Seychelles intends for coastal planning and infrastructure to be regulated at the national and local level to prioritise the consideration of "blue" Nature-based Solutions (NbS) for climate resilience;
- Seychelles will protect its blue carbon ecosystems, i.e., at least 50% of its seagrass and mangrove ecosystems by 2025, and 100% of seagrass and mangrove ecosystems by 2030;
- Seychelles will establish a long-term monitoring programme for seagrass and mangrove ecosystems by 2025 and include the Greenhouse Gas (GHG) sink of Seychelles' blue carbon ecosystems within the National GHG Inventory (NGGI) by 2025;
- Seychelles commits to the implementation of its adopted Marine Spatial Plan and the effective management of the 30% marine protected areas within the Seychelles' Exclusive Economic Zone.

Towards these targets, Seychelles committed to:

- Mapping the full extent of the blue carbon seagrass and mangrove ecosystems within its waters and measuring their carbon stock values. These assessments will inform our goal to include these ecosystems within our GHG inventory by 2025.

Seychelles Seagrass Mapping and Carbon Assessment Project

The *Seychelles Seagrass Mapping and Carbon Assessment Project* was initiated to address the above commitment and evaluate the coverage and carbon storage capacity of Seychelles' seagrasses 3 (Figure 4). The project addresses mapping and carbon data gaps, advances scientific understanding in the country, provides capacity building to support future surveys and a blueprint for further development of seagrass mapping and blue carbon research regionally.

Project goals were achieved through a series of workshops held in the Seychelles between March 2022 and August 2022, an extensive field campaign collecting vegetation samples and sediment cores across many inner and outer island sites and ground verification data for national seagrass maps. Field operations were severely delayed because of national and international travel and movement restrictions imposed on operations in response to the Covid-19 pandemic but were successfully conducted between October 2021 and April 2022. Field data fed into a mapping protocol based on satellite technology. Sediment and vegetation samples were processed and analysed at the University of Seychelles, with additional analyses conducted at laboratories outside of the country through support of RAF7020 IAEA AFRA project, which adds value to national ambitions and capacity in Seychelles. Information and outputs have been collated and passed to the Seychelles Ministry of Agriculture, Climate Change and Environment (MACCE) alongside this report.

Seychelles Seagrass and Carbon Mapping Project

Project will provide the scientific information needed to support country's climate action

Seagrass meadows store vast amounts of atmosphere-warming carbon in their underlying soil and are a nature-based solution to climate change. To generate a validated countrywide map and carbon stock estimate for seagrass in Seychelles, researchers will use remote satellite imaging and field data collections. This information will serve as the scientific baseline for policymakers to include seagrass protections in the country's Nationally Determined Contribution (NDC) to the Paris Agreement.

1. Mapping seagrass using satellite imagery

In the first phase of the project, researchers collect countrywide satellite images of the ocean. These images show the presence of seagrass, along with other ocean habitats, such as coral reefs. Because cloud cover and water clarity can affect the quality of the satellite imagery, field data is also collected to differentiate the images.

2. Field data collections on seagrass meadows

Researchers collect seagrass data throughout Seychelles, gathering information on the different species and density of seagrass, and taking soil core samples to estimate the carbon stored beneath the meadows.

3. Data is analyzed to estimate seagrass extent and carbon stock

The satellite images and field data are analyzed and used to produce a high-accuracy, field-validated map of seagrass distribution and extent. The soil cores are analyzed for their carbon content and used to generate a first-time estimate of carbon stock for seagrass meadows in the country.

4. Scientific information informs policy decisions

This scientific information on the distribution of seagrass and its associated carbon stock gives policymakers the information they need to include the protection of seagrass in their NDCs as a nature-based solution to climate change.

Figure 4: Overview of the Seychelles Seagrass Mapping and Carbon Assessment Project

Methods

The sampling methodologies for carbon estimation follow the recommendations of the Coastal Blue Carbon manual (Howard et al. 2014) and the revised Intergovernmental Panel on Climate Change (IPCC) carbon accounting standards for coastal wetlands (IPCC 2013).

The mapping of seagrass area, especially when conducted at large spatial scales required for national assessments involves the melding of field ground truth data with satellite imagery. Direct mapping of carbon is not possible, and therefore relies on cores to sample carbon stored in subsurface sediments and above ground vegetation. Carbon values estimated for cores are then interpolated to national estimates based on spatially continuous map data.

Estimating the national carbon stock ($Total\ Carbon\ (Tonnes)$) combines an estimate of the aerial extent of seagrass habitats ($Seagrass\ Area\ (Ha)$) (i.e. a map of seagrass) and an estimate of organic carbon for a given area of seagrass habitat ($C_{Org}\ (Tonnes\ Ha^{-1})$). Total Carbon is therefore calculated according to Equation 1 below:

$$Total\ Carbon\ (Tonnes) = Seagrass\ Area\ (Ha) \times\ C_{Org}\ (Tonnes\ Ha^{-1}) \qquad (1)$$

Remote Sensing and Mapping

Methods and techniques for mapping tropical marine and coastal environments from satellite data have been established across coral reef and intertidal habitats (Rowlands et al. 2012; Purkis et al. 2019). Emerging techniques favour the use of cloud computing environments such as Google Earth Engine (GEE) to manage the greater handling and computational loads of analysis (Traganos and Reinartz 2018; Lyons et al. 2020; Mora-Soto et al. 2020). To deliver seagrass maps for Seychelles, we will build on methods developed in the Mediterranean Sea (Traganos and Reinartz 2018; Traganos et al. 2018), and since adapted to specific sites in the Western Indian Ocean (WIO), including in East Africa (Traganos et al. 2022). The work incorporates multi-temporal NICFI PlanetScope image mosaics into a Sentinel-2 workflow providing additional opportunities to increase map accuracy, and resilience to data gaps as described in Lee et al. (2023).

GROUND TRUTH

Detailed ground survey was conducted at 16 island and atoll locations encompassing the inner (Mahé, Praslin and La Digue) and outer islands (Desroches, D'Arros, St Joseph Atoll & Northern Amirantes Bank, Farquhar, Cosmoledo, Alphonse Group, Astove, and Denis); see Table 2. Surveys were conducted from a range of vessels and platforms including dive boats, skiffs, kayaks. Over 50 predominantly Seychellois researchers spanning more than 20 institutions were involved in data gathering (see ‘Partners and collaborators’), equating to ~450 surveyor’s days.

Over 40,000 georeferenced photo quadrats were collected by teams of divers and/or snorkelers adapting the methodologies utilised during the Allen Coral Atlas mapping project (Roelfsema et al. 2015); Roelfsema et al. (2021), Figure 5). Photo quadrats were collected along transects oriented to traverse a range of probable habitat types such as seagrass, coral, and algae identified from visual interpretation of satellite imagery (Figure 9). In the case of SCUBA transects, divers typically started at a maximum depth of 25 m on a transect bearing that ran perpendicular to shore, and at a designated depth that ran parallel to shore on the designated depth contour between 10 and 5 meters. Photographs were taken from a downward facing view, between 5 and 7 m apart along the transect. Photographs were geotagged by cross referencing the time a photo was taken to the time and position (latitude and longitude) recorded using a GPS within a towed surface marker buoy. The ~40,000 photographic images were then analysed using the Coral Net deep learning software (Beijbom et al. 2015) training a classifier on 79,400 points taken from 1,588 images Figure 6. Images were annotated by percentage cover of benthic flora, fauna, rock and sediment with accuracy of classifying sand and seagrass both over 90%, and an overall accuracy across all substrate types of 76% (Figure 6); illustrations of classified images are provided in Figure 7.

When assessing deeper areas, or if restricted by the size of the available survey team, or where deployment was impractical, georeferenced drop-camera video was collected following methodologies of Rowlands et al. (2012). Video drops were collected at intervals of between 200 and 300 m depending on the variability of bottom types seen in satellite imagery and encompassing different depth and exposure regimes (Figure 8). Additional historical/legacy data, contextual information and maps were provided into the project from various institutions and individuals including ICS, BERI-UniSey, Ministry of Agriculture, Climate Change and Environment (MACCE), Seychelles Fishing Authority (SFA), Marine Conservation Society Seychelles (MCSS), Jeanne A Mortimer and Jude Bijoux. Nonetheless, some gaps in ground truth remain on the Mahé plateau, Aldabra Atoll, and several other outer island locations. Benthic data from all field surveys were then classified to classes based on the dominant cover characteristics of Seagrass, Coral/Algae, Microalgal Mats, Sand, Rock, Rubble, and a Mixed (co-dominant) class (Figure 9).

To map seagrass habitats at a national scale, satellite images were used, following the processing workflow outlined in Figure 10. Two types of freely available satellite data were used: 1) Sentinel-2 imagery from the European Space Agency (ESA), which has a 10 m image pixel; and 2) The biannual composites of the Surface Reflectance PlanetScope image product supplied at a 5m pixel resolution through the Norway's International Climate and Forests Initiative (NICFI) satellite data program. Together these two sensor constellations deliver an expanding image data stack spanning the Earth’s tropics, together. The specific temporal span of satellite data varies depending on historical and ongoing satellite tasking, but for many locations’ dates extends back to ~2015, with satellite revisit times ranging from 1-5 days.

Table 2: Field data summary

Region	Location	Sediment cores	Vegetation/ Root Samples	Drop Camera Videos	Georeferenced Photo quadrats
Inner Islands	Mahé	16	4	101	16,413
	Praslin & La Digue	21	0	0	12,736
Outer Islands	Desroches	17	11	212	3,908
	D'Arros, St Joseph Atoll & Northern Amirantes Bank	8	8	241	1,732
	Farquhar	7	6	63	1,336
	Cosmoledo	8	8	40	1,351
	Alphonse Group	9	9	95	1,363
	Astove	4	4	0	654
	Denis	0	0	15*	247
	Owen Bank (Mahé Plateau)[a]	2	0	180	0
Legacy (Various)	(Providence Bank, Platte, Alphonse, Mahé, Desroches, D'Arros, Mahé Bank, Bird)	0	0	26[b]	996
	Total	92	50	793	40,736

[a] Additional data collected in Apr 2024 on Greenpeace Rainbow Warrior Cruise.

[b] Legacy data from BRUV video stations and collected before 2021.

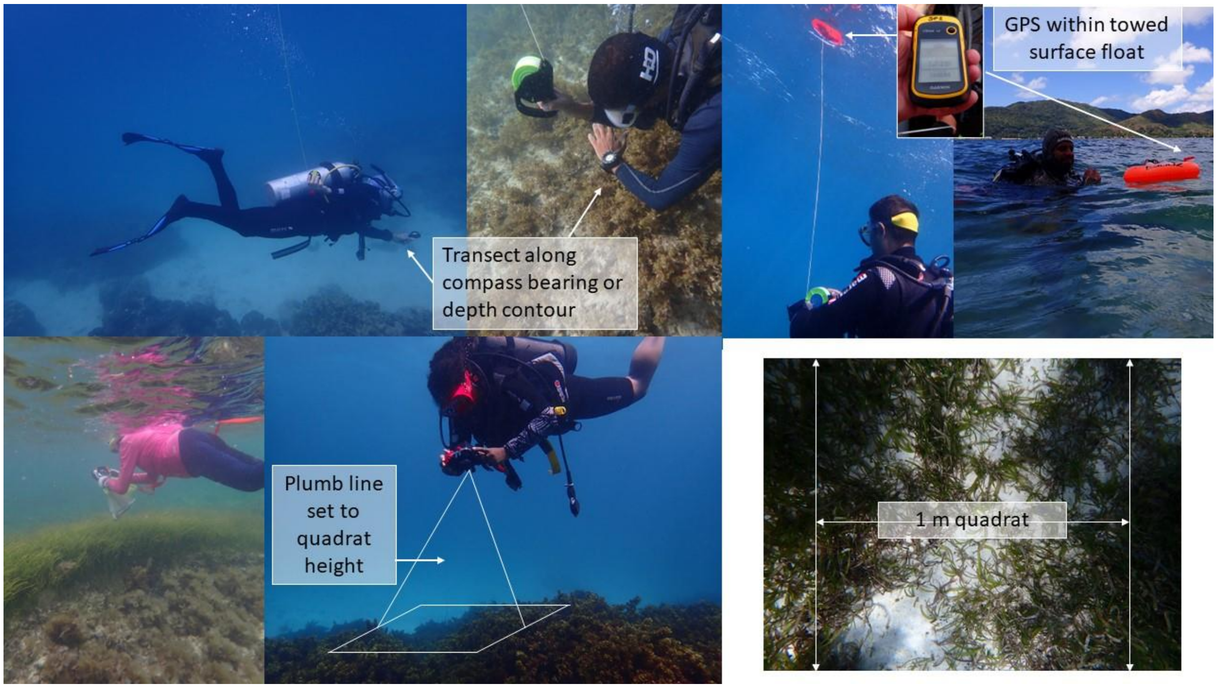
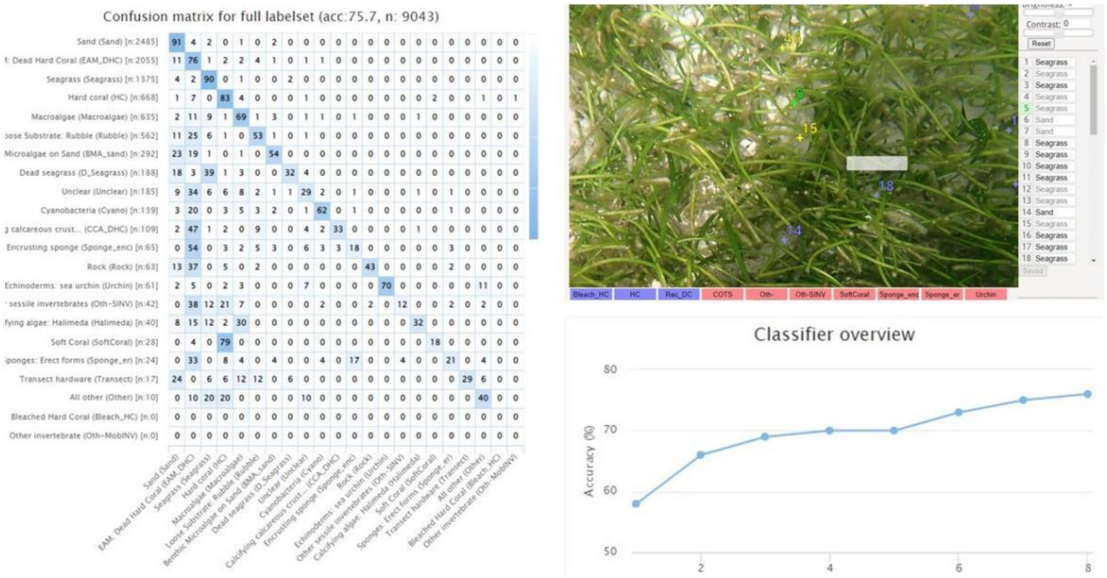


Figure 5: Collection of photo quadrats used in ground truthing and data analysis. Photo quadrats are collected by a survey team using SCUBA or snorkel. Transect bearings are followed using a compass bearing or visible landmark. Photographs are geotagged using a towed GPS. Photo quadrats are taken from a vertical position above the seabed, with a plumbline used to ensure quadrat photos equate to a 1 m ground distance in the shortest dimension – see Roelfsema et al. (2015) for further details on method.


