Blue Carbon Ecosystems of the South Pacific

Field-based carbon assessments in Fiji, Papua New Guinea, Solomon Islands, and Vanuatu

Blue Carbon Ecosystems Assessments for SPREP component of the MACBLUE project.

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Disclaimer
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About this document

About the project

The project contributes to the Secretariat of the Pacific Regional Environment Programme (SPREP)'s component of the Management and Conservation of Blue Carbon Ecosystems (or MACBLUE) project, aiming to "*contribute to human and technical capacity to the mapping, management and rehabilitation of coastal ecosystems."* The MACBLUE project is a joint effort between the Deutsche Gesellschaft fur International Zusammenarbeit (GIZ), The Pacific Community (SPC) and SPREP. Its aim is to *"strengthen coastal biodiversity conservation and management through protection and rehabilitation incentives for coastal carbon sinks in Pacific Island countries."* The project requires Blue Carbon assessments in Fiji, Papua New Guinea, Solomon Islands, and Vanuatu.

The data collected will allow inventories of associated natural capital and will support government partners to better develop and implement conservation, management, and rehabilitation efforts. Good quality mapping and assessment data is essential for developing informed conservation and rehabilitation plans. This project seeks specifically to:

- Verify satellite mapping,
- Assess carbon sequestration rates in seagrass and mangrove habitats,
- Evaluate coastal blue carbon habitats,
- And to train and build capacity in each of the countries.

Scope of this report

This report forms one part of a series of Seagrass and Mangrove (SaM) Ecosystem Assessment Reports for Stage 4 (Carbon Assessment Reports) of the project titled *"Consultancy services to conduct Blue Carbon Ecosystems Assessments for SPREP component of the MACBLUE project".* This report is specific to fieldwork assessments conducted in Fiji, Papua New Guinea, Solomon Islands, and Vanuatu for this project. It includes:

- The methods for field carbon assessments, laboratory analysis and carbon stock calculations,
- The results of the seagrass and mangrove carbon assessments conducted in-country,
- A summary of the findings, conclusions, and limitations of this study.

Foreword

Blue carbon ecosystems, specifically, mangroves and seagrasses, play a crucial role in regulating our climate by capturing and storing atmospheric carbon dioxide. These ecosystems are capable of sequestering up to five times more carbon than terrestrial forests. However, when disturbed or removed, they release significant amounts of stored carbon back into the atmosphere. Protecting and restoring them is therefore essential for safeguarding biodiversity and mitigating climate change.

The Blue Carbon Stock Assessment report represents a significant milestone in advancing blue carbon stock and emission data for seagrass and mangrove ecosystems in the Pacific. For the first time, a coordinated, standardised, and field-based blue carbon stock assessment was conducted across four Pacific Island nations – Fiji, Papua New Guinea, Solomon Islands and Vanuatu. The methods adhered to the Intergovernmental Panel on Climate Change (IPCC) guideline, and the multi-country approach allowed meaningful comparisons between countries and contexts to understand patterns, identify priority areas for protection and inform future management interventions. The produced Tier 2 data support the countries in their national greenhouse gas inventories, their reporting to international agreements such as the Nationally Determined Contributions (NDCs) and the development of appropriate national policies.

The study found that mangrove ecosystems in the Pacific store significant amount of carbon which are comparable, and in some cases exceeding, global averages. Most of these carbon, 70 – 83% are found below ground. The carbon stock levels in seagrass were determined to also align with global averages, specifically in Papua New Guinea and Vanuatu. Emission levels were found to be typically higher at sites where mangroves were cleared for development and relatively less at sites disturbed by natural events such as cyclones.

The study is commissioned under the Management of Blue Carbon Ecosystems in Pacific Island Countries (MACBLUE) project, implemented by the Secretariat of the Pacific Regional Environment Programme (SPREP) in partnership with Deutsche Gesellschaft fur International Zusammenarbeit (GIZ) and the Pacific Community (SPC).

On behalf of SPREP, I extend our appreciation to Alluvium International Group for leading the implementation of the study in collaboration with our key government partners in the four countries whose collective efforts have made this project and study a success. We are sincerely grateful for the support of the local communities across the 131 sites assessed who, through Free, Prior and Informed Consent (FPIC), generously shared their lands, waters, and knowledge to make this study possible.

The results stand as both a scientific contribution and a call to action, emphasizing the urgent and collective actions needed to safeguard seagrass and mangrove ecosystems, while highlighting the contribution of blue carbon studies in enhancing knowledge and capacity in this field.

Sefanaia Nawadra

Director General SPREP

Acknowledgements

We gratefully acknowledge the many individuals, communities, and organizations who made this blue carbon assessment project possible across Fiji, Papua New Guinea, Solomon Islands, and Vanuatu.

We extend our special thanks to the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) for their generous funding and support, which made this work possible.

This work was made possible through the generous support and collaboration of local communities, who welcomed us onto their lands and waters. We respectfully recognize the importance of the Free, Prior and Informed Consent (FPIC) process, which was followed in all locations. Communities were notified prior to our arrival, and permissions were formally granted by village chiefs, provincial administrators, and local leaders. Their trust and hospitality were essential to the success of this project.

Across the project, Turang Teuea and Paul Maxwell led project management, with field assessments coordinated by Emily Saeck and Erin Thompson. Field assessments were led by a dedicated team of botanists and ecologists, including Ana Backstrom, Emily Saeck, Erin Thompson, Rohan Khot, Chrissi Charles, Paul Maxwell, Patrick Pikacha, Simon Albert, Alistair Grinham, Fernanda Adame, and Nicholas Grundy. Blue carbon expert advice and oversight were provided by Cath Lovelock, Fernanda Adame, Simon Albert, Patrick Pikacha, and Alistair Grinham. Mapping support was led by Aakash Malik and Erin Thompson, in collaboration with SPC and GIZ. Charlotte Warfield and Erin Thompson led the big job of data management and analysis.

Field assessments in each country required the support of teams of local experts and field support, as summarised here. We hope we have not left anyone out.

Fiji

Local Expert Advice: Helen Sykes, Milika Sobey, Paula Tuvura

Fieldwork Coordination: Manasa Vulu, Vasiti Vosabalavu Naikoyadau, Shyam Lodhia, Turang Teuea

Fieldwork Support: Nick Metherall, Shyam Lodhia, Semi Lawevuso, Paula Tuvura, Mereoni Taga, Kalesi Tuitui Nadalo, Etuate Serevi, Vasiti Vosabalavu Naikoyadau, Mr Henry Miller, Mr Tom, Miss Sala, Mr Ben

We extend our sincere thanks to the village heads (Turaga ni Koro), provincial and National Government offices who granted permission and supported this research, including:

- Ministry of iTaukei Affairs
- Roko Tui and Assistant Roko Tui, Rewa Provincial Office
- Turaga ni Koro for Nakadrudru, Galoa Island, and Tavea
- Tui Labasa Ratu Jone Qomate
- Turaga ni Koro for Mali Island
- Solomone Qilatabu and Joji Lalabalav for Ovalau Island and Lomaiviti Province
- Mr Asaeli Tamanitokula – Bua Province
- Mr Manasa Vula – Cakaudrove Province
- Ms Vasiti Vosabalavu Naikoyadau – Macuata Province
- Maria Dali – Rewa Province

Papua New Guinea

Local Expert Advice: Phelameya Haiveta, Patrick Pikacha, Japheth Gai, Marika Seden

Fieldwork Coordination and Community Liaison: Phelameya Haiveta, Japheth Gai, Akanisi Lomaloma, Gideon Bogosia, Gerard Avoa, Benjamin Keni, Marika Seden, Tiana Reimann, Artie Jacobson, Dainah Gigiba, Lulu Osembo

Fieldwork Support: Tiana Reimann, Marika Seden, Isaac Rounds, Priscilla Pep, Paul Taro, Ray Barrette, Seawomen of Melanesia, Artie Jacobson, INLOC Ranger Program, Tobby Jinga, Nembo Oro, Marzena Marinjembi, Japheth Gai, Turang Teuea

We extend our sincere thanks to the community leaders, provincial administrations and National Government authorities who granted permission and supported this research, including:

- Climate Change and Development Authority
- Conservation and Environment Protection Authority
- National Research Institute
- Village Headman, Old Mawatta
- Village Headman, Lavatbura
- Youth President, Maiwara Village
- Bautama Seventh Day Adventist Church
- Lulu Osembo – Milne Bay Province
- Benjamin Keni – Central Province / Hiri District
- Dianah Gigiba – South Fly District
- Gideon Bogosia – New Ireland Province
- Desmond Mondo Poka Vaghelo – West New Britain Province

Solomon Islands

Local Expert Advice: Myknee Sirikolo, Veira Pulekera, Simon Albert

Fieldwork Coordination, Fieldwork Support and Community/Provincial Liaison: Sammy Airahui, Myknee Sirikolo, Veira Pulekera

We extend our sincere thanks to resources owners, provincial governments, community chief and leaders, rangers and National Government participated in this study in four Provinces, with relevant permits under MECDM & Provincial Government. Among those we wish to acknowledge include:

- Ministry of Environment, Climate Change, Disaster Management and Meteorology
- Environment and Conservation Department
- Climate Change Division
- Ministry of Forestry and Research
- Ministry of Fisheries and Marine Resources
- Village Chief, Takwa
- Village Chief, Michi

- Village Chief, Chumbikopi
- Village Chief, Nazareth
- Village Chief, Baolo
- Malaita Province
- Santa Isabel Province
- Western Province
- Guadalcanal Province

Vanuatu

Local Expert Advice: Rolenas Tavue Baereleo, Dean Launder, Milika Sobey

Field Coordination and Community Liaison: Moses Amos, Clay Sara, Malili Malisa

We extend our sincere thanks to the community leaders, provincial and National Government offices who granted permission and supported this research, including:

- Department of Environmental Protection and Conservation
- Chief, Malokillikilli
- Chief, Paonangisu
- Chief, Peskarus
- Mayor, Sanma Province
- Town Clerk and Deputy Town Clerk, Luganville
- Malampa Province

We are deeply grateful to all who contributed their time, expertise, and hospitality. This project would not have been possible without your support.

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GLOSSARY

AG	Above-ground
BD	Bulk Density
BG	Below-ground
C	Carbon
CC	Carbon concentrations
FPIC	Free, Prior and Informed Consent
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit (German Corporation for International Cooperation)
MACBLUE	Management and Conservation of the Blue Carbon Ecosystems
NGO	Non-Governmental Organisation
PNG	Papua New Guinea
SaM	Seagrass and Mangrove
SE	Standard Error
SOC	Soil organic carbon
SPC	The Pacific Community
SPREP	Secretariat of the Pacific Regional Environment Programme
TCS	Tree carbon storage
TECs	Total ecosystem carbon stocks

1 Introduction

1.1 Background

1.1.1 Seagrass and mangroves are valuable coastal ecosystems for Pacific Island Nations

Blue Carbon Ecosystems (BCEs) such as Seagrass and Mangrove (SaM) ecosystems provide substantial ecological, economic, and social benefits, significantly supporting the lives and livelihoods of Pacific Island Nations.

SaMs capture and store carbon, acting as highly effective carbon sinks and play a crucial role in climate change mitigation. These systems, despite being much smaller in size than terrestrial forests, sequester carbon at a much greater rate. When these systems are degraded or removed, a large amount of carbon is emitted back into the atmosphere where it can contribute to climate change.

Ecologically, these habitats serve as critical nurseries for numerous marine species, enhancing biodiversity and supporting fisheries that are vital for food security. Mangroves, with their complex root systems, stabilise coastlines, reduce erosion, and protect against storm surges and tsunamis. Economically, these ecosystems support artisanal and commercial fisheries, providing livelihoods for coastal communities. Additionally, they attract ecotourism, which generates income and promotes conservation efforts. Socially, SaMs contribute to the cultural heritage of Pacific communities, offering resources for traditional practices and medicines.

The protection and restoration of these BCEs, not only protects their carbon stores contributing to climate change mitigation but is essential for the sustainable development and resilience of Pacific Island Nations in general.

1.1.2 Rapid assessment across four Pacific Island Nations: Fiji, Papua New Guinea, Solomon Islands, and Vanuatu

Understanding the unique characteristics and vulnerabilities of these ecosystems across the Pacific Island Nations is critical for their management and protection, particularly in the context of land development, climate change, and sea-level rise. Many previous studies have focused on assessments at the scale of individual sites and locations; however, no prior study has sought to compare carbon stocks and ecological characteristics and threats using a standardised method across four Pacific Island Nations (Fiji, Papua New Guinea, Solomon Islands, and Vanuatu). This is due to logistical difficulties and the vast geographic spread of the islands, which can hinder extensive research efforts.

This project aims to fill this gap by applying rapid assessment methods for evaluating the carbon stocks, ecological characteristics, condition, biodiversity, and threats to seagrass and mangrove ecosystems. Rapid assessment methods are advantageous because they enable researchers to cover larger spatial areas efficiently, providing a comprehensive overview of ecosystems across diverse locations. This broad spatial coverage facilitates comparative analyses, helping to identify patterns and trends that may not be apparent in smaller-scale studies. Additionally, these methods allow for the quick identification of high-priority areas for further research, restoration, and protection efforts, ensuring that resources are allocated effectively to the most critical sites.

1.2 Purpose of this document

This report forms one part of a series of Seagrass and Mangrove (SaM) Ecosystem Assessment Reports for Stage 4 (Carbon Assessment Reports) of the project titled *"Consultancy services to conduct Blue Carbon Ecosystems Assessments for SPREP component of the MACBLUE project".* This report is specific to fieldwork assessments conducted in Fiji, Papua New Guinea, Solomon Islands, and Vanuatu for this project. It includes:

- The methods for field carbon assessments, laboratory analysis and carbon stock calculations,
- The results of the seagrass and mangrove carbon assessments conducted in-country,

- A summary of the findings, conclusions, and limitations of this study.

This document forms the introduction and method section of the report. The results are in separate documents, one for each of the four countries assessed.

1.3 About the project

This project contributes to SPREP's component of the MACBLUE project, aiming to "*contribute to human and technical capacity to the mapping, management and rehabilitation of coastal ecosystems*" (www.macblue-Pacific.info). The Management and Conservation of Blue Carbon Ecosystems (or MACBLUE) is a joint effort between the Deutsche Gesellschaft fur International Zusammenarbeit (GIZ), The Pacific Community (SPC) and The Secretariat for the Pacific Regional Environment Programme (SPREP). Its aim is to "strengthen coastal biodiversity conservation and management through protection and rehabilitation incentives for coastal carbon sinks in Pacific Island countries." The project requires Blue Carbon assessments in Fiji, Papua New Guinea, Solomon Islands and Vanuatu.

The data collected for this project will allow inventories of carbon stocks and associated natural capital and will support government partners to better develop and implement conservation, management, and rehabilitation efforts. Good quality mapping and assessment data is essential for developing informed conservation and rehabilitation plans. This project seeks specifically to:

- Verify satellite mapping
- Assess carbon sequestration rates in SaM ecosystems
- Evaluate coastal blue carbon habitats
- And to train and build capacity in each of the countries.