Confusion matrix for full labelset (acc:75.7, n: 9043)

	Sand (Sand)	EAM: Dead Hard Coral (EAM_DHC)	Seagrass (Seagrass)	Hard coral (HC)	Macroalgae (Macroalgae)	Loose Substrate: Rubble (Rubble)	Benthic Microalgae on Sand (BMA_sand)	Dead seagrass (D_Seagrass)	Unclear (Unclear)	Cyanobacteria (Cyano)	Calcifying calcareous crust... (CCA_DHC)	Encrusting sponge (Sponge_enc)	Rock (Rock)	Echinoderms: sea urchin (Urchin)	Other sessile invertebrates (Oth-SINV)	Calcifying algae: Halimeda (Halimeda)	Soft Coral (SoftCoral)	Sponges: Erect forms (Sponge_er)	Transect hardware (Transect)	All other (Other)	Bleached Hard Coral (Bleach_HC)	Other invertebrate (Oth-MobINV)
Sand (Sand) [n:2485]	91	4	2	0	1	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
: Dead Hard Coral (EAM_DHC) [n:2055]	11	76	1	2	2	4	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
Seagrass (Seagrass) [n:1375]	4	2	90	0	1	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hard coral (HC) [n:668]	1	7	0	83	4	0	0	0	1	0	0	0	0	0	0	0	2	0	0	1	0	1
Macroalgae (Macroalgae) [n:635]	2	11	9	1	69	1	3	0	1	1	0	1	0	0	0	1	0	0	0	0	0	0
ose Substrate: Rubble (Rubble) [n:562]	11	25	6	1	0	53	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Microalgae on Sand (BMA_sand) [n:292]	23	19	1	0	1	0	54	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dead seagrass (D_Seagrass) [n:188]	18	3	39	1	3	0	0	32	4	0	0	0	0	0	0	0	0	0	0	0	0	0
Unclear (Unclear) [n:185]	9	34	6	6	8	2	1	1	29	2	0	1	0	0	0	1	0	1	0	0	0	0
Cyanobacteria (Cyano) [n:139]	3	20	0	3	5	3	2	0	1	62	0	1	0	0	0	0	0	1	0	0	0	0
calcareous crust... (CCA_DHC) [n:109]	2	47	1	2	0	9	0	0	4	2	33	0	0	0	0	1	0	0	0	0	0	0
Encrusting sponge (Sponge_enc) [n:65]	0	54	0	3	2	5	3	0	6	3	3	18	0	0	0	0	0	3	0	0	0	0
Rock (Rock) [n:63]	13	37	0	5	0	2	0	0	0	0	0	0	43	0	0	0	0	2	0	0	0	0
Echinoderms: sea urchin (Urchin) [n:61]	2	5	0	2	3	0	0	0	7	0	0	0	0	70	0	0	0	0	0	11	0	0
sessile invertebrates (Oth-SINV) [n:42]	0	38	12	21	7	0	0	0	0	2	0	0	2	0	12	0	0	2	0	2	0	0
fying algae: Halimeda (Halimeda) [n:40]	8	15	12	2	30	0	0	0	0	0	0	0	0	0	0	32	0	0	0	0	0	0
Soft Coral (SoftCoral) [n:28]	0	4	0	79	0	0	0	0	0	0	0	0	0	0	0	0	18	0	0	0	0	0
ponges: Erect forms (Sponge_er) [n:24]	0	33	0	8	4	0	4	0	0	4	0	17	0	0	4	0	0	21	0	4	0	0
Transect hardware (Transect) [n:17]	24	0	6	6	12	12	0	6	0	0	0	0	0	0	0	0	0	0	29	6	0	0
All other (Other) [n:10]	0	10	20	20	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	40	0	0
Bleached Hard Coral (Bleach_HC) [n:0]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Other invertebrate (Oth-MobINV) [n:0]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Contrast: 0

1 Seagrass
2 Seagrass
3 Seagrass
4 Seagrass
5 Seagrass
6 Sand
7 Sand
8 Seagrass
9 Seagrass
10 Seagrass
11 Seagrass
12 Seagrass
13 Seagrass
14 Sand
15 Seagrass
16 Seagrass
17 Seagrass
18 Seagrass

Figure 6 Classification of georeferenced photoquadrats (upper left) using Coral Net; (upper right). The classifier is trained by the analyst and improves in accuracy as more training images and points are classified; (lower left) confusion matrix of benthic classes.

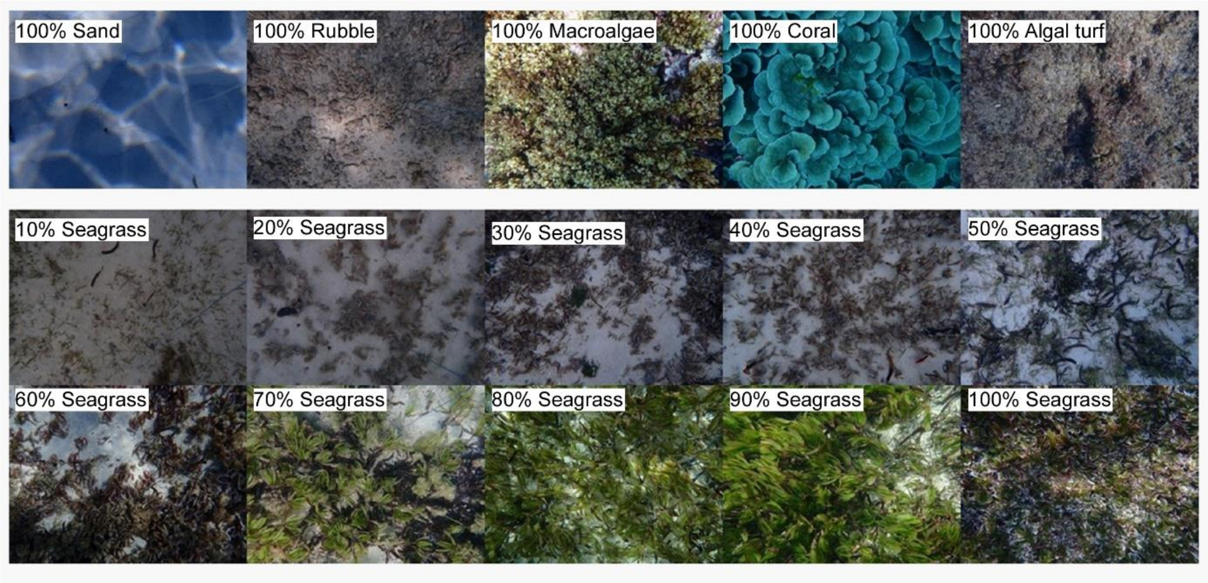


Figure 7 Cover of different benthic (sea floor) types: (upper panel) 100% cover of sand, rubble, macroalgae, coral, algal turf; (lower panel) 10-100% cover of seagrass (various species) shown in 10% increments.

Figure 8: Drop camera video. Percent cover is calculated in broad benthic classes based on cover in bottom region of unique video frames sampled along 10 m transects, with individual transects separated by at least 15 m.

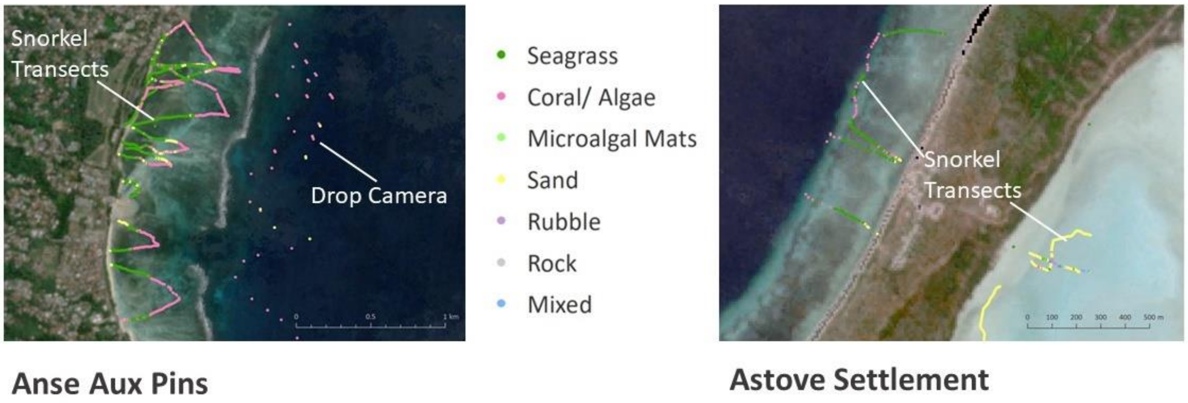


Figure 9: Examples of transect and drop-camera data classified for two different locations (left) Anse Aux Pins, Mahé; (right) Astove atoll.

SEAGRASS MAPPING

Image pre-processing

Prior to classification, the initial stack of satellite imagery was processed through several filtering and pre-processing steps 9 (Figure 10). For a given region, an initial multi-temporal stack of Sentinel-2 (S2) Level-2A (L2A) Surface Reflectance data product was assembled within Google Earth Engine (GEE). Images were then be filtered for cloud cover, removing scenes from the image archive with more than 25% cloud cover. Additional pixels flagged as clouds by the image providers' cloud detection algorithm ('Quality Assurance' – Cloud flags) were then removed from each scene. The stack of images was then reduced to a single image mosaic based on the 20th percentile value of each image pixel. This multi-temporal approach to pre-processing is an effective means to filter light and dark artefacts, delivering a seamless mosaic across multiple scenes, and circumventing the challenge of tidal ranges as the lower 20% reflectance composite is the quantitative analogue of a low tide composite.

NICFI PlanetScope NICFI data from 2015-2020 were also used to create an image composite. An interval mean of the 10th percentile and median (50th percentile) was used to reduce both the cloud shadows and sun glint on the nationally aggregated composite. While the images were atmospherically corrected based on terrestrial models, previous studies in East Africa showed that the atmospherically corrected surface reflectance could also be used for seagrass mapping (Traganos et al. 2022). The surface reflectance image composite was assumed to be the normalised water leaving reflectance and was then divided by pi to obtain sea surface water leaving reflectance. Depth invariant bands and normalised difference bands of the four spectral bands (blue, green, red, NIR) were included to increase the feature space used to classify benthic habitats on the satellite imagery.

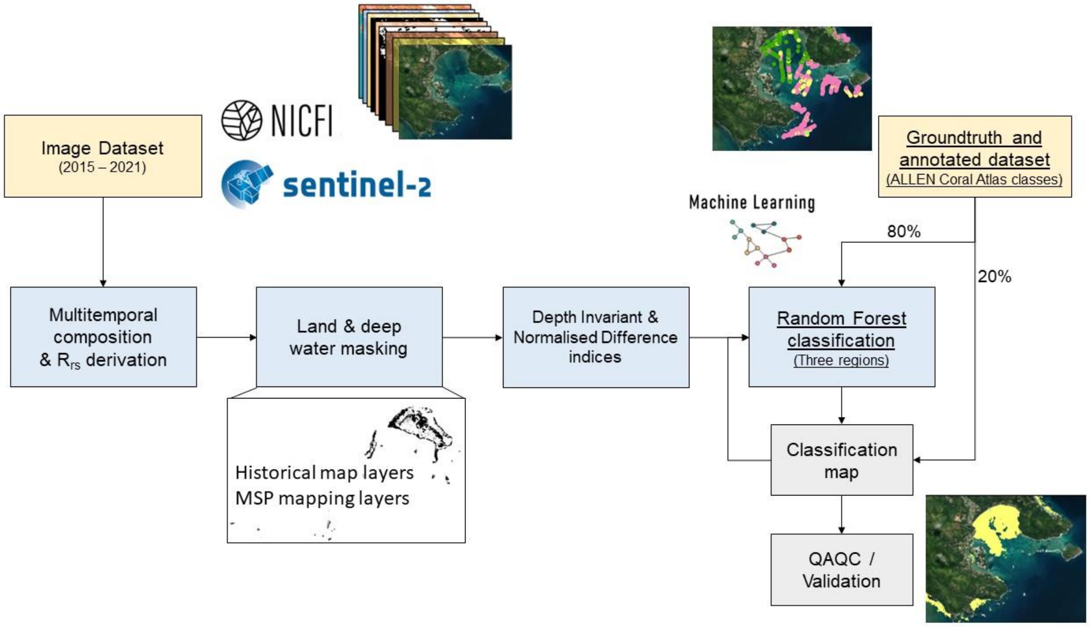


Figure 10: Pre-processing and classification workflow for satellite imagery through to a validated map product

Image masking

Satellite based techniques for seagrass mapping are depth limited by the optical properties of the water. Where water is calm and clear, seagrass systems may be imaged to a maximum depth of ~30m, while turbid conditions may obscure the seabed or reduce the depth of effective light penetration. The image composite was therefore masked for land and deep water, to focus analysis on shallow waters where seagrass is 'mappable'. Automated workflows (Traganos et al. 2022).,, may be further supplemented by historical map data to determine the areas of interest, as was recently conducted in Seychelles. Use of such automated workflows also serve to highlight any image or data quality gaps, for which additional imagery may be required. A Green-NIR NDWI band was used in conjunction with an Otsu's threshold as an initial process to mask out the land pixels. A true colour hue-saturation-brightness value (HSV) transformation was also obtained, and the HSV bands were used to help identify 'deep water pixels'.

Regional Classification

Image characteristics were found to vary latitudinally and away from the inner islands (largely in response to cloud effects and data availability). It was therefore useful to split the EEZ of Seychelles.). into three geographic regions for classification purposes. These are: North (Mahé Plateau including the Inner Islands), Central (Amirantes, Platte, Coëtivy and Alphonse group) and Southern (Southern islands including Aldabra, Cosmoledo, Providence Bank and Farquhar groups), see Figure 11.

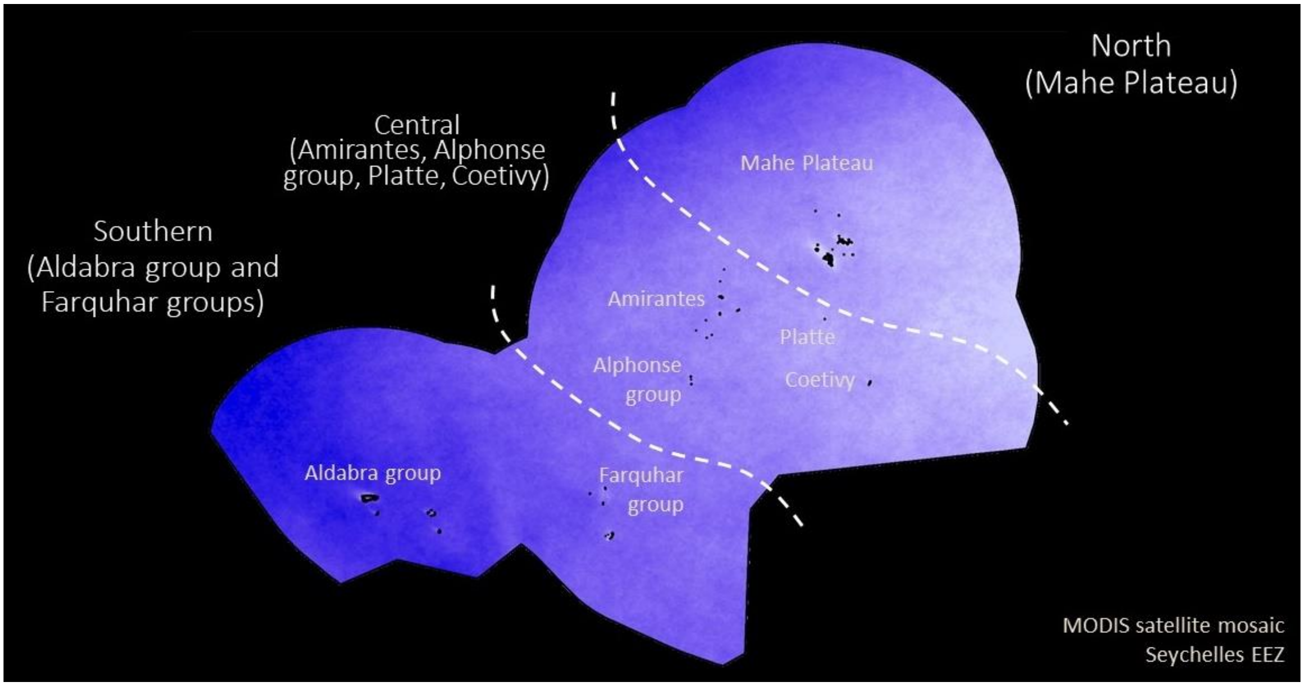


Figure 11 North, Central and Southern geographic regions used in model development overlaying MODIS satellite cloud cover estimates across the Seychelles EEZ. Brighter shade indicates higher proportion of cloud cover in a region

As the ground truth data included GPS tracks with individual points within close to each other (1-5 m), the dataset was thinned out by selecting only the modal class per NICFI Planetscope pixel. Additional points were created using expert knowledge to improve the spatial representation of each class. A bathymetry threshold of 15 m, identified using the Allen Coral Atlas benthic map, was then used to divide the classes into their shallower and deeper subclasses. The classes were randomly split into training and test dataset by an 80:20 ratio. The training data was then normalised by retaining only values between the 5th and 90th percentile to remove anomalous points. No normalisation was performed on the test dataset to maintain the strictness of the validation test. Image bands spanning the visible spectrum (443–705 nm), textural data layers, and other derived metrics from the pre-processed image composite are then analysed along with field ground truth data and run via a machine learning Random Forest (RF) classifier within a machine learning framework. The Random Forest model was applied via the smileRandomForest function (number of trees = 50) in Google Earth Engine. Following, the accuracies were calculated.