2 Past studies

Existing knowledge of blue carbon stocks in Pacific Island Nations is limited and fragmented, particularly for mangrove and seagrass ecosystems. Here we have summarised some geographically relevant study findings in Table 1. In Fiji, localised studies—such as those by Cameron, Lovelock, and Adame (2021)—have focused on key river deltas like Ba, Tuva, and Rewa on Viti Levu.[1] These studies estimated total ecosystem carbon stocks (TECS) in mangroves at approximately 481.6 Mg C ha^{-1}, which is lower than global averages.[2,3] However, this figure is likely an underestimate, as most soil carbon in deltaic systems is stored below 1 m depth, and the Fiji study only sampled to 1.5 m. This highlights the importance of deeper soil sampling for accurate carbon accounting, especially in sediment-rich environments.

In contrast, Papua New Guinea, Solomon Islands, and Vanuatu have seen even fewer studies, with most data derived from small-scale or site-specific assessments. Papua New Guinea, despite having some of the most extensive mangrove forests in the region, lacks comprehensive carbon stock inventories. Similarly, the Solomon Islands and Vanuatu have limited published data on mangrove or seagrass carbon stocks, making regional comparisons difficult.

Regional studies such as Donato et al. (2011), which sampled soil carbon to depths of up to 3 m across the Indo-Pacific, underscore the significance of deep soil carbon pools in mangrove ecosystems. Our study—which has focused on the top 1 m of soil—likely provides valuable but conservative estimates of carbon stocks. However, by providing a standardised assessments approach across many sites across the four countries of Fiji, Papua New Guinea, Solomon Islands and Vanuatu, the results of this carbon assessment will allow us to characterise the variation in carbon stocks across the mangrove and seagrass ecosystems of the Pacific Island Nations and help fill this knowledge gap.

[1] Cameron, M. J., Lovelock, C. E., & Adame, M. F. (2021). Carbon stocks of mangrove forests in Fiji: Implications of soil depth and land use. Forest Ecology and Management, 482, 118879. https://doi.org/10.1016/j.foreco.2020.118879

[2] Kauffman, J. B., Bernardino, A. F., Ferreira, T. O., Giovannoni, L. R., & Jesus Garcia, M. (2020). Carbon stocks of intact mangroves and carbon emissions arising from their conversion in the Dominican Republic. Ecological Applications, 30(3), e02089. https://doi.org/10.1002/eap.2089

[3] Alongi, D. M. (2023). Blue carbon ecosystems and climate change mitigation: A global perspective. Springer.

Table 1. Summary of past studies of seagrass ecosystem carbon stock assessments in Pacific Island Nations and other surrounding nations.

Country	Above-ground Biomass (Mg C ha^{-1})	Below-ground Biomass (Mg C ha^{-1})	Live Seagrass Biomass (Mg C ha^{-1})	Soil Organic Carbon Content (%)	Soil depth profile (cm)	Total Soil Carbon (Mg C ha^{-1})	Total Ecosystem Carbon (Mg C ha^{-1})	Notes and citation
Indonesia	0 .01 – 1 .85	0.05 – 1.84			≤ 100	0.32 – 65.8		Based on a review of available literature for 13 countries in Southeast Asia.[4]
Palau & Yap	0.39	-	0.12	16.7	14	48.0	48.12	Carbon stock of Micronesian mangroves and adjacent seagrass communities.[5]
Fiji	-	0.32 – 0.95	0.21	0.5 – 0.95%	10	31 – 47	78.21	Carbon storage in seagrass meadows near Rewa River and Sigatoka River in Viti Levu, Fiji.[6]
Singapore	0.09	0.07	0.16	1.1	100	138	138	Carbon stock assessment of intertidal ecosystems in Chek Jawa, Singapore.[7]
Australia	-	-	-	1.26	240	365.09	365.09	Sedimentary carbon stock assessment in Coffs Harbour, Australia.[8]

[4] Stankovic, M., Mishra, A. K., Rahayu, Y. P., Lefcheck, J., Murdiyarso, D., Friess, D. A., ... & Prathep, A. (2023). Blue carbon assessments of seagrass and mangrove ecosystems in South and Southeast Asia: Current progress and knowledge gaps. *Science of the Total Environment*, *904*, 166618.
[5] Kauffman, J. B., Heider, C., Cole, T. G., Dwire, K. A., & Donato, D. C. (2011). Ecosystem carbon stocks of Micronesian mangrove forests. *Wetlands, 31*(2), 343–352. https://doi.org/10.1007/s13157-011-0148-9
[6] Singh, S., Lal, M. M., Southgate, P. C., Wairiu, M., & Singh, A. (2022). Blue carbon storage in Fijian seagrass meadows: First insights into carbon, nitrogen and phosphorus content from a tropical southwest Pacific Island. *Marine Pollution Bulletin, 183*, Article 113432. https://doi.org/10.1016/j.marpolbul.2022.113432
[7] Phang, V. X. H., Chou, L. M., & Friess, D. A. (2015). Ecosystem carbon stocks across a tropical intertidal habitat mosaic of mangrove forest, seagrass meadow, mudflat and sandbar. *Earth Surface Processes and Landforms, 40*(11), 1387–1400. https://doi.org/10.1002/esp.3745
[8] Brown, D. R., Conrad, S., Akkerman, K., Fairfax, S., Fredericks, J., Hanrio, E., Sanders, L. M., Scott, E., Skillington, A., Tucker, J., van Santen, M. L., & Sanders, C. J. (2016). Seagrass, mangrove and saltmarsh sedimentary carbon stocks in an urban estuary; Coffs Harbour, Australia. *Regional Studies in Marine Science, 8*, 1–6. https://doi.org/10.1016/j.rsma.2016.08.005

Table 2. Summary of previous studies of mangrove ecosystem carbon stock assessments in Pacific Island Nations and other surrounding nations

Country	Above-ground Biomass (Mg C ha^{-1})	Below-ground Biomass (Mg C ha^{-1})	Live Tree Biomass (Mg C ha^{-1})	Soil Organic Carbon Content (%)	Soil profile depth (cm)	Total Soil Carbon (Mg C ha^{-1})	Total ecosystem carbon (Mg C ha^{-1})	Notes and citation
Papua New Guinea	242.4 – 432.5	-	-	-	NA	-	-	Global study based on remotely sensed measurements of tree cover and canopy heights, no localised field data[9]
Fiji			4.5 – 231.7	1.76 – 10.83	150	83.9 – 490.3	132.8 – 772.8	Viti Levu: Ba, Rewa, Nadroga-Navosa [10]
Vanuatu	536.9 – 1,318.4	486.6	155 – 747	-	-	-	-	Biomass surveys of Amal/Crab Bay and Eratap in Vanuatu dominated by *Bruguiera gymnorrhiza*, *Rhizophora sp., Xylocarpus granatum, Ceripos tagal,* and *Avicennia marina*.[11]
Palau & Yap	588	483	657	~18.3	160	1058.3	1,715.3	Mangrove carbon stocks in Palau & Yap.[12]
Australia	297	312			3500	1530	2139	Queensland, *Rhizophora stylosa* dominated, Base on published and unpublished data by authors [13]
Indonesia	19	< 684 *			62		703	*Rhizophora stylosa* dominated; based on published and unpublished data by authors[14]
Indonesia	0.03 – 742.6	0.16 – 211.2			≤100	2 – 575		Based on review of available literature for 13 countries in Southeast Asia [15]