Areas of the outer rim were mapped through a combination of NICFI PlanetScope, and Sentinel-2 and occasionally Landsat data, however there remained cloud cover and image quality issues in some areas. In such cases, the dense seagrass polygons created for the Seychelles-MSP were accepted where they correlated to discernible seafloor features or discernable features were manually digitised if providing good congruence through to areas mapped directly from NICFI PlanetScope or Sentinel-2 data and supported by field survey.

This approach is reliable for processing large satellite data, handling collinearity and nonlinearity between predictor variables, and proving robust against overestimates and noise in the input data. The approach has delivered robust results in local-to-global remote sensed sensing-based mapping within both local and cloud environments (Traganos and Reinartz 2018; Lyons et al. 2020; Traganos et al. 2022; Rowlands et al. In Prep). The output is a spatially explicit seagrass map layer. This data layer can be subjected to further validation to identify and correct any mapping errors and amend the classification approach. In the Seychelles case study, for example, differences were noted in spectral character of imagery across depth and latitude resulting in development of nuanced models accounting for these differences (Rowlands et al. In Prep), while work in East Africa highlights the need for consideration of turbidity gradients (Traganos et al. 2022). Final map products have been delivered to MACCE in GIS-ready data formats suitable for use by a variety of stakeholders.

Carbon Assessment

SEDIMENT CORES

A total of 90 undisturbed sediment cores were taken across the entire subtidal area using a Universal Corer® 1(Figure 12; Aquatic Research Instruments - 68 mm internal diameter, 120 cm long), from eight locations distributed along a latitudinal gradient (Figure 13). The corer was pushed, then hammered into the sediment to a depth of 120 cm or until bedrock was struck (i.e., depth of maximum penetration or refusal). The corer was then retrieved, and the intact sediment core was taken to the shore to be extruded. Because access was easier to for coring in shallower environments, coring effort was skewed towards shallower depths, though across the span of the project most depths were cored at least once 3 (Figure 14). In shallow water depths a full range of depths of penetration were recorded from a few centimetres to the maximum corer length (120 cm), In depths exceeding ~10 m however most cores penetrated at least 50 cm into the of sediment 4 (Figure 15). Cores were extruded and sliced every centimetre in the top 20 cm with a ceramic blade, then every 2 cm down to the bottom of the core 5 (Figure 16). Samples were preserved in pre-labelled zip bags in darkness and at 4^{o}C. For every sample, the fresh and the dry weights were determined after drying at 60^{o}C (72h to 96h) to a constant weight.

The dry bulk density (*DBD* in g/cm^3) was computed according to Equation 2 and 3:

$$DBD\ (gcm^{-3}) = \frac{Dry\ weight\ of\ sample\ (g)}{Volume\ of\ soil\ sample\ (cm^3)} \tag{2}$$

where,

$$Volume\ of\ soil\ sample\ (cm^3) = (\pi \times radius\ of\ the\ corer)^2 \times height\ of\ the\ slice \tag{3}$$

Measurements of barrel length, depth of penetration and length of retrieved core were collected to compute a core averaged $Compaction\ correction\ factor$ for each core according to Equation 4.

$$Compaction\ correction\ factor\ = \frac{length\ of\ retrieved\ core\ (cm)}{depth\ of\ penetration\ (cm)} \tag{4}$$

Figure 12: Collection of sediment cores in different environments using the Universal Corer® (Aquatic Research Instruments - 68 mm internal diameter, 120 cm long)

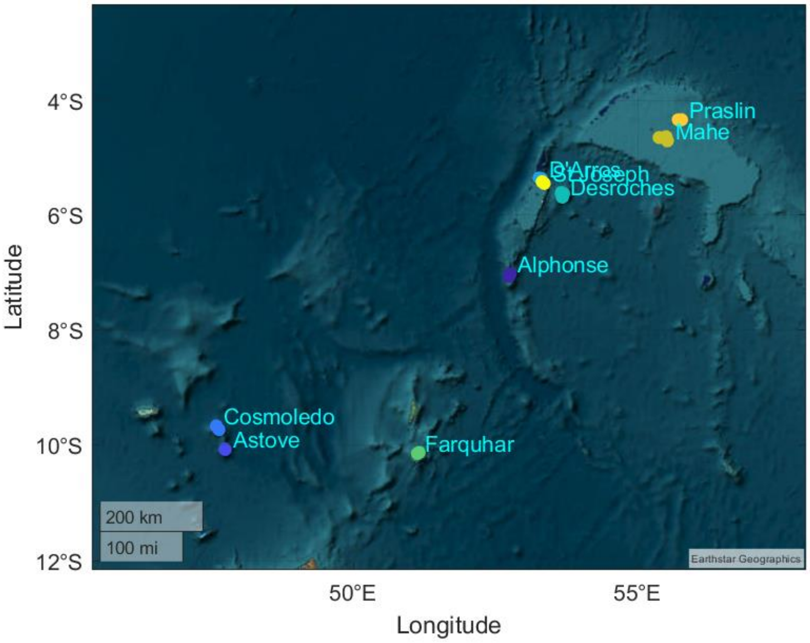


Figure 13: Eight locations where sediment cores were collected during the field work phase of the project.

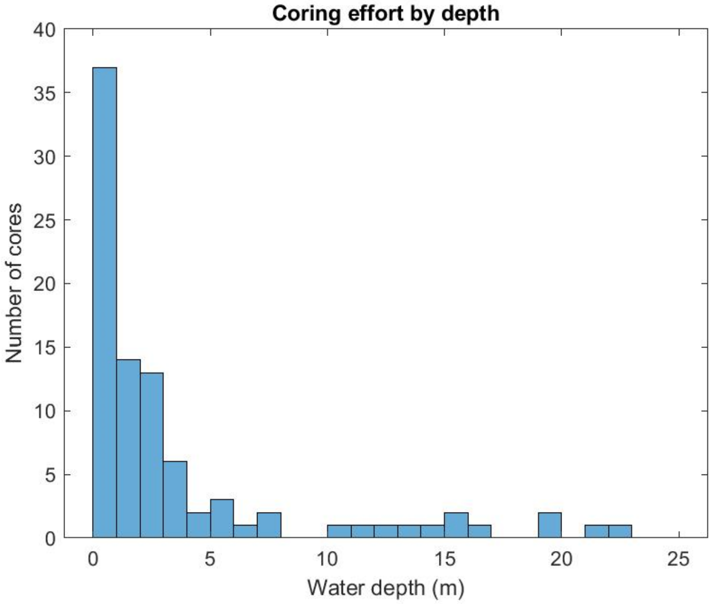


Figure 14: Histogram of coring effort showing the number of cores collected at each depth (1m depth bins). Depth is the non-tide adjusted depth, as recorded at time of sampling.

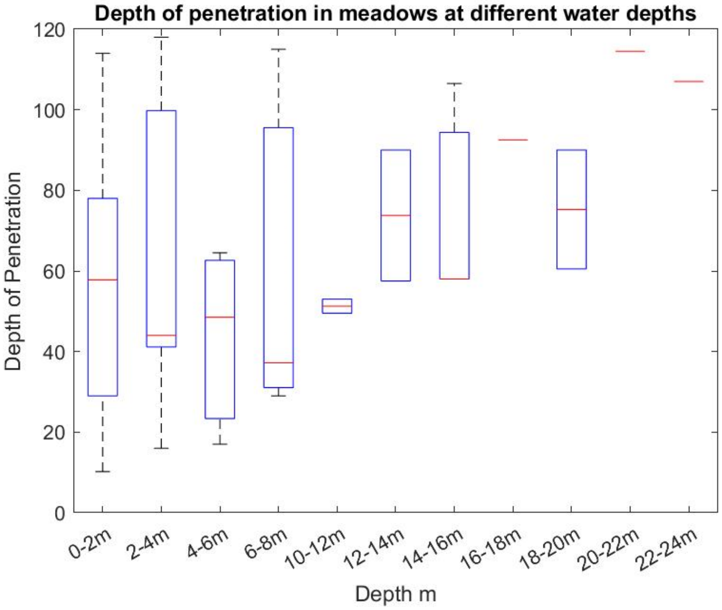


Figure 15: Depth of penetration (~depth of refusal) achieved for cores collected at different water depths shown for 2 m depth bins.

Figure 16: Extruding and cataloguing of sediment samples.

PLANT BIOMASS

Above ground vegetation and detritus samples were collected at most sites sampled (Figure 17). In most cases a 30 × 30 cm quadrat was used. Leaves and stems were cut flush to the seabed using a dive knife and collected into a sample bag. Surface detritus falling within the quadrat was also collected. These 'vegetation' samples were supplemented by 32 'full plant samples' collected using a 10 cm internal diameter PVC pipe corer following methods described in Howard et al. (2014), placed over an area assessed as representative of the site sampled for sediment. The full plant samples were separated into carbon pools comprising roots, shoots, rhizomes, and leaves (separated where possible by species) as well as detritus and epibionts. Samples were dried at 60ºC (72h to 96h) to a constant weight and finely chopped in a food processor.

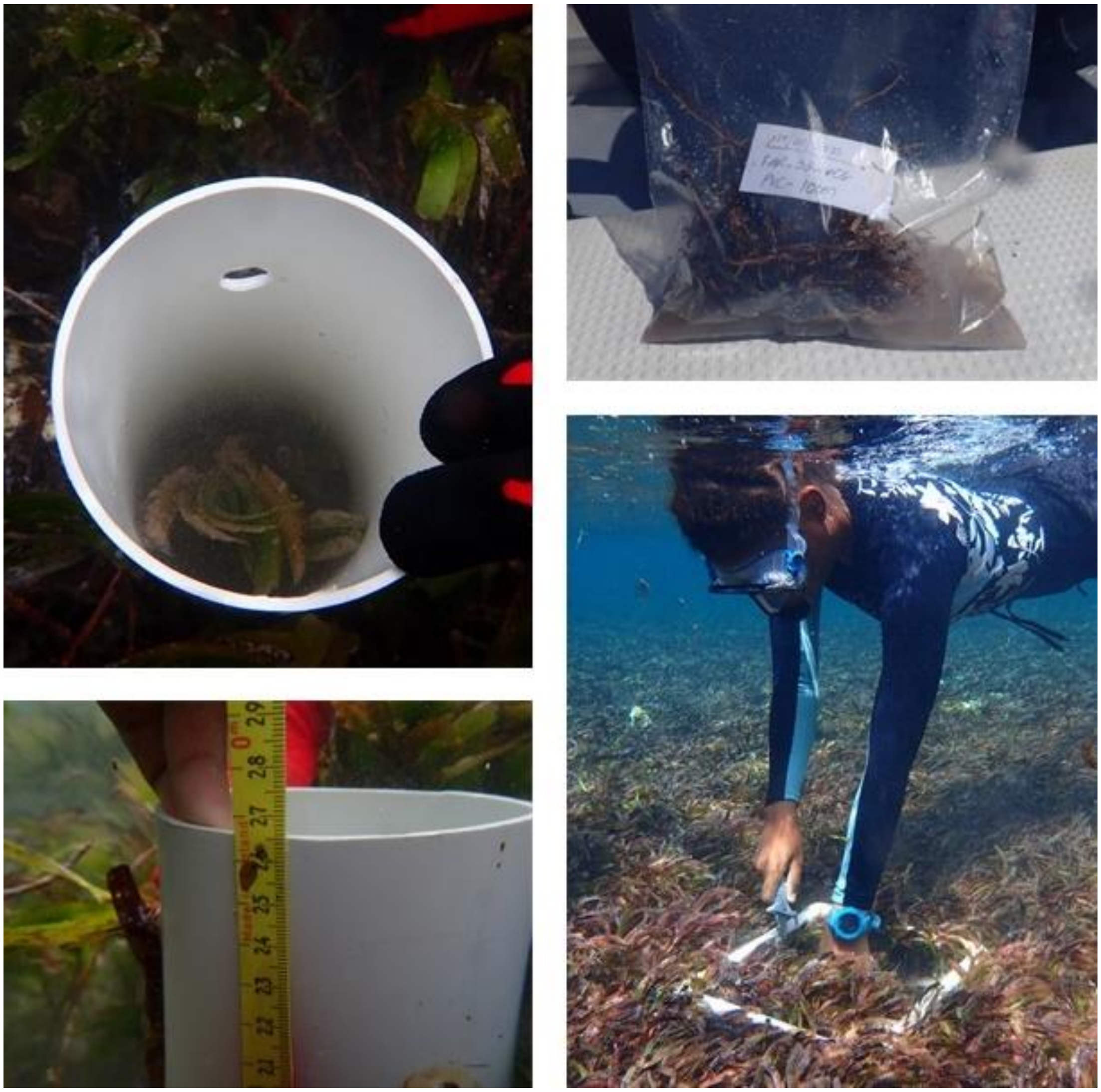


Figure 17: Sampling above and below ground biomass and detritus using a 10 cm PVC pipe and a 30 x 30 cm quadrat.

CARBON ANALYSIS

Seychelles seagrasses are composed of tropical species growing in calcareous sediments (soil). The organic carbon (C_{Org}) content of a soil sample can be measured by using either an automated elemental analyser where the sample is combusted in a furnace and the detector returns the amount of CO_2 resulting from the oxidation of the organic matter. Another approach that we used consists in a combination of elemental analysis and or using Loss on Ignition (LOI) where the sample is combusted into ash in a muffle furnace. The loss of weight is assumed to be organic matter, from which organic carbon is determined using the empirical relationship built on a subset of representative samples assessed using by elemental analysis. While a global empirical relationship is commonly used as a Tier 1 approach (Howard et al. 2014), best practice in-line with a Tier 2-3 IPCC approach we aimed at is to derive the locally relevant empirical relationship (Howard et al. 2014). Therefore,

while all 90 cores were analysed using the more cost effective LOI method, 89 sub-samples from 13 cores were also assessed using an elemental analyser to confirm an appropriate empirical model for Seychelles. Sequestration rates (i.e. the rate at which carbon is accumulated in the seabed) which was assessed using the lead-210 (^{210}Pb) method for 23 cores.

Loss On Ignition (LOI)

A subsample of ~1.00 g of each slice was homogenised by hand in a mortar, dried overnight at 105^{o}C, transferred into pre-weighed ceramic crucibles (Haldenwanger© 79C-3) and weighed with an analytical scale (AND GH-300) to the precision of a tenth of milligram ($Dry\ Weight_{105}$) (Figure 18).

Percent Organic Matter (OM%) was computed as the percent change in weight of the dried sample after ashing at 550^{o}C for 6 hours in a muffle furnace, described as LOI_{550} in Heiri et al. (2001) see Equation 5:

$$LOI_{550} = \frac{(Dry\ Weight_{105} - Dry\ Weight_{\ 550})}{Dry\ Weight_{\ 105}} \times 100 \tag{5}$$

The calcium carbonate ($CaCO_3$) component of the sample was computed as the change in weight of a sample after further combustion at 950^{o}C for 2 hours. During this process, $CaCO_3$ is converted into quicklime (CaO), see Equation 6:

$$LOI_{950} = \frac{(Dry\ Weight_{550} - Dry\ Weight_{\ 950})}{Dry\ Weight_{\ 105}} \times 100 \tag{6}$$

Assuming a weight of 100.09 g mol^{-1} for $CaCO_3$ and 56.08 g mol^{-1} for CaO, the weight loss by LOI at 950°C was multiplied by 1.785 to theoretically equal the calcium carbonate content in the original sample. Organic matter and calcium carbonate (OM% and $CaCO_3$%) are expressed as a percentage of the dry mass of each sample. Soil carbon density was calculated for all the soil subsamples in each core and summed. The same methodology was applied to vegetation samples collected at the same location to obtain their relative OM% (and $CaCO_3$% when applicable, e.g. for the calcareous *Halimeda* algae).

Carbon estimates are presented for a maximum decompressed depth of 100 cm or a minimum depth of 30 cm, depending on the depth at which substrate resistance was met. decompressed Some studies and sampling guides recommend extrapolating data to 1 m (to permit global comparison). This was not possible in most cases due to the relatively shallow sediment accumulation depth. Our cores and probes typically reached depth of refusal at shallower than 1m - especially on geologic features such as backreefs. Thus, the values presented are a more robust and true assessment of the carbon stocks in study area.

Figure 18: Processing of soil and vegetation samples at the University of Seychelles

Elemental Analysis (EA)

Elemental analysis for Carbon, Hydrogen and Nitrogen (CHN) was conducted on 13 cores, assessing 89 samples spanning a range of depths below surface, with approximately 15g dried sediment samples shipped to the University Hawaii Hilo laboratory for analysis. Samples were acidified and subjected to elemental analysis to determine the organic and inorganic carbon component. A further 17 vegetative material samples of leaves and stems (n = 14) and roots and rhizomes (n = 3) were also analysed. As recommended in (Howard et al. 2014). The organic matter content (C_{Org}) of sediment was computed, using the locally derived empirical relationship (Equation 10 in the results section), but also discussed in relation to the global relationship described in (Fourqurean et al. 2012).