[9] Simard, M., Fatoyinbo, L., Smetanka, C., Rivera-Monroy, V.H., Casta˜neda-Moya, E., Thomas, N., Van der Stocken, T., 2019. Mangrove canopy height globally related to precipitation, temperature and cyclone frequency. Nat. Geosci. 12 (1), 40–45.
[10] Cameron, C., Kennedy, B., Tuiwawa, S., Goldwater, N., Soapi, K., & Lovelock, C. E. (2021). High variance in community structure and ecosystem carbon stocks of Fijian mangroves driven by differences in geomorphology and climate. *Environmental Research*, *192*, 110213
[11] Baereleo, R., Kalfatak, D., Kanas, T., Bulu, M., Ham, J., Kaltavara, J., Sammy, E., Dovo, P., Duke, N., MacKenzie, J., Sheaves, M., Johnston, R., & Yuen, L. (2025). *Mangrove EcoSystems for Climate Change Adaptation and Livelihoods (MESCAL) Biodiversity Assessments Technical Report*. Viliame Pita Waqalevu (Ed.). Vanuatu: MESCAL Project.
[12] Kauffman, J. B., Heider, C., Cole, T. G., Dwire, K. A., & Donato, D. C. (2011). Ecosystem carbon stocks of Micronesian mangrove forests. *Wetlands, 31*(2), 343–352. https://doi.org/10.1007/s13157-011-0148-9
[13] Daniel M Alongi (2012) Carbon sequestration in mangrove forests, Carbon Management, 3:3, 313-322, DOI: 10.4155/cmt.12.20
[14] Daniel M Alongi (2012) Carbon sequestration in mangrove forests, Carbon Management, 3:3, 313-322, DOI: 10.4155/cmt.12.20
[15] Stankovic, M., Mishra, A. K., Rahayu, Y. P., Lefcheck, J., Murdiyarso, D., Friess, D. A., ... & Prathep, A. (2023). Blue carbon assessments of seagrass and mangrove ecosystems in South and Southeast Asia: Current progress and knowledge gaps. *Science of the Total Environment*, *904*, 166618.

Country	Above-ground Biomass (Mg C ha^{-1})	Below-ground Biomass (Mg C ha^{-1})	Live Tree Biomass (Mg C ha^{-1})	Soil Organic Carbon Content (%)	Soil profile depth (cm)	Total Soil Carbon (Mg C ha^{-1})	Total ecosystem carbon (Mg C ha^{-1})	Notes and citation
Singapore	138	52	190	4.5	100	307	497	Carbon stock assessment in Chek Jawa mangrove dominated by *Avicennia sp., Bruguiera cylindrica, Ceriops tagal, Excoecaria agallocha, Rhizophora sp., Sonneratia caseolaris,* and *Xylocarpus moluccensis.*[16]
Australia	-	-	-	4.17	300	1069.81	1069.81	Sedimentary carbon stock assessment in Coffs Harbour, Australia.[17]

*The value includes below-ground soil carbon, carbon originating below-ground biomass will be less.

[16] Phang, V. X. H., Chou, L. M., & Friess, D. A. (2015). Ecosystem carbon stocks across a tropical intertidal habitat mosaic of mangrove forest, seagrass meadow, mudflat and sandbar. *Earth Surface Processes and Landforms, 40*(11), 1387–1400. https://doi.org/10.1002/esp.3745

[17] Brown, D. R., Conrad, S., Akkerman, K., Fairfax, S., Fredericks, J., Hanrio, E., Sanders, L. M., Scott, E., Skillington, A., Tucker, J., van Santen, M. L., & Sanders, C. J. (2016). Seagrass, mangrove and saltmarsh sedimentary carbon stocks in an urban estuary; Coffs Harbour, Australia. *Regional Studies in Marine Science, 8*, 1–6. https://doi.org/10.1016/j.rsma.2016.08.005

3 Method

3.1 Summary

For each country, four to eight representative locations, with known mangrove and seagrass presence, were selected for the carbon stock assessment. At each of these locations, the following carbon assessment method was applied to two to eight sites:

1. Above-ground and below-ground biomass assessments
2. Soil organic carbon sampling.

The fieldwork survey methods implemented for this project were developed based on the following resources:

- *Coastal Blue Carbon: Methods for assessing carbon stocks and emissions factors in mangroves, tidal salt marshes, and seagrasses* (Howard et al. 2014[18])
- *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetland* (Hiraishi et al. 2014[19])
- *Coastal Wetlands in National Greenhouse Gas Inventories: Advice on reporting emissions and removal from management of Blue Carbon ecosystems* (Green et al. 2013[20])
- *Manual for mangrove monitoring in the Pacific Islands region* (Ellison et al. 2012[21])
- *Intertidal Spot-checks: Quick guide to collecting intertidal field validation data for seagrass mapping* (McKenzie and Yoshida, 2023[22])
- *Subtidal Spot-checks: Quick guide to mapping subtidal seagrass using drop-camera (*McKenzie and Yoshida, 2024[23])
- *Guidelines for Undertaking Rapid Biodiversity Assessments in Terrestrial and Marine Environments in the Pacific,* (Patrick et al. 2014[24])

The full fieldwork survey methodology is described in detail in *Blue Carbon Ecosystems Assessment for Carbon Stock, Biodiversity and Threats: Training and Field Manual* (Alluvium International and EcoFutures 2024[25]).

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[18] Howard, J., Hoyt, S., Isensee, K., Telszewski, M., Pidgeon, E. (eds.) (2014). *Coastal Blue Carbon: Methods for assessing carbon stocks and emissions factors in mangroves, tidal salt marshes, and seagrasses.* Conservation International, Intergovernmental Oceanographic Commission of UNESCO, International Union for Conservation of Nature. Arlington, Virginia, USA.
[19] Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. and Troxler, T.G. (eds). (2014). Published: IPCC, Switzerland
2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands https://www.ipcc.ch/publication/2013-supplement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories-wetlands/
[20] Green, Carly., Lovelock, Catherine E., Sasmito, Sigit., Hagger, Valerie. and Crooks, Stephen. (2021). Coastal Wetlands in National Greenhouse Gas Inventories: Advice on reporting emissions and removal from management of Blue Carbon ecosystems. Published by Australian Aid, University of Queensland, Environmental Accounting Services, Silvestrum Climate Associates.
[21] Ellison, Joanna., Jungblut, Vainuupo., Anderson, P., and Slaven, Christian. (2012). Manual for Mangrove Monitoring in the Pacific Islands Region. Published by Secretariat of the Pacific Regional Environment Programme (SPREP).
[22] McKenzie and Yoshida, (2023), Intertidal Spotchecks: Quick guide to collecting intertidal field validation data for seagrass mapping. Seagrass-Watch HQ. Clifton Beach, Queensland, Australia
[23] McKenzie and Yoshida, (2024). Subtidal spot-check: Quick guide to mapping subtidal seagrass using drop-camera. Seagrass-Watch HQ. Clifton Beach, Queensland, Australia
[24] Patrick, B., McClellan, R., Martin, T., Tocher, M., Borkin, K., & Smith, D. (2014). Guidelines for Undertaking Rapid Biodiversity Assessments in Terrestrial and Marine Environments in the Pacific. Apia, Samoa: SPREP, Wildlands, Australian Aid
[25] Alluvium International and EcoFutures. 2025. Blue Carbon Ecosystems Assessment for Carbon Stock, Biodiversity and Threats: Training and Field Manual (Version 21 Feb 2025). Prepared for SPREP.