Carbon sequestration rates

An assessment of sediment accumulation rates over the past decade/century was made by assessing 23 sediment cores using excess Lead-210 accumulation (^{210}Pb) method (Arias-Ortiz et al. 2018a). The sediment cores that had been sliced every 1 or 2 cm, dried were sieved at 63 μm to conduct the analyses in the fine (clay) fraction. The concentrations of ^{210}Pb along the cores were determined through the analysis of its granddaughter Polonium-210 (^{210}Po) by alpha spectrometry after addition of Polonium-209 (^{209}Po) as an internal tracer and digestion in acid media using an analytical microwave (Sanchez-Cabeza et al. 1998). Some samples from each core were analysed by gamma spectrometry to determine the concentrations of Radium-226 (^{226}Ra). The concentrations of excess ^{210}Pb used to apply the age models were determined as the difference between total ^{210}Pb and ^{226}Ra (supported ^{210}Pb) as described in (Krishnaswamy et al. 1971; Arias-Ortiz et al. 2018b).

Results

An initial interpretation and presentation of results is provided below. A more detailed and exhaustive analysis of the data will be completed and submitted for publication in an academic journal in Spring 2023 (Rowlands et al., in prep) and should be referenced as the definitive output of the project.

Habitat Mapping

A total of 1,599 km2 (159,920 ha) seagrass were mapped across Seychelles (Figure 19), however seagrass habitat was not distributed evenly across the geographic regions studied.

In the Northern region (Mahé Plateau; Figure 20) the majority of seagrass was found on the outer rim of the platform where 52,661 ha of seagrass habitat were mapped. Seagrass was less abundant in the granitic inner islands compared to similar sized systems in the coralline outer islands, with seagrass tending to be limited to sheltered reef flats, and bays. Around Mahé, the most extensive seagrass beds were found near Anse Aux Pins (Au Cap), Baie Ternay, île Therese, and in Saint Anne Marine National Park. While the majority of seagrass was still shallow (< 2 m depth) in the shallows between Sainte-Anne and Cerf Islands, some of the deeper seagrass habitat of the inner islands was found in the marine park with small patches located up to 10 m depth. Praslin had the most extensive seagrass habitat of the inner islands, particularly at Grande Anse, and Baie Sainte-Anne with mixed species seagrass beds extending to about 8 m depth. At Silhouette, seagrass was reported at a few locations at low densities (<10% cover), often intermixed with macroalgae, and with patch sizes below the minimum mapping unit of 10m^2. Thus, while known to be present, no seagrass was mapped for this location.

The Central region (Amirante, Platte and Coëtivy) contained the most extensive seagrass habitat (Figure 21), with 72,582 ha seagrass mapped. Seagrass with the community dominated by *Thalassia hemprichii* was the prevalent habitat on shallow reef flat areas, and close to islands. The most extensive seagrass areas however comprised *Thalassodendron ciliatum* meadows found at depths below 5 m and spanning much of the Amirantes Bank, and Desroches Atoll.

In the Southern region (Aldabra and Farquhar groups) (Figure 22), a total of 33,793 ha of seagrass were mapped. Seagrass was particularly prevalent on Providence Bank (20,477 ha), but also Cosmoledo (5,800 ha), Aldabra (3,495 ha), and Farquhar (3,493 ha). For Providence Bank much seagrass was mapped on the backreef, and shallow ribbon reefs towards the centre of the platform. Cosmoledo and Aldabra also had extensive seagrass in sheltered areas inside the atolls.

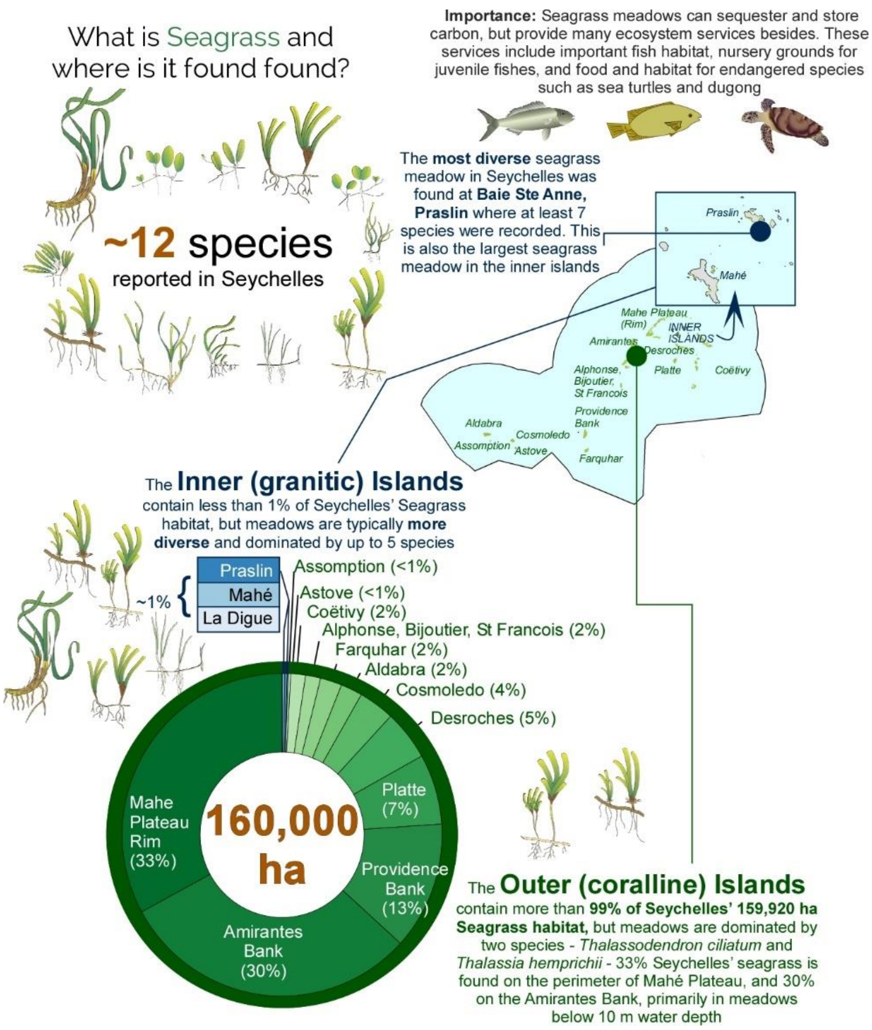


Figure 19: Reported species and area of seagrass habitat mapped across Seychelles. The majority of Seagrass habitat is located in the Outer (coralline) islands, however seagrass meadows in the inner islands are often more species rich (see Figure 20 -Figure 22 and Table 3 for full details).

COMPARISON TO OTHER STUDIES

The total of 1,599 km^2 (159,920 ha) seagrass is estimated for Seychelles (Table 3). This estimate is much lower than the ~2 million ha previously estimated through the Seychelles Marine Spatial Plan (SMSP) desk top mapping exercise (The Nature Conservancy 2022), but higher than recently published (2022) estimates for Seychelles through the Allen Coral Atlas (ACA) maps of ~26,000 ha (Table 3). In the case of the SMSP mapping, field data collected under the present project highlights where discrepancies and inaccuracies occur. The SMSP mapping suggests large areas of Seagrass in deeper areas of the Mahé Plateau below ~20m, however groundtruth collected or collated under the auspices of the present study suggests seagrass is in fact rare and infrequent in this area. Differences to the ACA maps are partially explained by the ACA mapping limiting their work to waters above ~10m, which excludes the majority of seagrass habitat in Seychelles.

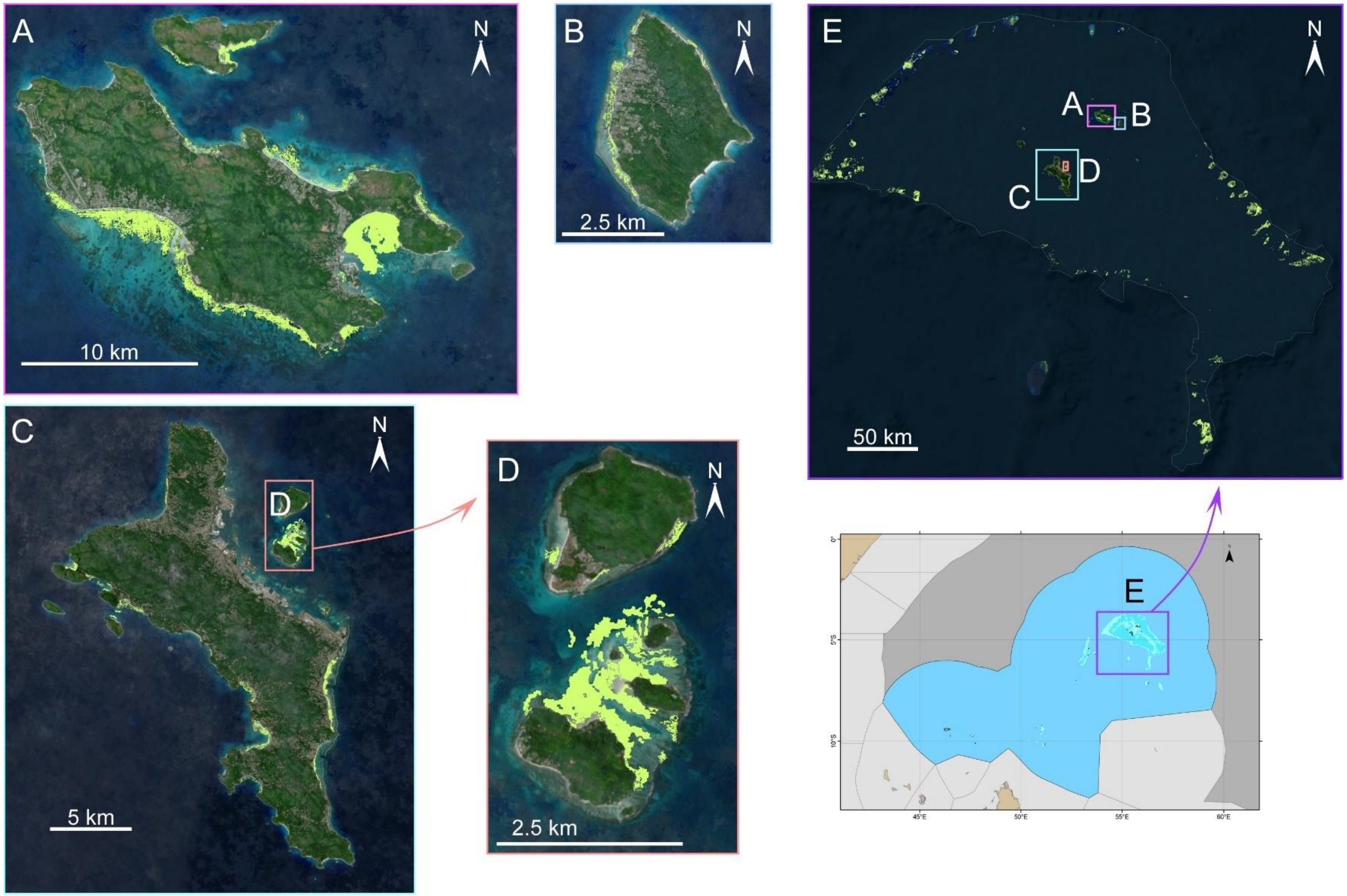


Figure 20: Seagrass maps for the Northern Region (Mahé Plateau) including: A) Praslin and Curieuse; B) La Digue; C) Mahé; D) Ste. Anne, Cerf & Long; and E) Outer Plateau Rim

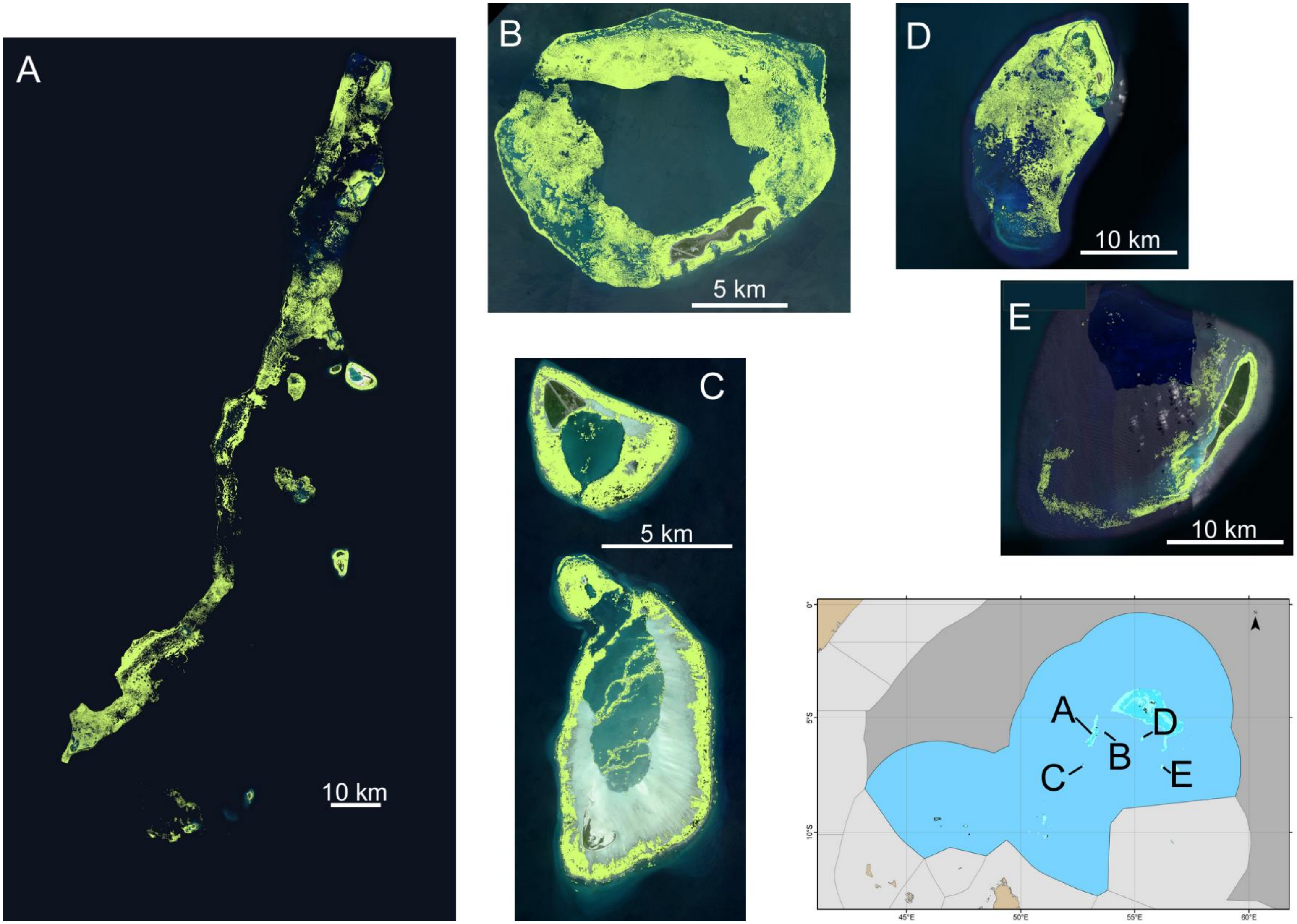


Figure 21: Seagrass maps for the Central region, including: A) The Amirantes Bank; B) Desroches; C) Alphonse/St Francois; D) Platte; and E) Coëtivy.

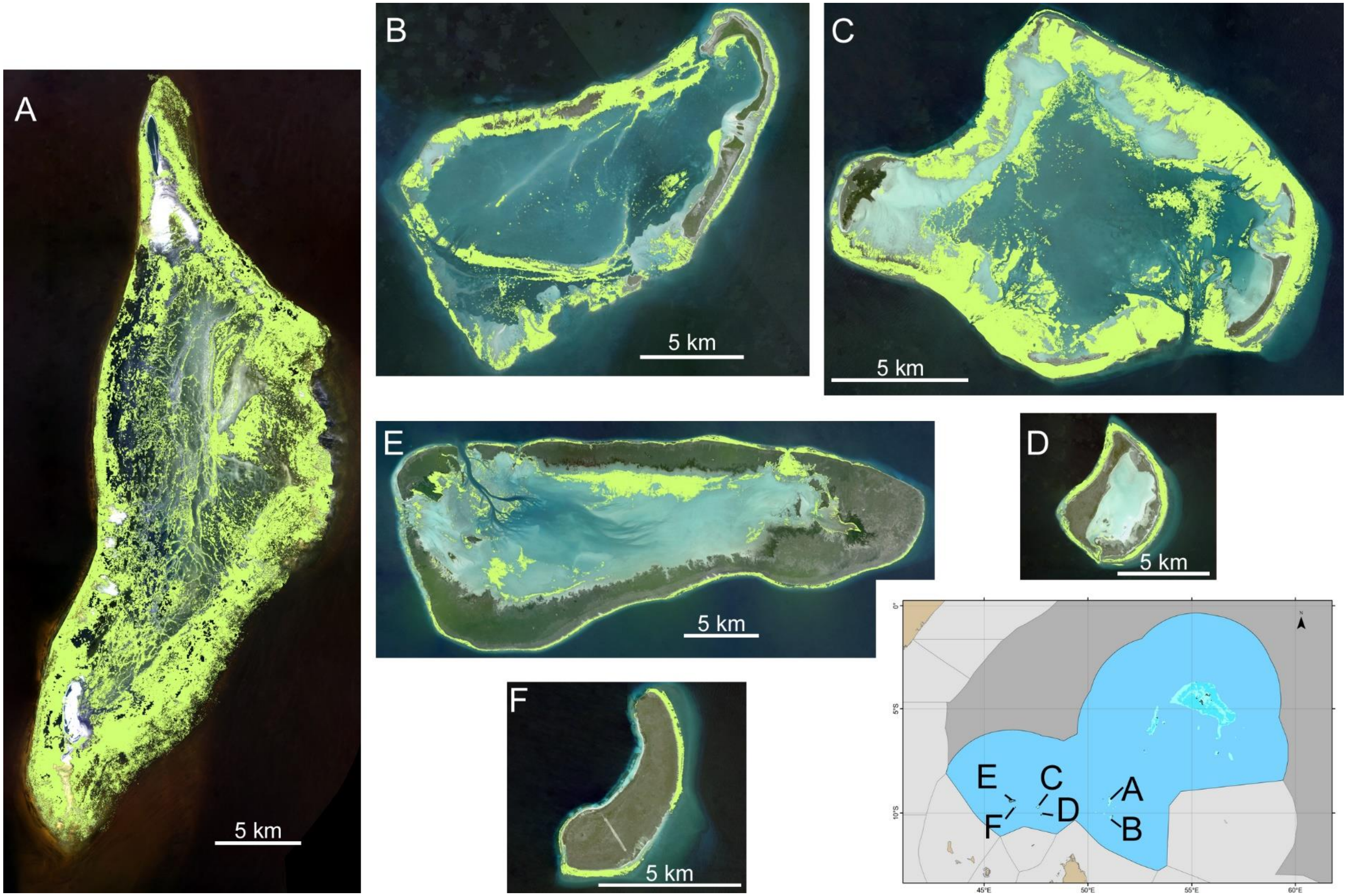


Figure 22: Seagrass maps for the Southern islands including: A) Providence Bank; B) Farquhar; C) Cosmoledo; D) Astove; E) Aldabra; and F) Assomption.

Table 3: Comparison of the present study to other seagrass mapping assessments in Seychelles, i.e. the Seychelles Marine Spatial Plan (SMSP - The Nature Conservancy 2022), the Allen Coral Atlas (ACA), the GEF-UNDP Outer Islands Project (OIP) and island-specific specific atlases (Praslin and Aldabra)

Region	Location	Present study Area (ha)	Proportion of total seagrass (%)	SMSP (ha)	ACA (ha)	OIP (ha)	Praslin Atlas (ha)	Aldabra - SH (ha)
Northern region (Mahé Plateau)	Mahé	225	0.14	104,095	321			
	Ste. Anne, Cerf & Long	127	0.08					
	Praslin	484	0.30	121,700	392		433	
	La Digue	26	0.02					
	Curieuse	25	0.02					
	Other Islands	2	<0.01					
	Outer Plateau Rim	52,661	32.93	813,795	120			
	Inner Plateau	0	0	651,531	11			
	Sub Total	53,550	33.49	1,691,121	844			
Central region	Amirantes Bank	48,475	30.31	222,754	1,359	644		
	Alphonse, Bijoutier, St Francois	2,441	1.53	4,263	1,834	4,277		
	Desroches	8,021	5.02	7,155	58	6,357		
	Platte	11,274	7.05	16,298	1,015			
	Coëtivy	2,371	1.48	65,268	39			

	Sub Total	72,582	45.39		315,739	4,305	11,278		
Southern region	Aldabra	3,495	2.19		13,145	808			430
	Assumption	149	0.09		159	27			
	Cosmoledo	5,800	3.63		8,573	2,369			
	Astove	380	0.24		389	120			
	Farquhar	3,493	2.18		10,688	1,611	5,310		
	Providence Bank	20,477	12.80		29,309	16,205			
	Bulldog, Wizard, McLeod. Umzinto etc. Banks	0	0		14,073	35			
	Sub Total	33,794	21.13		76,336	21,175	5,310		
Total		159,920	100		2,083,196	26,324	16,588		

ACCURACY & DATA GAPS

The maps are presented as a binary habitat classification (Seagrass / Non-seagrass). Habitats are mapped at the finest resolution of 5m resolution, however because both NICFI PlanetScope and Sentinel-2 (pixel resolution 5 and 10 m respectively) were used in the formulation of overall maps, various data cleaning and filtering processes, and contextual information was brought into the classification process, the realized mapping unit may be a slightly larger pixel resolution. Accuracy varied across the three regions used for mapping and sensor. Mapping was most accurate in the Southern region, followed by Central region, and finally Northern region (Table 4). The performance of the classification was quantitatively assessed via the overall map accuracy (Equation 7), the seagrass-class producer's accuracy (PA; Equation 8) and user's accuracy (UA; Equation 9). These metrics are commonly used in remote sensing (Maxwell and Warner 2020), and calculated as follows:

$$Overall\ Accuracy\ (OA) = \frac{Number\ of\ correctly\ classified\ samples}{Number\ of\ Total\ Samples} \tag{7}$$

And for a given class i:

$$Class\ Producer's\ Accuracy, PA_i = \frac{Number\ of\ correctly\ classified\ samples\ in\ class\ i}{Number\ of\ samples\ in\ reference\ data\ for\ class\ i} \tag{8}$$

$$Class\ User's\ Accuracy, UA_i = \frac{Number\ of\ correctly\ classified\ samples\ ifor\ class\ i}{Number\ of\ classified\ samples\ for\ class\ i} \tag{9}$$

Most of the mapping was conducted using PlanetScope data, however outputs from Sentinel-2 were fused where data was missing, or issues of data quality were noted (visual assessment of PlanetScope data and map output).

What is mapped as seagrass (a green pixel on the map) covers a range of percent seagrass cover on the ground; with ground truth data typically collected at ~1m scale (Figure 23). Across the inner and outer islands, areas mapped as seagrass had a mean of ~50% seagrass however typically ranged between 20 and 90% cover of seagrass, within a matrix of sand (mean ~25%), and to a lesser extent turf, macroalgae, and rubble (mean all < 10%). Non seagrass habitat was dominated by sand (mean ~40%), turf algae (mean ~25%), or macroalgae (mean ~15%), but seagrass was also present in some cases at a low (5-10%) proportion of cover.

Table 4: Accuracy metrics for initial mapping conducted using NICFI PlanetScope and Sentinel-2 data

	Metric	**PlanetScope (NICFI)**	**Sentinel-2 (ESA)**
Northern region (Mahé Plateau)	Overall accuracy	69.7%	66.9%
	PA (Seagrass)	57.2%	54.3%
	UA (Seagrass)	65.9%	61.5%
Central region	Overall accuracy	64.2%	56.3%
	PA (Seagrass)	80.2%	77.0%
	UA (Seagrass)	70.4%	67.6%
Southern region	Overall accuracy	68.4%	64.2%
	PA (Seagrass)	81.9%	79.6%
	UA (Seagrass)	73.9%	73.5%

PA = Producers Accuracy; UA = Users Accuracy

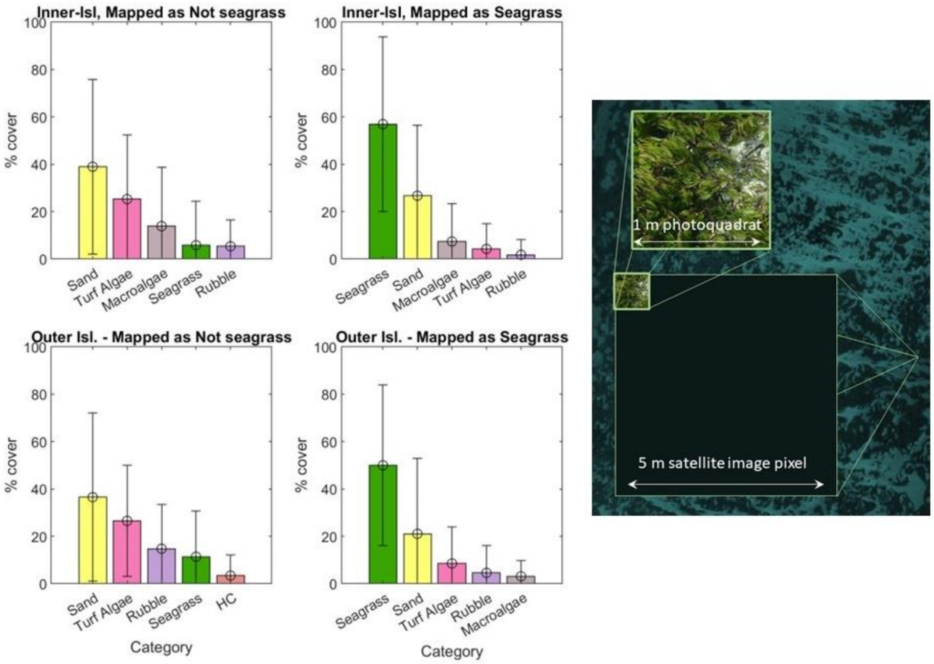


Figure 23: Comparison of percent cover categorized into different benthic categories for (left sub-plots) areas mapped as non-seagrass and (right subplots) mapped as seagrass. Percent cover is estimated from ground truth data assembled from photo-quadrat, drop-camera or legacy survey. Shown for (upper row) inner islands and (lower row) outer islands. Images to the right of plots show potential mismatches of scale between seagrass patches and meadows, individual mapped pixels, and photo-quadrats used in ground truth.

Mahe Plateau and Outer Rim

Despite a high quantity of seagrass habitat mapped on the outer rim of the Mahé Plateau (52,660ha; Table 3), it should be noted that for logistical reasons, except for Denis Island, Much of the outer rim of the Mahé Plateau was not visited during the scope of the initial project to collect ground truth.

Within the scope of the project, additional ground truth was however kindly provided to the project for a few locations across the wider plateau by the Seychelles Fishing Authority (SFA), but limited to 197 broadly distributed points (i.e. Legacy data from BRUV video stations and collected before 2021; Table 2). No seagrass was observed in points deeper than 30 m across the centre of the Mahé Plateau, supporting masking of such regions from mapping. Above 30 m, seagrass habitat accounted for 19 of 86 total points (22%) and was only found in the outer rim areas where seagrass, as mapped within this study. Collection of further ground truth data from these regions is however merited to corroborate the large quantity of seagrass mapped in this region (30% Seychelles' total).

A research cruise to sites surrounding the Owen Bank in the west of the Mahe Plateau in April 2024 permitted assessment of a further 180 sites and revealed often extensive *Thalassodendron* meadows, interspersed with rocky reef frameworks and sandy sediment areas. Habitat across this area reached a shallowest point of around 9 m depth. Seagrass was concentrated at depths down to about 25 m, however sparse patches of *Halophila* sp, were viewed at depths down to ~35m. Given the sparse nature of such patches, these patches are not generally mapped.

Coarser satellite imagery (10 m pixel Sentinel 2 compared to 5m pixel PlanetScope), and greater mapping depth (10-25m compared to 0-10 m) mean seagrass estimates may be slightly overestimated across much of the Amirantes and Margins of the Mahe Plateau, when compared to inner and outer island atoll locations, where seagrass tends to extend into the shallows and intertidal. At greater water depth the ability to discern small and narrow sand patches is reduced as there is more opportunity for light to be refracted by the water column. The total seagrass area mapped is however likely to be a conservative estimate, as seagrass in Seychelles reach depths at or exceeding that which can be mapped from satellite methods.

Given the apparent predominance of seagrass on the margins of the Mahe Plateau further survey of such regions is therefore merited to confirm, refine, and provide additional confidence in the maps produced for this region, and by extension the overall area of seagrass estimated for Seychelles.

Seagrass Morphometrics

Measurements of seagrass samples show the highest canopy was associated with *Enhalus acoroides* (58.5cm), followed by *Thalassodendron cilatum*, which could be quite variable (median mean canopy = 17.4cm; minimum = 3.4cm; maximum = 54.4cm) (Figure 24). The longest roots and rhizomes measured were for *Thalassodendron cilatum*, however similar median root lengths were also recorded for *Oceana (= Cymodocea) serrulata*, *Cymodocea rotundata*, *Syringodium isoetifolium*, and *Thalassia hemprichii*. It should be noted however that field sampling methodologies were designed for assessing above ground carbon content rather than for capturing maximal root and rhizomes length and so may not have extended vertically downwards to the pull length at it is likely that roots and rhizomes would be sliced during the vegetation coring process.

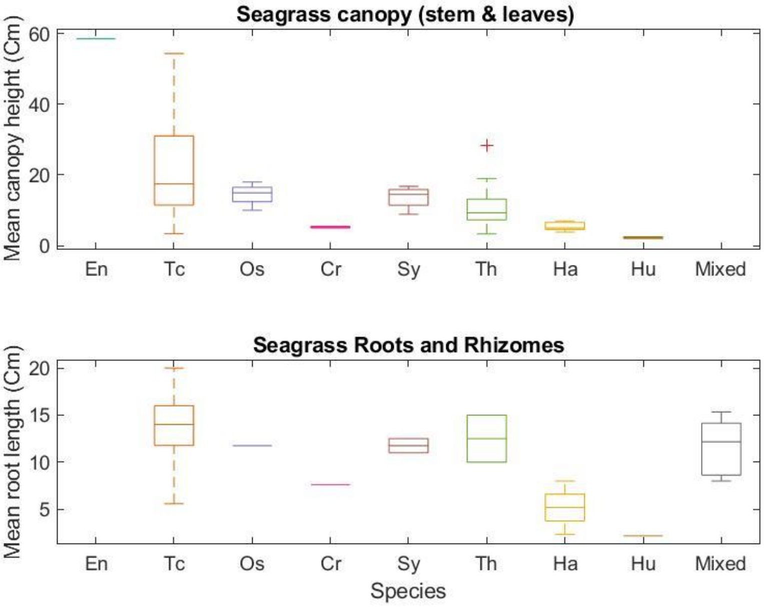


Figure 24: Comparison of canopy height and maximal root/rhizome length measured within vegetation cores, split by species (En = Enhalus acoroides, Tc = Thalassodendron ciliatum, Os = Oceana (=Cymodocea) serrulata, Cr = Cymodocea rotundata, Sy = Syringodium isoetifolium, Th = Thalassia hemprichii, Ha = Halophila spp, Ho = Halodule spp.). Note a root and rhizome sample was not collected for Enhalus.