3.2 Site selection

Before commencing field work, sites were identified and selected in stage 2 of this project (Alluvium International and EcoFutures 2024[26]) based on a framework of site prioritisation criteria. This framework was informed by project logistics, stakeholder input, and existing protocols/guidelines for carbon assessments.

A key priority for the site selection process was to ensure that all habitat types, geomorphological settings, and land-use conversion levels (as described in Table 3) were representatively sampled across all countries.

Caveat: While sites were chosen to capture variability across different settings, they were not randomly selected and therefore do not constitute a statistically representative sample. Site selection was strongly influenced by practical considerations, including accessibility, safety, and landholder permissions. This limitation should be considered when interpreting results, particularly when extrapolating findings to broader regional or national scales.

Table 3. Sampling design variables and associated categories.

Variable	Categories
Habitat type	Seagrass Mangroves
Geomorphology[27]	Riverine Tidal Creek Open Coast Calcareous Island Lagoon
Land-use conversion[28]	Intact Degraded Converted

[26] Alluvium International and EcoFutures. 2024. STAGE 2 – Priority Sites Identification Report. Blue Carbon Ecosystems Assessments for SPREP component of the MACBLUE project. Prepared for SPREP.
[27] Rovai, A. S., Twilley, R. R., Castañeda-Moya, E., Riul, P., Cifuentes-Jara, M., Manrow-Villalobos, M., ... & Pagliosa, P. R. (2018). Global controls on carbon storage in mangrove soils. *Nature Climate Change*, *8*(6), 534-538.
[28] Adame, M. F., Connolly, R. M., Turschwell, M. P., Lovelock, C. E., Fatoyinbo, T., Lagomasino, D., ... & Brown, C. J. (2021). Future carbon emissions from global mangrove forest loss. *Global change biology*, *27*(12), 2856-2866.

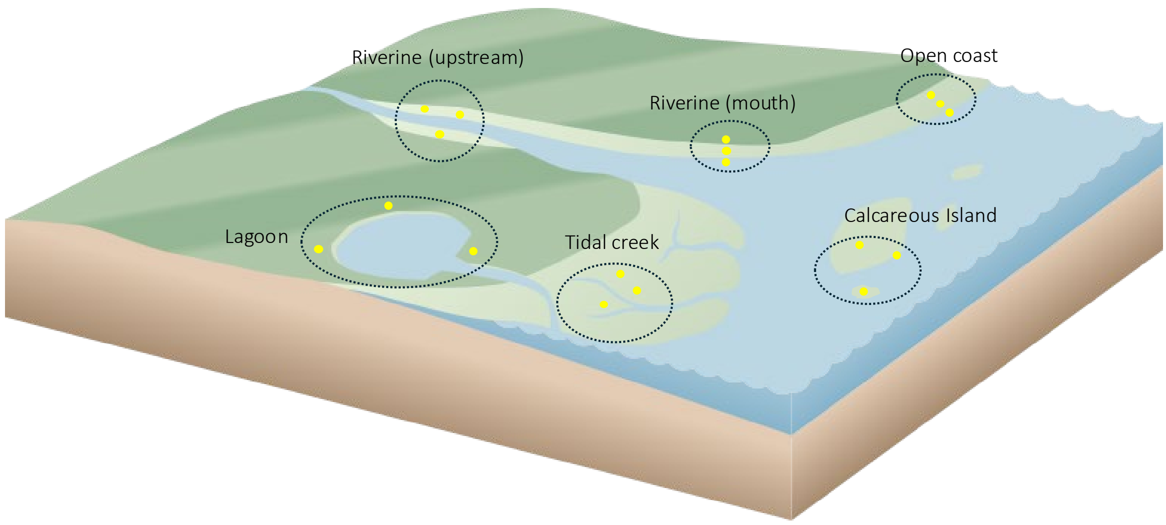

Figure 1. Conceptual diagram demonstrating the different geomorphological settings that should be represented when considering site selection. Black circles represent site options, and yellow circles represent plots within a site.

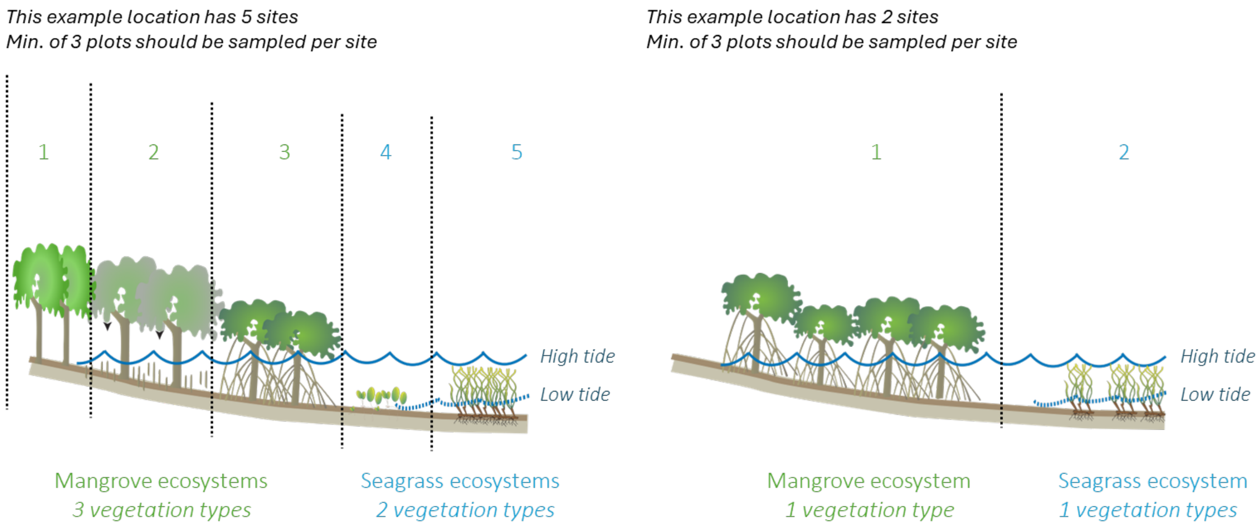

Figure 2. Vegetation type (including structure and species composition) is used to select sites, these two diagrams demonstrate how some locations may require fewer sites than others to ensure variability in carbon stocks is adequately represented by the assessment.

3.2.1 Geomorphology

Global studies of mangrove soil carbon have found that mangrove soil carbon significantly varies between geomorphological settings such as river deltas, lagoons, and islands[29] (Figure 1). This is because different processes dominate, such as tides, river discharge, temperature, precipitation, and evapotranspiration, in different geomorphological settings, influencing the soil chemistry and mangrove ecosystem. As such, to ensure variation in mangrove soil carbon is appropriately represented by this study, the geomorphic setting has been considered in the sampling design.[30] In each country, sites were selected to ensure where possible sampling was conducted in all categories shown in Table 1.

3.2.2 Land-use conversion

Prioritising conservation and restoration efforts for blue carbon habitats requires an understanding of 1) avoided carbon emissions due to the prevention of loss; and 2) gained carbon stocks due to restoration.[31] Different types of land-use conversions are related to different carbon emission predictions. Specifically, they have been found to vary between land-use changes due to: (a) conversion to commodities, such as agriculture or aquaculture; (b) coastal erosion; (c) clearing; (d) extreme climatic events; and (e) conversion to human settlements.[32] As such, sampling across a gradient of land-use conversion levels has been included in sampling design (Table 1). This approach will ensure the data collected from this study allows land-use drivers for carbon stocks to be integrated into Nationally Determined Contributions to the Paris Agreement and support each country's ability to predict and prioritise conservation and management.