Carbon Assessment

ELEMENTAL ANALYSIS

Elemental analysis indicated most seagrass soils contained a low percentage of organic carbon. Samples from the 13 cores analysed for organic carbon exhibited organic carbon concentrations ranging from 0.14- to 4.32%, and a mean of 2.13 % ± 0.89. These samples corresponded to LOI values ranging from 2.69 to 10.98 % (Figure 25a). The analysis of the 17 vegetation samples returned organic carbon concentrations ranging from 13.4- to 36.1%, and a mean of 29.2% ± 5.8, corresponding to LOI values ranging from 9.7 to 83.6 % (Figure 25b). The derived allometric models were applied to samples analysed through loss on ignition methods for sediment samples according to Equation 10 as follows:

$$\%C_{Org} = 0.42943 \times \%LOI - 0.25447 \quad (10)$$

Above ground biomass samples according to Equation 11 as follows:

$$\%C_{Org} = 0.47382 \times \%LOI \quad (11)$$

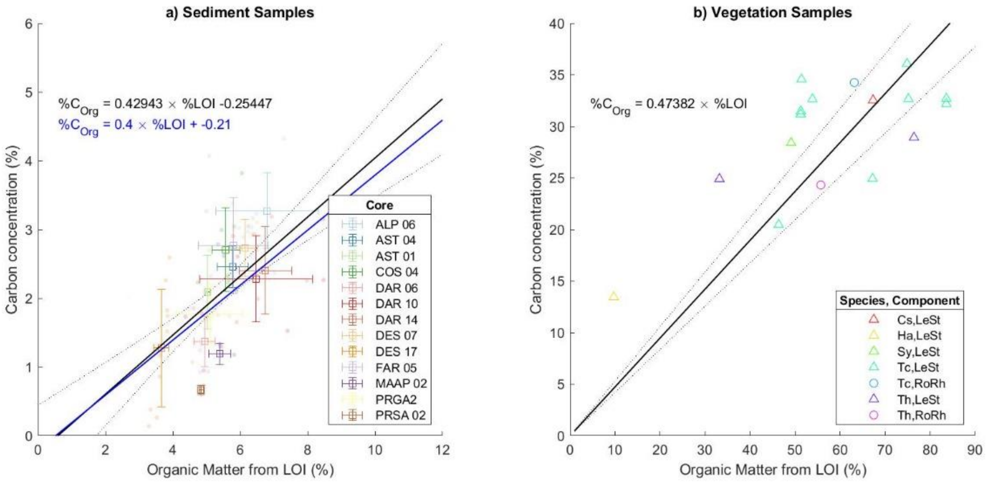


Figure 25 Relationship between carbon concentration assessed using loss on ignition (LOI) and elemental analysis. a) Relationship between LOI and percent C_{Org} in sediment samples from 13 cores (92 samples) across Seychelles; and b) 17 leaf and stem (LeSt) or Root and Rhizome (RoRh) samples. Derived allometric equations and relevant linear model for $\%C_{Org}$ are shown in black text/ black line. Blue text and line relate to model of (Fourqurean et al. 2012).

LOSS ON IGNITION (LOI)

Sediment cores

The balance in sampling yielded many more cores in shallow environments 3 (Figure 14), yet it is also clear that the depth of sediment beneath seagrass ecosystems tends to be greater in deeper environments (Figure 16). When carbon stocks are assessed against water depth, we see a general trend of increasing carbon stocks in deep water seagrass meadows from a median value of ~93 Mg ha^{-1} at water depths of 0-2 m, rising to a median of ~180 Mg ha^{-1} for cores taken at water depths greater than 20 m water depth (Figure 27). The trend of increasing organic carbon values with depth was seen in cores below 10 m in the North (Mahé and Praslin), Central (Amirantes Bank, D'Arros and St Joseph and Desroches), and Southern (Farquhar, Alphonse, and Cosmoledo groups) geographic regions (Figure 28).

To account for sampling variability across depths Figure 14 the median organic carbon was assessed at each sampling depth (2 m depth bins), with the mean of these values taken as most representative of Seychelles - **118 MgC$_{Org}$ ha^{-1}** (Figure 26)

Differences were seen in the median and higher ranges of organic carbon values measured for different species, however sediment in meadows dominated by the most heavily sampled and dominant species (*Thalassodendron ciliatum* and *Thalassia hemprichii*) had very similar carbon values (Figure 29). Lowest carbon was associated with areas where *Halophila spp.* or *Halodule spp*. were the dominant species. Both species are considered pioneer and non-perennial species with delicate leaves and relatively shallow root systems (Figure 3, Figure 24), only sparsely covering the substrate.

While the depth of sediment was typically lower for shallow-water seagrass meadows, samples taken from cores in these environments were richer in carbon, with a median percentage organic carbon of around 6% sample weight within cores collected in water depths of up to 8m Figure 30). This decreased to around 4% in samples collected at deeper water depths. At the same time, the C$_{Org}$ contents recorded in shallow environments were more variable. Cores collected in water depths shallower than 5 m occasionally exceeded 16% organic carbon per sample. For samples collected at depths between 8 and 24m there was very little variability, with most core samples having an organic carbon content of ~4%. Overall patterns of carbon accumulation with water depth (Figure 27) relate more to the thickness of sediment (Figure 31), than to a proportionally high organic carbon content at these water depths (Figure 30).

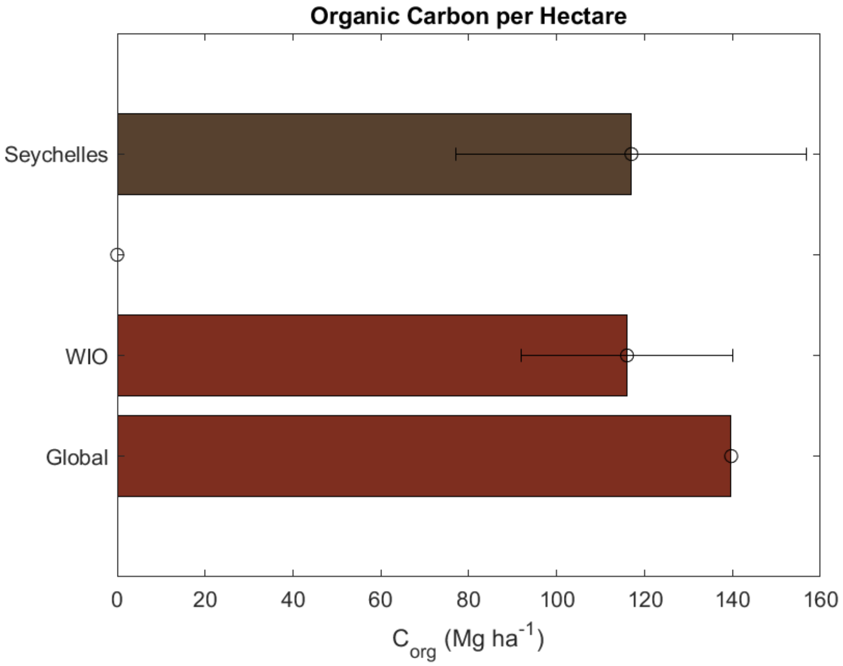


Figure 26: Organic carbon (Tonnes ha^{-1}) for upper bar: Seychelles - median organic carbon calculated at different depths (Figure 26)(Figure 27). Data for the Western Indian Ocean (WIO), and Global data sets (Fourqurean et al. 2012) are shown in lower two bars for comparison.

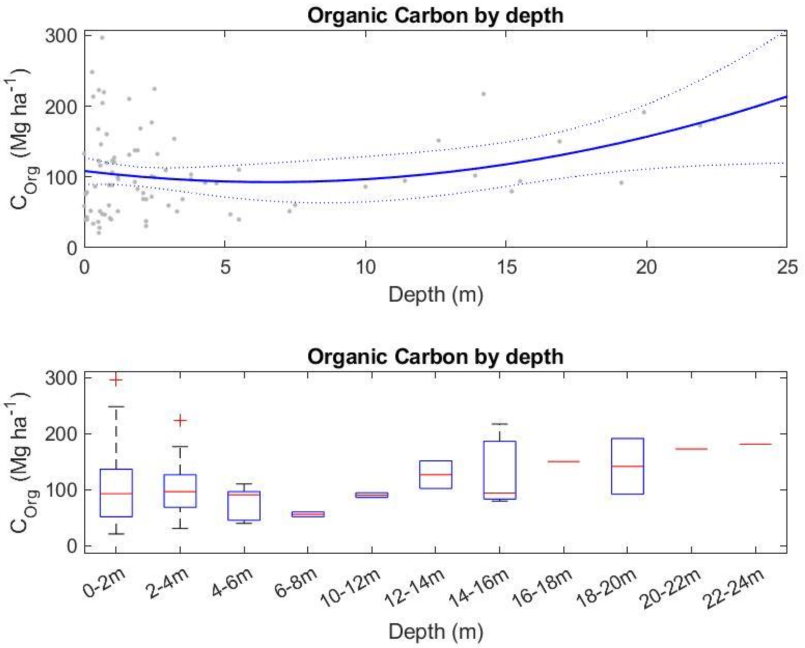


Figure 27: Organic Carbon (Mg ha^{-1}) recorded at different water depths showing: (top) Quadratic model to data; and (bottom) boxplots showing median organic carbon at different water depths (2 m depth bins). Note uneven sampling with greater sampling of seagrass in shallow environments.

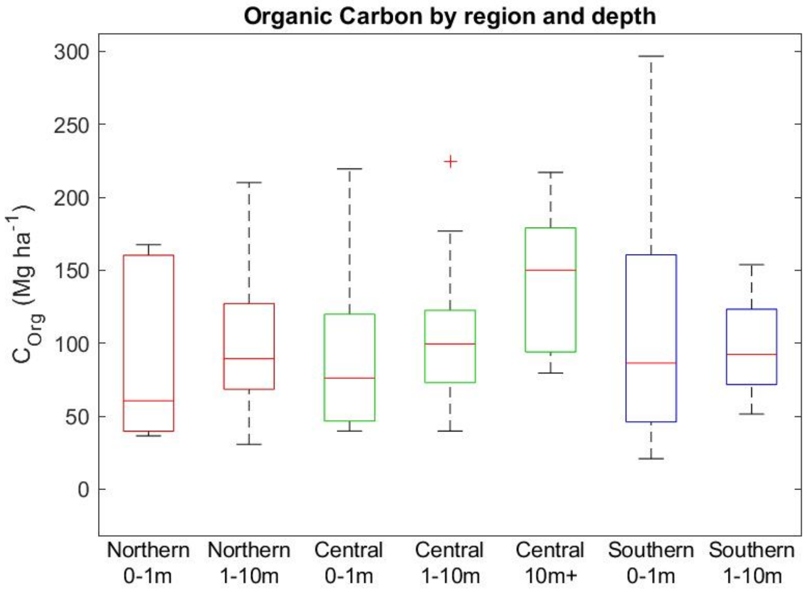


Figure 28: Organic Carbon (Mg ha^{-1}) recorded in different regions of Seychelles (North = Mahé/Praslin; Central = Amirantes Bank and Desroches; South= Farquhar, Alphonse and Cosmoledo groups) and depths, with data pooled into 0-1, 1-10 and >10 m water depth.

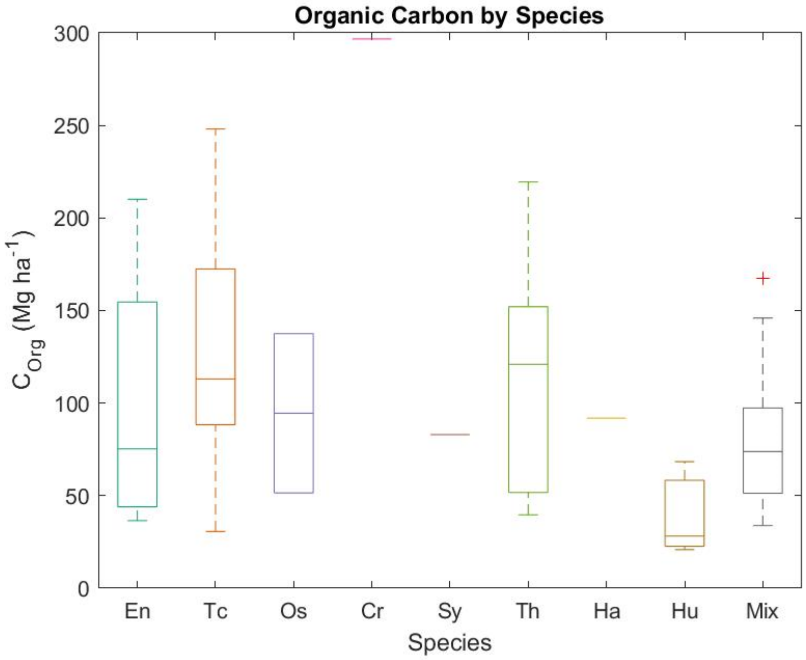


Figure 29: Organic Carbon (Mg ha-1) recorded for different species. En = Enhalus acoroides (n=4), Tc = Thalassodendron ciliatum (n=38), Os = Oceana (=Cymodocea) serrulata. (n=2), Cr = Cymodocea rotunda, Sy = Syringodium isoetifolium (n=1), Th = Thalassia hemprichii (n=7), Ha = Halophila spp (n=1), Hu = Halodule spp (n=3). Mixed = mixed and unsorted species but dominated by Tc in most cases (n=24).

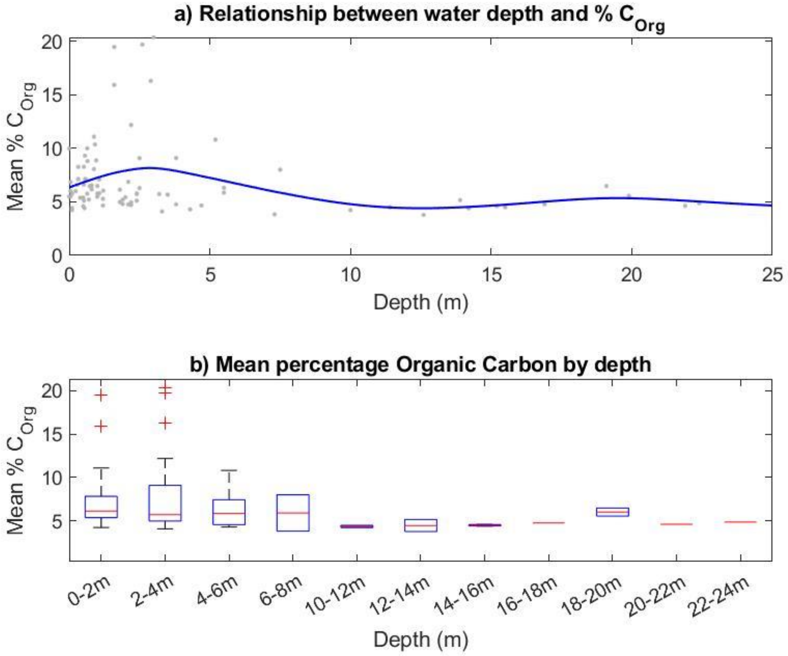


Figure 30: Distribution of mean percentage organic carbon recorded for samples from each sediment core by depth. a) fitted line to data (smoothing spline; smoothing parameter = 0.07); (b) boxplots showing distribution of data in 2 m depth bins.

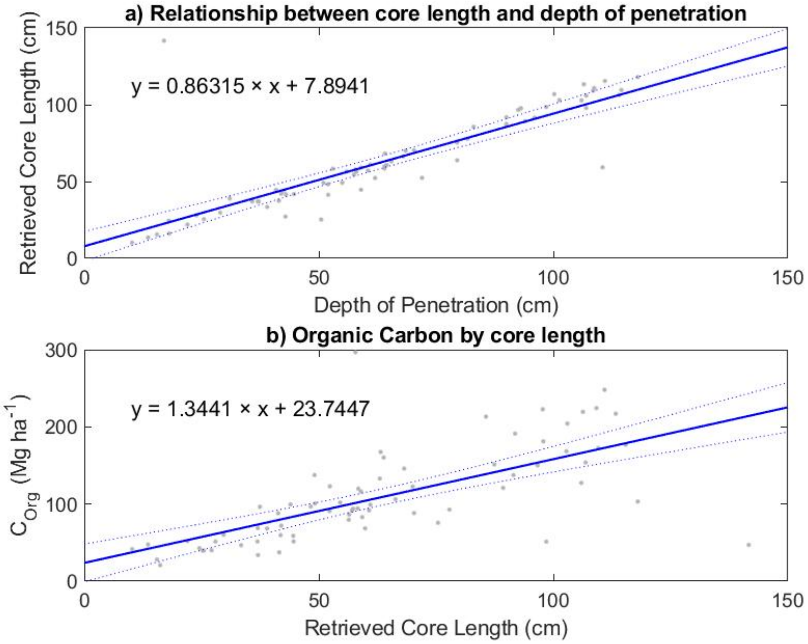


Figure 31(a) Relationship between Depth of penetration (cm) and the retrieved core length; (b) relationship between Organic Carbon (Mg ha^{-1}) and core length retrieved

Above and below ground biomass

Above ground biomass was split into 'leaf and stem', 'detritus' and 'epibiont' pools. C_{Org} was found to be highest in the leaf and stem pools, in particular for *Thalassodendron ciliatum* (median = 0.08 tonnes ha^{-1}), and lowest in the detritus and epibiont pools (Figure 32). Below ground, the roots, and rhizomes of *Thalassodendron ciliatum* contained the highest carbon with a median of 0.55 tonnes ha^{-1}, with other species having a median between 0.01 and 0.07 tonnes ha^{-1}. The above and especially below ground pools of the of the locally rare *Enhalus acoroides* seagrass were however minimally sampled due to risks of disturbing rare patches through invasive and destructive sampling techniques.