[29] Rovai, A. S., Twilley, R. R., Castañeda-Moya, E., Riul, P., Cifuentes-Jara, M., Manrow-Villalobos, M., ... & Pagliosa, P. R. (2018). Global controls on carbon storage in mangrove soils. *Nature Climate Change*, *8*(6), 534-538.

[30] Dürr, H. H., Laruelle, G. G., van Kempen, C. M., Slomp, C. P., Meybeck, M., & Middelkoop, H. (2011). Worldwide typology of nearshore coastal systems: defining the estuarine filter of river inputs to the oceans. *Estuaries and coasts*, *34*, 441-458.

[31] Adame, M. F., Connolly, R. M., Turschwell, M. P., Lovelock, C. E., Fatoyinbo, T., Lagomasino, D., ... & Brown, C. J. (2021). Future carbon emissions from global mangrove forest loss. *Global change biology*, *27*(12), 2856-2866.

[32] Goldberg, L., Lagomasino, D., Thomas, N., & Fatoyinbo, T. (2020). Global declines in human-driven mangrove loss. Global Change Biology, 26(10), 5844–5855. https://doi.org/10.1111/gcb.15275

3.3 Site prioritisation framework

Logistics and safety concerns were equally significant criteria for site selection. Given this, priority was given to sites where:

- Seagrass and mangroves were confirmed present.
- Sites representing two or more categories were present in the surrounding area.
- Accessibility to the location and associated sites was high.
- Safety risk to the field team was low.
- Likelihood of community consent to visit and sample was high.

Table 4 outlines the criteria that were used to select priority sites. Combinations of priority locations were then compared. Table 5 describes the criteria used to assess various combinations of sites.

Table 4. Criteria used to rank and select short list of priority sites.

Category	Criteria for individual sites	Description
Habitat	Mangroves present	Sites where both mangrove and seagrass are present are preferred from a logistics perspective. Sites with relatively large habitat extents are preferred as they represent significant carbon stocks for each country.
	Seagrass present	As above.
	Endemic species present	Sites where endemic species are present are relatively unique and unlikely to represented by existing allometric that do not represent their unique carbon stocks; as such understanding carbon stocks in these habitats are key to more accurate national carbon stock assessments.
Access & safety	Travel cost to access site	Sites that minimise travel costs are favoured, reducing budget costs and allowing more sites to be surveyed.
	Travel time between sites	Sites that minimise travel time are favoured, allowing more sites to be surveyed.
	Travel mode between sites	Sites that have fewer, easier and safer modes of transport are favoured, allowing more sites to be surveyed.
	Access at site	Sites where access is not complex are favoured, as this reduces survey time and allows more sites to be surveyed.
	Hazards at site	Sites where risks to field staff safety are lowest are favoured. Hazards may include saltwater crocodiles, aggressive dogs, hostile individuals from local community, or regions with high criminal activity.
Community engagement	Community	Sites must have a community that is aware, engaged and welcoming of the project on their land.
	NGO	Ideally, sites have an NGO actively working with the local community.
	FPIC (free prior informed consent)	Ideally, an FPIC process has been formally completed.
National priorities	Local management site	The MACBLUE project will identify one Local Management Site per country. These sites are a priority for carbon stock assessment.
	National priority	Sites that have been identified as a priority by the MACBLUE NSC.

Category	Criteria for individual sites	Description
	Conservation value	Sites of high conservation significance.
Other considerations	Existing data/projects/baselines	Sites that have been extensively studied for carbon stocks in mangroves and seagrass will be a low priority compared to sites with no baseline. Sites that have a baseline only and/or limited previous studies will be prioritised.
	Permit	Sites where research permits are unlikely to gain approval within the project timeframes have low priority.

Table 5. Criteria used to rank and establish best combination of the priority sites

Category	Criteria for site combinations	Description
Representativeness	Floristically representative	Balanced representation of dominant floristic types across sites is required (rather than a suite of sites that are floristically very similar).
	Climate vulnerability	Range of climate vulnerabilities represented across sites (rather than all sites that are vulnerable to the same climate risks).
	Land use management	Dominant land-use practices represented across the suite of sites selected.
Logistics	Total time lost to travel between sites	Relatively short distances between sites resulting in low to no days lost to travel, will be favoured over large distances between sites, with multiple flights/long boat rides required, result in many days lost to travel.
	Total travel cost to access all sites	Total travel costs to access sites needs to be minimised / fit within budget allocation.

3.4 Carbon sampling

3.4.1 Sample plot design

A minimum of three plots were sampled per site to ensure that variation was captured at each site. Plots were selected with the aim of accurately representing the site (e.g., geomorphology, flora, fauna, and degradation level present). Figure 3 shows plot design for mangrove and seagrass plots. A sediment core was taken at the centre of each plot, and mangrove or seagrass above-ground biomass observations were measured within the plot area.

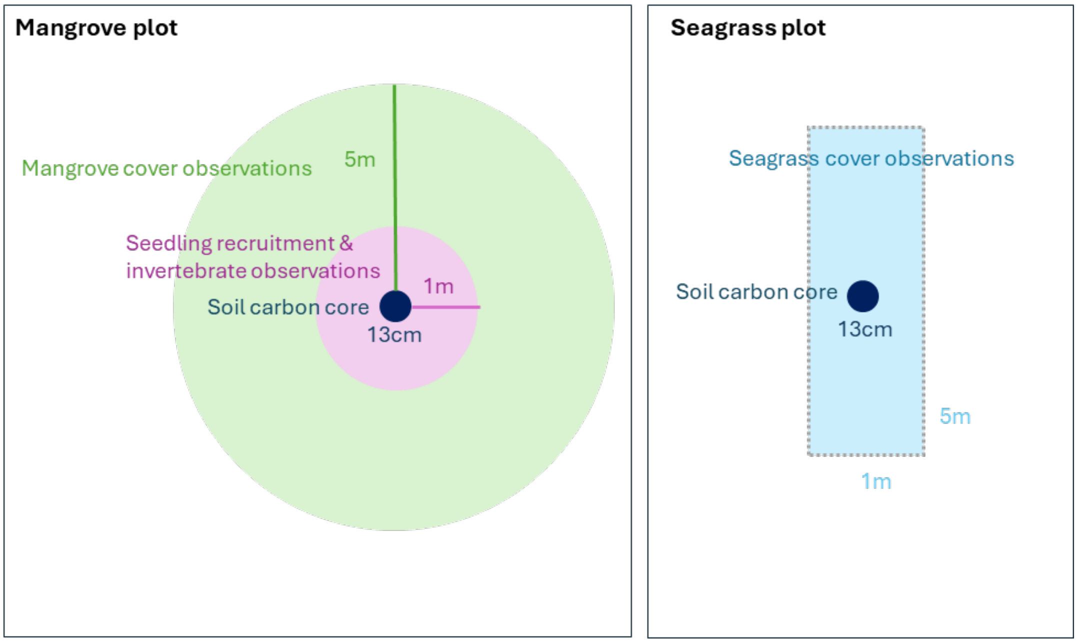

Figure 3. Representation of plot layout, showing core at the centre of each plot and different plot dimensions for mangrove and seagrass plots (note that 3 plots are needed per site as per Figure 1). Mangrove plot size varied between 2 and 10 m radius, and when a mangrove site, a minimum of 20 trees were measured per plot.

3.4.2 Mangrove above and below-ground biomass carbon sampling

Within each mangrove plot, all mangrove tree species were identified and their Diameter at Breast Height (DBH) was recorded. The level of decay of each tree was also noted, according to Kauffman, J.B. and Donato, D.C. 2012 [33]

Figure 4. Diameter at Breast Height (DBH) and species were recorded for each tree within a plot.