Relative to the scale of the carbon pool estimated from sediment, the above and below ground carbon pools are relatively small and, in most cases, represent less than 1% of the total carbon pool (sediments + above ground biomass). **Future assessments may therefore reasonably neglect above ground biomass and dedicate more effort to below ground biomass.**

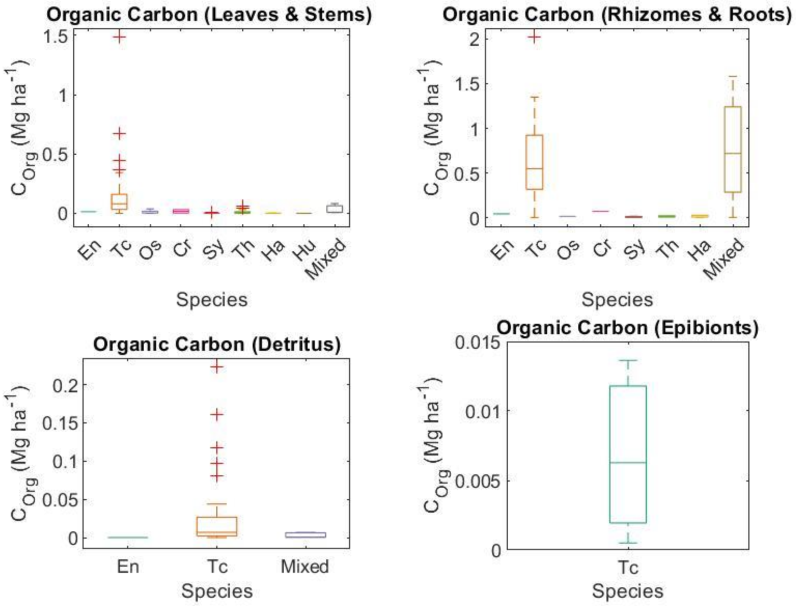
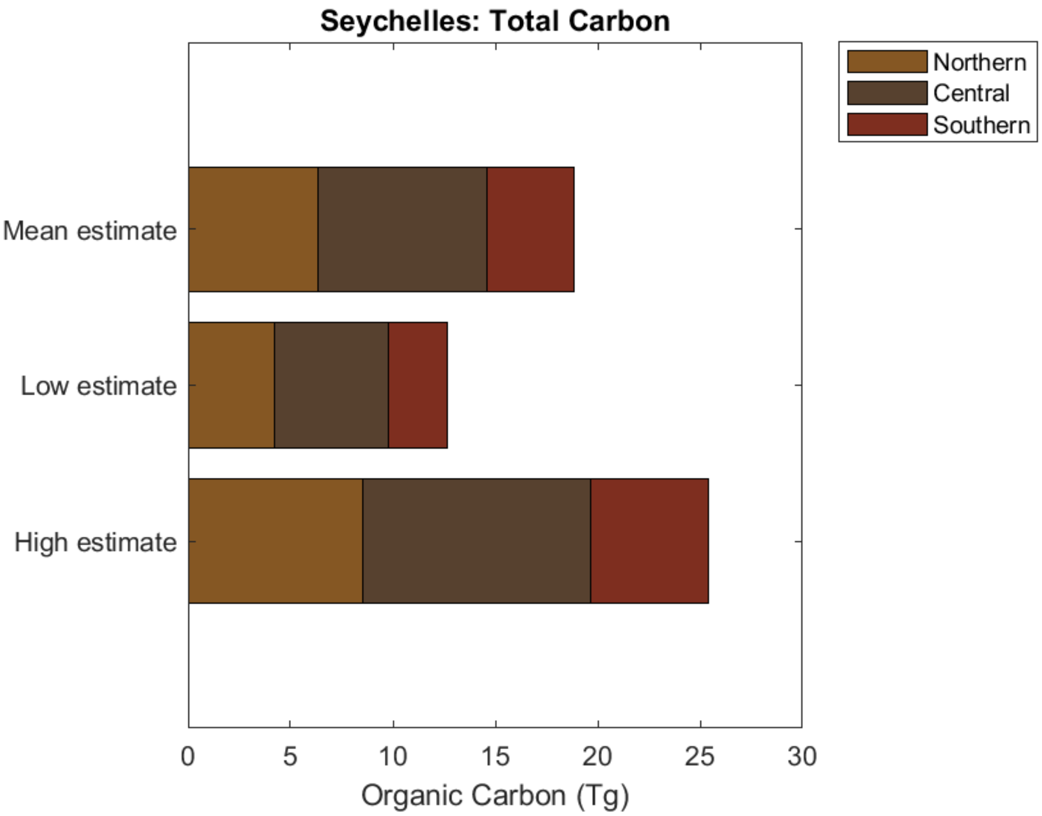


Figure 32: Estimates of Organic Carbon (Mg ha^{-1}) found in different carbon pools for different species (En = Enhalus acoroides, Tc = Thalassodendron ciliatum, Os = Oceana (=Cymodocea) serrulata, Cr = Cymodocea rotundata, Sy = Syringodium isoetifolium, Th = Thalassia hemprichii, Ha = Halophila spp, Hu = Halodule spp. Mixed = mixed and unsorted species but dominated by Tc in most cases).

Carbon Stock Assessment

Total carbon stock associated to seagrasses is estimated (mean estimate) as 18,870,560 tonnes or ~18.9 Tg C (Figure 33; Table 5). Lower and higher estimates of 12.6 and 25.4 Tg C respectively are calculated based on the standard deviation of carbon per hectare values estimated at different depths (Figure 26). Reflecting differences in mapped area, the largest contribution to the national estimate comes from seagrass in the central region composed of the Amirantes, Platte, and Coëtivy.



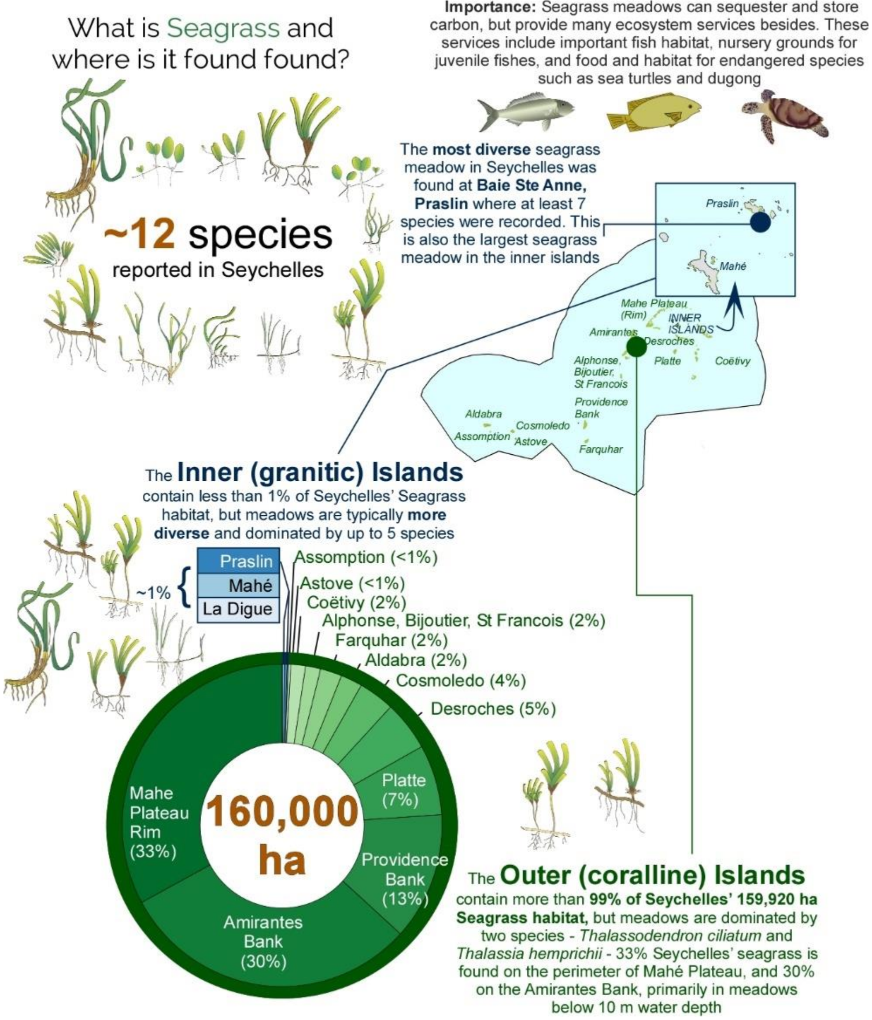


Figure 33: Estimated total organic carbon for Seychelles based on median depth averaged Mg ha^{-1} estimates of stored carbon (Figure 26) and seagrass mapping (Figure 19). Stacked colours represent different regions, (North = Mahé/Praslin; Central = Amirantes, Platte, Coëtivy; Southern = Aldabra, Cosmoledo, Farquhar groups).

Table 5: Seagrass carbon stores in Seychelles Blue Carbon Ecosystems (BCE). Values for seagrass this study. Values for mangroves from Wartman et al. (2022)

	Total BCE	Mangroves	Seagrass
Area (ha)	162,115	2,195	159,920
% BCE area		2.0%	98.0%
Avg Core Carbon (C_{Org} ha^{-1})		472	118
Total stock (Mt C_{Org})	19.6	0.7	18.9
Total BC (Mt CO_2 e)	71.7	2.5	69.2
% total BCE Carbon stock		3.5%	96.5%
Annual CO_2 sequestration (kt CO_2e yr^{-1})	524.0	14.0	510.0
% total BC sequestration		2.7%	97.3%

Carbon Sequestration Rate

Sequestration rate describes how quickly, or perhaps more accurately slowly, carbon is accumulated in the seabed. Samples from 23 cores were analysed for ^{210}Pb, to determine sediment accumulation rates during the last decades/century. For 12 cores assessed, the resulting concentrations of excess ^{210}Pb suggest intense mixing of the sediment, thus the sedimentation rate could not be estimated. Nonetheless, an excess of ^{210}Pb suggests net sediment accumulation. In 11 cores sedimentation rates were determined as between 0.34 and 2 g cm^{-2} yr^{-1}, with a mean of 0.71 g cm^{-2} yr^{-1} (Table 1). These rates are calculated at core depths below 10-15 cm, as profiles in the upper section of all cores are indicative of high levels of mixing. It is likely that mixing dominates the profile in many cases and estimates of sediment accumulation should therefore be taken as an upper limit.

The accumulation rate for organic carbon ranged from 0.35 to 2.51 tonnes C ha^{-1} yr^{-1}, and a **mean accumulation rate of 1.07 ± 0.65 tonnes C ha^{-1} yr^{-1}**, calculated for sediment depths up to 30 cm. If we interpolate these rates to the full length of each respective core, this suggests that carbon within these cores represents **between 60 and 300 years of carbon accumulation**. This range can be considered broadly indicative of the number of years required to sequester and store an equivalent amount of carbon, should these sediments be disturbed, leading to an emission of the stored carbon.

Using the **median sequestration rate (0.87 t C_{org} ha^{-1} yr^{-1}),** taken as more conservative than using the mean rate which is subject to outliers, and the estimated area of seagrass habitat (159,920 ha), this suggests approximately **139,000 t C_{Org} or ~510,000 tCO_2e (510 kt CO_2e) are sequestered by seagrass meadows** in Seychelles each year.

Table 6: Carbon sedimentation rate calculated from eleven cores exhibiting excess ^{210}Pb

Region	**Island/Atoll**	**Core Id**	**Water Depth (m)**	**Sedimentation Rate (g cm^{-2} yr^{-1})**	**Accumulation Rate (t C$_{Org}$ ha^{-1} yr^{-1})**
Inner (granitic) Islands	Mahé Plateau	MASA03	0.5	2.00 ± 0.30	2.51
	Praslin	PRGA-2 04	2.0	0.34 ± 0.04	0.64
Outer (coralline) Islands	Desroches	DES 06	19.9	0.34 ± 0.02	0.63
	Desroches	DES 07	2.5	0.38 ± 0.07	0.87
	Amirantes Bank	DAR 06	22.4	0.77 ± 0.06	1.23
	St Joseph	DAR 14	0.8	0.84 ± 0.07	1.07
	Farquhar	FAR 06	0.7	0.85 ± 0.10	1.8
	Cosmoledo	COS 04	0.7	0.46 ± 0.02	0.4
	Astove	AST 04	0.2	0.80 ± 0.13	0.35
	Alphonse	ALP 03	0.6	0.57 ± 0.04	0.82
	Bijoutier Island	ALP 06	0.3	0.44 ± 0.03	1.41
Mean				0.71 ± 0.08	1.07 ± 0.65
Median				0.57	0.87

Discussion

Estimating the amount of carbon that seagrass stores within plant tissues and the associated sediments is key to understanding its role in climate change and how managing blue carbon ecosystems such as seagrass might help to address it. In addition to mapping seagrass, sediment cores and vegetation samples were collected. These were analysed using loss on ignition (LOI) and elemental analysis to determine the organic content. Combined with habitat mapping, these values can be used to estimate the total carbon stored – the carbon stock. Further radio isotope analysis was conducted to establish rates of carbon sequestration (i.e. how fast or slow carbon is being stored) allowing comparison to other sources of carbon emission in the economy.

Seagrass Habitat

The detailed mapping of the project estimates a **total of 159,920 ha** of seagrass habitat in Seychelles (Table 3). This is a significant reduction on previous estimates suggesting over 2 million ha of seagrass existed within Seychelles' EEZ (The Nature Conservancy 2022). In contrast to the SMSP ecosystem services report, which identified the Mahe Plateau as holding most seagrass habitat in Seychelles, this study identifies the rim habitats of the Mahé Plateau (33% / 52,661 ha) and Amirantes Bank (30% / 48,475 ha) as holding the majority of Seychelles' seagrass habitat; much of this being comprised of dense *Thalassodendron ciliatum* meadows, which dominate and deep banks, atoll and bank rims, and lagoonal floors.

In this study seagrass was mapped to a maximum depth of ~25m, however ground truth did on occasion extend to deeper depths. Dense groundtruth around the inner islands, supported by sparse groundtruth across the remainder of the Mahé Plateau however supports the view that most of the inner area of the plateau is dominated by sandy sediments, algae, and rocky substrates, and seagrass patches are sparse and rare. Potential for any 'unmapped' seagrass is likely to be highest in the outer rim and Amirantes Bank where extensive seagrass beds are already identified Figure 20.

Significant areas of seagrass were also located in Providence Bank (14% / 20,477 ha), Platte (8% / 11,274 ha), and Desroches Atoll (6% / 8,021 ha). The largest contiguous meadow mapped was in the Amirantes Bank (~10,000 ha), with large meadows also recorded at Desroches Atoll (~5,000 ha). It should be noted however that the ability to differentiate between individual patches becomes more challenging with depth, thus small gaps within the meadow structure may be missed conflating the size of meadows with increasing depth.

In the granitic inner islands, seagrass is less abundant and constrained to depths shallower than ~10m. Expansive *Thalassodendron ciliatum* meadows that typify much of the outer islands are found at Grand Anse Praslin, but are otherwise rare or interspersed with other species. The largest contiguous seagrass meadows near Mahé are found at Anse aux Pins (51 ha), with slightly larger meadow found at Sainte Anne Marine Park (127 ha). The largest meadows in the inner island are however found at Baie Sainte Anne, Praslin (168 ha)

and Grand Anse, Praslin (121 ha). Though smaller than most of the seagrass meadows in the outer islands, these meadows are characterised by greater seagrass species diversity, and are locally important, delivering a diversity of ecosystem services in addition to carbon storage. Moreover, their relative proximity to high human population centres and historical coastal development places them at high risk of loss or degradation.

Carbon Storage

When biases in sampling effort by depth are allowed for, on a core-by-core basis no substantial difference in carbon storage beneath seagrass meadows can be seen in the inner (granitic) islands and outer (coralline) islands (Figure 28). While cores in shallow water (<2 m water depth) seagrass meadows had a higher concentration of carbon per cm^3 in many cases, cores tended to accumulate more carbon with greater water depth because of greater core length (greater depth of penetration). In shallow water environments including back reefs and on atoll rims the bedrock may be located close to the surface sediment. Holes or pockets in the backreef, allow for occasional deep cores and elevated carbon storage, while a variable wave energy climate and potential for resuspension may also account for high values of total carbon estimated in some locations. At depths below ~10 m, which are less impacted by waves and currents, the sediment accumulation rate and estimated total carbon is more uniform between cores and geographies. Thus, while water depth was not specifically accounted for when making stock estimates, **many outer island locations where seagrass is found deeper, and geomorphology supports the accumulation of sediments, is likely to support greater carbon store.** Cores with large carbon values, such as seen near an island on the rim of Cosmoledo (~300 tonnes C_{Org} ha^{-1}) is an outlier. The value is more reminiscent of values seen in mangrove ecosystems (Table 5), and so may represent input from local mangrove system, or a seagrass system rooted on an ancestral mangrove stand.