3.4.3 Soil carbon sampling

One soil core was taken at the centre of each plot using a sediment coring device. The coring device used varied depending on the site conditions and the most suitable option available. This included a sediment core sampler, modified PVC pipes, gouge augers, a grab sampler, and/or syringes (Figure 5, Figure 6, and Figure 7).

[33] Kauffman, J.B. and Donato, D.C. 2012 Protocols for the measurement, monitoring and reporting of structure, biomass and carbon stocks in mangrove forests. Working Paper 86. CIFOR, Bogor, Indonesia.

Figure 5. Demonstration of soil gouge auger operation to obtain mangrove soil core.

Figure 6. Demonstration of Universal Sediment Corer operation to obtain submerged soil cores.

Figure 7. Grab samplers (left) were used for sampling submerged soil and syringe sub-sampling (right).

After taking a soil core, they were photographed or drawn and also described. The length of soil cores and the hole depth were measured, and where possible, the cores were divided into segments at 0-15 cm, 15-30 cm, 30-50 cm, and 50+ cm (Figure 8). At each segment midpoint, a sample of known volume was collected. After measuring and recording the sediment samples' volume, the samples were dried using a dehydrator for 12-24 hours or until completely dry.

A soil sub-sample from every depth category up to 1 m (i.e. 0-15 cm, 15-30 cm, 30-50 cm, and 50+ cm) was sought for all plots (Figure 8). However, the number of depths sampled varied between cores due to conditions of the site or at the time of sampling. For example, at some sites, there were shallow sediments that didn't reach a full meter (i.e. shallow reef bedrock), which was often the case in the seagrass meadows. At other sites, the mangrove sediments were sand-dominated, affecting core integrity, especially under inundated conditions. Where crocodile risk was high and/or deep water, the only equipment used was a grab sampler that could be safely operated from a boat, however, only surface sediments could be obtained (Figure 7).

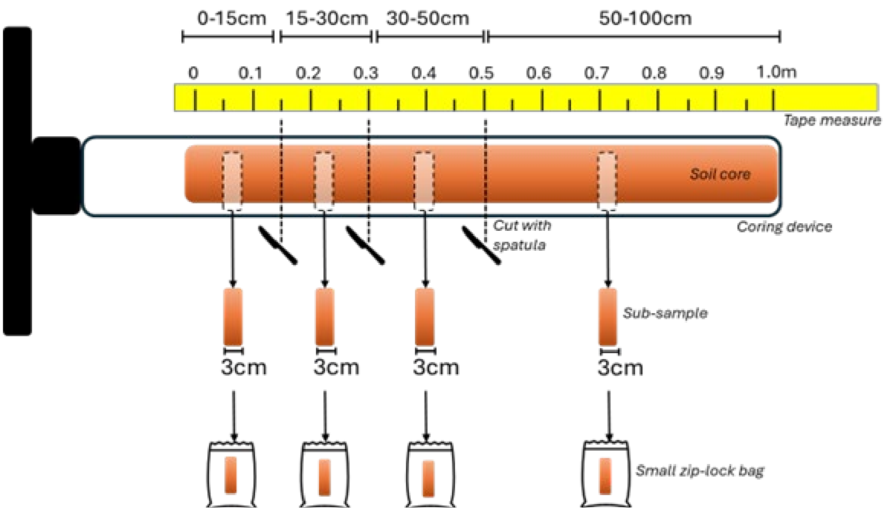

Figure 8. Diagram and photos demonstrating the method for sub-sampling a soil core.

3.4.4 Soil carbon laboratory analysis

Laboratory analysis of dried soil samples followed standardised protocols outlined in the Coastal Blue Carbon Manual[34]. Bulk Density (BD) was determined by oven-drying a known volume of soil at 60°C until constant weight was achieved, then dividing the dry mass by the original volume. For carbon analysis, sub-samples were finely ground and analysed for total carbon using dry combustion in an elemental analyser. To determine soil organic carbon, inorganic carbon was removed via acid fumigation prior to analysis, ensuring accurate quantification of the organic fraction.

3.5 Carbon stock calculations

3.5.1 Allometric equations for above and below-ground carbon

Seagrass

Above-ground (AG) and below-ground (BG) biomass carbon was not assessed for seagrass meadows in this study due to its relatively minor contribution to the total carbon pool, with over 95% of seagrass carbon typically stored in the sediment. Additionally, standardised allometric equations for estimating biomass carbon are limited or not well-developed for many seagrass species, particularly in Pacific Island contexts, making consistent and accurate estimation challenging. As a result, the focus was placed on sediment carbon, which represents the dominant carbon stock in seagrass ecosystems.

Mangroves

Tree Carbon Storage (TCS) refers to the amount of carbon stored within trees (Figure 9), which can be stored in above-ground biomass (in their trunks, stems, foliage, aerial roots and prop roots) and below-ground biomass (in their roots). Total TCS refers to the sum of the carbon stored in trees both above-ground (AG) and below-ground (BG).

Allometric equations were used to estimate the AG biomass of all trees measured in the field. Species-specific equations were used whenever available to ensure accurate biomass calculations (Table 6). In cases where species-specific equations were not available, general allometric equations were applied (Table 6). The carbon content of biomass was calculated by multiplying by a factor of 0.48 for AG biomass and 0.39 for BG biomass.

[34] Conservation International, Intergovernmental Oceanographic Commission of UNESCO, and International Union for Conservation of Nature. (2014). *Coastal Blue Carbon: Methods for assessing carbon stocks and emissions factors in mangroves, tidal salt marshes, and seagrass meadows*. UNESCO.

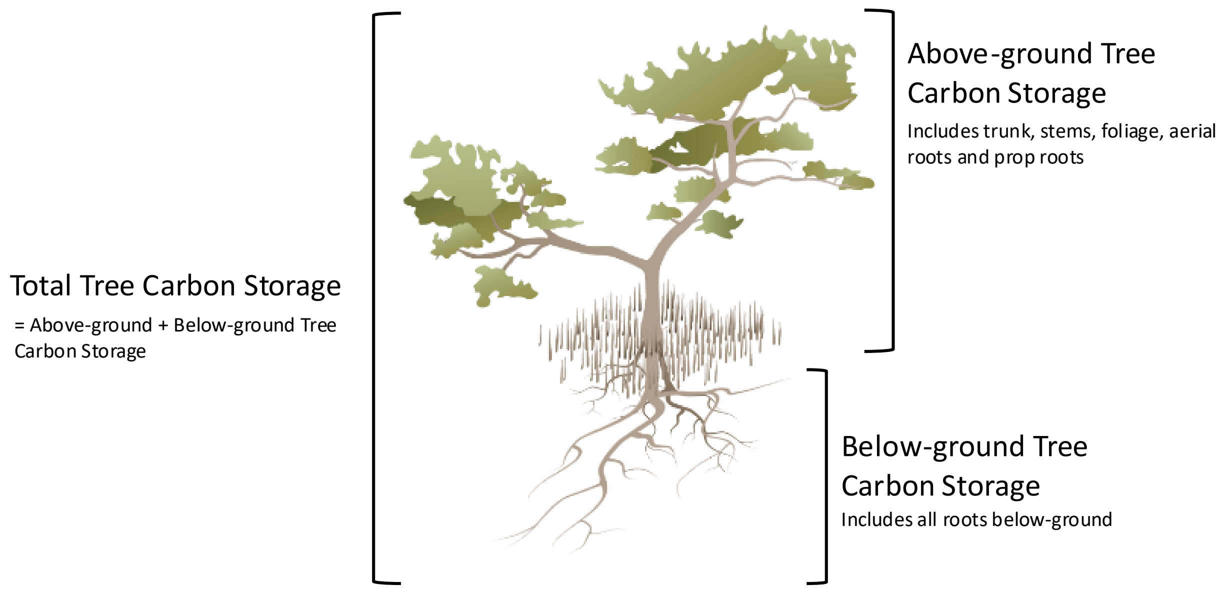

Figure 9. Illustration of Total Tree Carbon Storage stored in trees both above and below-ground.