Sedimentation and carbon accumulation rates is highly variable between locations. The relatively high accumulation rate recorded in a core from Ste Anne Marine Park, an area with large seagrass meadows may reflect both the productivity of meadows in the vicinity and deposition of carbon in sediments from nearby islands. Overall, mean (1.07 ± 0.65 tonnes C_{Org} ha^{-1} yr^{-1}) and median (0.87 tonnes C_{Org} ha^{-1} yr^{-1}) rates of carbon accumulation sit within the distribution of global values. They are higher than values witnessed at sites bordering the Indian Ocean such as for *Thalassia sp.* in the Red Sea (Serrano et al. 2018) and *Posidonia sp.* in Australia (Serrano et al. 2016) but lower than values seen in other seagrass systems such as *Thalassia sp.* meadows in Colombia (Serrano et al. 2021) or *Posidonia sp.* meadows in the Mediterranean (Gacia et al. 2002).

Across Seychelles' seagrass, an estimated 510 ktCO_2e is sequestered annually. The amount of carbon sequestered by seagrass is therefore more than three times the current (2018 estimate) emissions from the transport sector in Seychelles (147.8 ktCO_2e), and a little less than the total national emissions and removals of Seychelles Energy Sector (518.5 ktCO_2e) (Government of Seychelles 2023).

The above estimate, while indicative of the relative importance of seagrass habitats and their potential for CO_2 mitigation within Seychelles' national carbon accounting should be treated with a degree of caution. High variability in both accumulation rate (Table 6) and organic carbon within cores from different environments (Figure 30) suggest sequestration is likely to vary within and between different meadows, different depositional settings, and between years. **Sequestration rates should not be used to justify or enable the continuation or expansion of emissions under a business-as-usual type scenario but may help Seychelles achieve its net-zero emission target by 2050 or before.**

The total seagrass carbon stock of ~18.9 million tonnes is equivalent to ~61 million tons of CO_2. This approximates to 120 years of carbon emitted by Seychelles' Energy Sector and 420 years the carbon emitted at current rates by Seychelles' Transport Sector (2018 estimates), and equates to approximately 55 years of Seychelles' 2030 projected annual CO_2 emissions (Republic of Seychelles 2021).

Seagrass, Blue Carbon and the Seychelles Marine Spatial Plan

In its 2021 NDC, **Seychelles committed to protect its blue carbon ecosystems**; to *"protect at least 50% of its seagrass and mangrove ecosystems by 2025 and 100% by 2030"* (Republic of Seychelles 2021).

In 2012, the Government of Seychelles set a goal for protected area expansion: "*50% of all terrestrial areas and 30% of the Exclusive Economic Zone including 15% in 'fully protected' areas"*. The Seychelles Marine Spatial Plan (SMSP) Initiative was launched in 2014 with three objectives: (1) to expand protection of marine waters to 30 per cent; (2) to address climate change adaptation; and (3) to support the Blue Economy. A key part of meeting the objectives for the 30 per cent protection goal and supporting the Blue Economy was designing a zoning framework for the full 1.35 million km^2 Seychelles EEZ. The most recent zoning framework identifies three Zones, with differing levels of protection (Table 7).

The distribution of seagrass habitat in relation to SMSP zoning and pre-MSP gazetted areas is shown in Figure 34 and Table 8. **A total of 99.5 % seagrass habitat is found within Zones 1 or 2 (designated MPAs), or a pre-SMSP protected area.**

Across Seychelles, 7% of seagrass is found within a 'Zone 1 - High Biodiversity Protection Area' designated as Marine National Parks MPAs, 90 % of seagrass is found within 'Zone 2 – Medium Biodiversity Protection and Sustainable Use Areas', designated as sustainable use MPAs, while 2.3% seagrass is found within Pre-MSP protected areas such as Marine National Parks, Marine Reserves. Most of the seagrass of the inner islands (Victoria Port Fee Boundary Area) is found within a zone 3 multiple use area as per the SMSP zoning design or Shell reserve.

Carbon stores take a long time to accumulate (60-300 years observed in this study) but have the potential for large scale and rapid emissions following any damage or disturbance. Activities that might disrupt and disturb the integrity of

seagrass ecosystems and their sediments are therefore likely to be incompatible with seagrass or need to be carefully managed.

The majority (90%) of Seychelles' seagrass habitat is in Zone 2 - Medium Biodiversity Protection and Sustainable Use Zone. The areas are gazetted as Sustainable Use Areas which is a new category under the Nature Reserves and Conservancy Act, 2022. As zone 2 is considered *"suitable for some level of extraction and seabed alteration"* (Table 7), the degree to which Seagrass habitat and carbon stores within this Zone 2 are effectively protected **depends on the scope and spatial placement of activities allowed under the SMSP**. Any seabed alteration would risk damaging delicate above and below ground plant structures, and mobilisation of sub-surface carbon stores leading to emissions.

Potentially damaging activities to seagrass systems include (but are not restricted to): direct trampling, fishing – particularly with gear that interacts with the bottom (e.g. trawls [currently banned in Seychelles], use of weighted nets or other gear etc); boat activity through disturbance and remobilisation of the seabed by propeller wash and anchor damage (especially from large craft) from recovering or dragging anchors; coastal and offshore development including activities such as dredging, infill or dumping of spoil for coastal landfill, harbour or marina expansion, pollution and runoff.

Crucially, **seagrass protection requires that management, through policies, regulations, licences or permitting, only allow activities that are consistent with avoiding and minimising impacts from potentially harmful activities that** alter the **sea bed or viability of a seagrass ecosystem.**

Complementing the plans of specific managed areas, national regulation should look to embed seagrass protection and ensure safeguards wherever possible within development and planning processes. A strong approach would include seagrass specific **requirements for Environmental Impact Assessment (EIA)**, and reporting prior to and after potentially harmful activities and avoidance and mitigation in areas where seagrass habitat is known or is likely to occur.

Ensuring planning adequately accounts for any potential losses and gains of seagrass habitat will also facilitate the commitment to include seagrass ecosystems within the Seychelles GHG inventory by 2025, by accounting for any damage and land use change.

Table 7 Seychelles MSP Zoning Framework: reproduced from Seychelles Marine Spatial Plan Initiative (2017). Bold emphasis our own.

Category	Name	Objective	Description
Zone 1	High Biodiversity Protection Zone	To allocate 15% of the EEZ and Territorial Sea for high marine conservation and biodiversity goals, for representative habitats and species.	High biodiversity protection zones conserve and protect the top priority areas for marine and coastal biodiversity in Seychelles. These zones are designated for habitats and species that may be rare, endangered, unique or with narrow distribution ranges. This zone includes breeding or spawning areas, key foraging habitat, fragile or sensitive species and habitats, and internationally significant areas. When combined, these zones provide habitats and species with long-term protection, and are sufficiently large to ensure ecological resilience and climate change adaptation. **This zone category is not suitable for extraction or sea bed alteration**.
Zone 2	Medium Biodiversity Protection and Sustainable Use Zone	To allocate 15% of the EEZ and Territorial Waters for medium marine conservation and biodiversity goals, for representative habitats and species. Sustainable uses are compatible with the biodiversity objectives in these areas.	Medium biodiversity protection and sustainable use zones are proposed to conserve areas that are suitable for medium levels of biodiversity protection and are also compatible with some sustainable uses. These zones include habitats and species that have some tolerance to disturbance and human activities. These zones also include regionally and nationally significant areas. This zone category is **suitable for some level of extraction and sea bed alteration, with appropriate management and direction, depending on the objective of each designated area**.
Zone 3	Multiple Use Zone	To allocate 70% of the EEZ and Territorial Waters to maximise uses and activities in Seychelles, with development aligned with long-term sustainability of the natural resources.	Areas are identified for **multiple uses and economic activity**. These include high value and/or high priority areas for the marine sectors that use Seychelles waters for economic, social and cultural benefits.

Table 8: Distribution of Seagrass habitat in relation to the Seychelles Marine Spatial Plan (SMSP)

	SMSP Zone / Type	Name	Island(s), Atoll, Bank	Seagrass Area (ha)*	Organic Carbon (t)	Organic Carbon (CO_2e)	Mapped seagrass Area (ha)*	Total Organic Carbon (t)*	Total Organic Carbon (CO_2e)*	Proportion of Seychelles Total (%)
Coraline Islands	Zone 1	Amirantes South National Park	Amirantes Bank	9,401	1,109,318	4,067,499	11,319	1,335,642	4,897,354	7.08
		D'Arros to Poivre Atolls National Park	Amirantes Bank	1,250	147,500	540,833				
		Bird Island National Park	Outer Plateau Rim	588	69,384	254,408				
		D'Arros Atoll	Amirantes Bank	80	9,440	34,613				
	Zone 2	Amirantes to Fortune Bank	Platte, Coëtivy, Amirantes Bank, Mahe Plateau	102,070	12,044,260	44,162,287	144,219	17,017,842	62,398,754	90.18
		Farquhar Archipelago	Providence Bank	20,477	2,416,286	8,859,715				
		Desroches Atoll	Desroches	8,021	946,478	3,470,419				
		Cosmoledo and Astove Archipelago	Cosmoledo & Astove	6,180	729,240	2,673,880				
		Farquhar Archipelago	Farquhar	3,493	412,174	1,511,305				
		Alphonse Group	Alphonse, Bijoutier, St Francois	2,441	288,038	1,056,139				
		Poivre Atoll	Amirantes Bank	789	93,102	341,374				
		African Banks	Amirantes Bank	502	59,236	217,199				
		Aldabra Group National Park	Assomption	149	17,582	64,467				
		Dennis Island	Outer Plateau Rim	97	11,446	41,969				
Granitic Islands	Zone 3		Praslin	473	55,814	204,651	614	72,452	265,657	0.38
			Mahé	117	13,806	50,622				
			La Digue	22	2,596	9,519				
			Other Islands	2	236	865				
Coraline Islands	Marine National Park or Reserve (Pre-MSP)	Aldabra Reserve	Aldabra	3,495	412,410	1,512,170	3,692	435,656	1,597,405	2.31
Granitic Islands		Ste. Anne Marine National Park	Ste. Anne, Cerf & Long	127	14,986	54,949				
		Curieuse Marine National Park	Curieuse & Praslin	36	4,248	15,576				
		Port Launay Marine National Park	Mahé	13	1,534	5,625				
		Baie Ternay Marine National Park	Mahé	13	1,534	5,625				
		Port Launay Wetland	Mahé	8	944	3,461				
	Shell Reserve (Pre-MSP)	Anse Aux Pins Shell Reserve	Mahé	75	8,850	32,450	79	9,322	34,181	0.05
		La Digue Shell Reserve	La Digue	4	472	1,731				
						Total	**159,923**	**18,870,914**	**69,193,351**	**100.00**

* Values rounded to nearest whole number

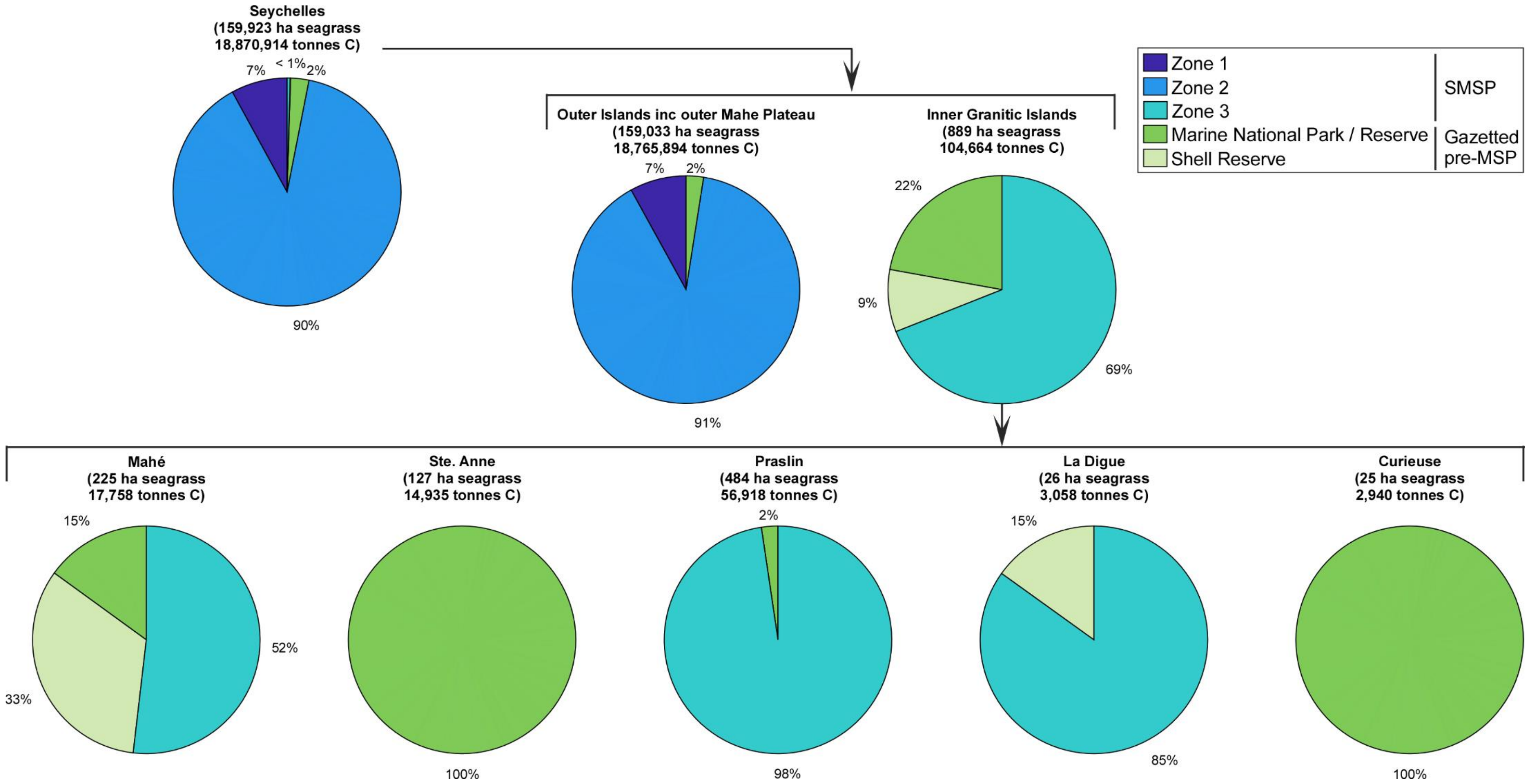


Figure 34: Distribution of seagrass habitat and associated carbon by different spatial management categories of the Seychelles Marine Spatial Plan (SMSP).

Conclusion

Seagrass is a nationally important blue carbon ecosystem. Despite having a quarter of the carbon per hectare of mangroves, because of its significant area seagrass contributes up to **96% of the total carbon stored within these two ecosystems** and **a total stock of 18.9 million tonnes Organic Carbon, or ~69 million tCO2e** (Table 5).

The Seychelles Seagrass Mapping and Carbon Assessment Project delivers data for Seychelles relevant to achieving commitments outlined in the Seychelles NDC (Republic of Seychelles 2021). Through detailed mapping and country specific data on carbon stocks, the project delivers a Tier 2 assessment. The project supports an onward commitment to include these ecosystems within Seychelles' GHG inventory by 2025 and the capacity to move towards a tier 3 assessments of key carbon stocks as recommended by the IPCC. Lessons learned and capacity built through the project will support onward detailed and repeated measurements of key stocks through time or modelling.

Within the 2021 NDC, Seychelles further committed to protect its blue carbon ecosystems, i.e., at least 50% of its seagrass and mangrove ecosystems by 2025, and 100% of seagrass and mangrove ecosystems by 2030. The majority of Seagrass looks to fall under Zone 1, 2, or Pre-MSP protected areas. While spatial management appears well aligned, **the effectiveness of such management in preventing any carbon emissions will hinge on the specific management strategy and regulatory regime implemented in each management area**.

Specific policies are needed to avoid and minimise identifiable impacts to seagrass habitat and/or sediments that might lead to substantial carbon emissions.

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