Upper and lower estimates of total TCS were calculated for each site. This study found that many large trees in the assessed Pacific countries exceeded the maximum DBH limits for their species-specific allometric equations. Applying these species-specific equations to larger trees typically results in conservative lower estimates of carbon stock. In contrast, using the general equation by Chave et al. (2005) tends to yield less conservative upper estimates. For this report, unless otherwise specified, we adopted the conservative lower estimates by applying species-specific equations, even for trees exceeding the recommended DBH range.

An example of overestimation is observed in Vanua Levu, where the upper estimate for total TCS was 181 Mg C ha^{-1}, compared to the lower estimate of 142 Mg C ha^{-1} (Figure 10). This pattern was consistent across most locations. This lack of difference was due to no trees exceeding the maximum DBH for the species-specific equation, resulting in unchanged results (Figure 10).

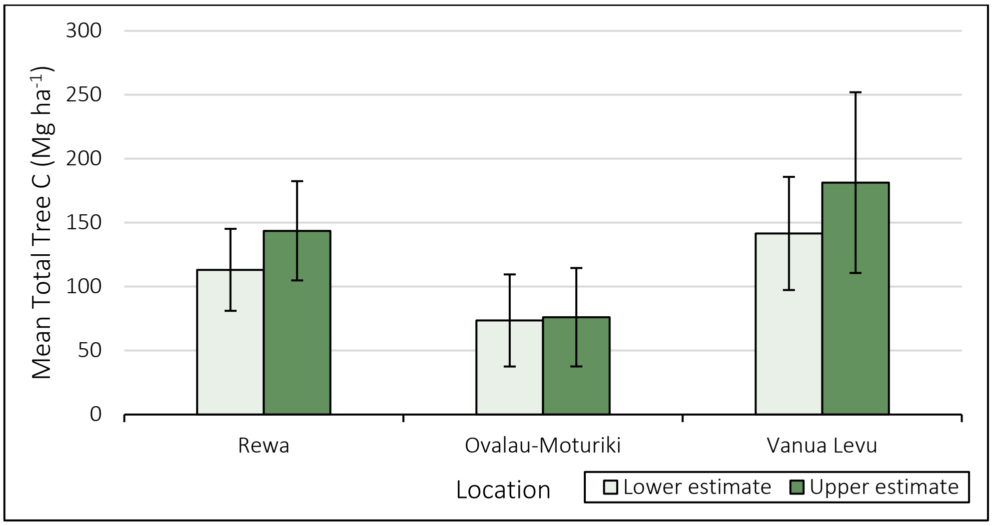

Figure 10. Upper and lower estimates of total mangrove Tree Carbon Storage in survey locations from this project in Fiji. Upper estimates (dark green) are calculated using species-specific allometric equations (Table 6). Lower estimates (light green) are calculated using general allometric equations from Chave et al. (2005). Error bars represent the standard error of the mean.

Table 6. The allometric equations utilised to calculate above-ground (AG) and below-ground (BG) biomass for different mangrove tree species.

Mangrove species	Prop Roots Biomass (*Rhizophora* spp.)	Total Above-ground (AG) Biomass (kg)	Total Below-ground (BG) Biomass (kg)	Wood density (g/cm³)	References	Origin	Max DBH (cm) for allometric equation
Avicennia marina	-	$0.308DBH^{2.11}$	$1.28DBH^{1.17}$	0.732	Comley and McGuinness (2005)	Northern Territory, Australia	AG and BG biomass: D_{max} = 25 cm
Avicennia alba	-	$0.308DBH^{2.11}$	$1.28DBH^{1.17}$	0.732	Comley and McGuinness (2005)	Northern Territory, Australia	AG and BG biomass: D_{max} = 25 cm
Avicennia officinalis	-	$0.308DBH^{2.11}$	$1.28DBH^{1.17}$	0.732	Comley and McGuinness (2005)	Northern Territory, Australia	AG and BG biomass: D_{max} = 25 cm
Acrostichum speciosum	-	-5.238+0.259H	-	-	Nurmalahayati et al. (2019)	Java Island, Indonesia	NA
Aegiceras corniculatum	-	0.251*wood density*$DBH^{2.46}$	$0.199W_D^{0.899}DBH^{2.22}$	0.81	Komiyama et al. (2005)	South-East Asia	AG biomass: D_{max} = 49 cm BG biomass: D_{max} = 45 cm
Bruguiera gymnorrhiza	-	$0.1858DBH^{2.3055}$	$0.0188(DBH^2H)^{0.909}$ $H = DBH/(0.025DBH+0.583)$	0.84	Clough and Scott (1989); Komiyama *et al.* (2008) original ref. Tamai *et al.* (1986).	Original paper from Malaysia but used in a recent paper for Fiji	AG biomass: D_{max} = 24 cm BG biomass: D_{max} = 33 cm
Bruguiera hainessi	-	$0.1858DBH^{2.3055}$	$0.0188(DBH^2H)^{0.909}$ $H = DBH/(0.025DBH+0.583)$	0.84	Clough and Scott (1989); Komiyama *et al.* (2008) original ref. Tamai *et al.* (1986).	Original paper from Malaysia but used in a recent paper for Fiji	AG biomass: D_{max} = 24 cm BG biomass: D_{max} = 33 cm
Bruguiera parvifola	-	$0.168DBH^{2.42}$	$0.0188(DBH^2H)^{0.909}$ $H = DBH/(0.025DBH+0.583)$	0.84	Clough and Scott 1989 Ref by Komiyama et al 2008	AG - Northern Australia BG- Original paper from Malaysia but used in a recent paper for Fiji	AG biomass: D_{max} = 21 cm BG biomass: D_{max} = 33 cm
Bruguiera sexangular	-	$0.1858DBH^{2.3055}$	$0.0188(DBH^2H)^{0.909}$ $H = DBH/(0.025DBH+0.583)$	0.84	Clough and Scott (1989) Komiyama *et al.* (2008) original ref. Tamai *et al.* (1986).	Original paper from Malaysia but used in a recent paper for Fiji	AG biomass: D_{max} = 24 cm BG biomass: D_{max} = 33 cm
Bruguiera exaristata	-	$0.227DBH^{2.41}$	$0.302DBH^{2.15}$	0.84	Comley and McGuiness 2005	Original paper from Malaysia but used in a recent paper for Fiji	AG biomass: D_{max} = 24 cm BG biomass: D_{max} = 33 cm

Mangrove species	Prop Roots Biomass (*Rhizophora* spp.)	Total Above-ground (AG) Biomass (kg)	Total Below-ground (BG) Biomass (kg)	Wood density (g/cm³)	References	Origin	Max DBH (cm) for allometric equation
Bruguiera cylindrica	-	$0.1858DBH^{2.3055}$	$0.0188(DBH^2H)^{0.909}$ H = $BH/(0.025DBH+0.583)$	0.81	Clough and Scott (1989); Komiyama *et al.* (2008) original ref. Tamai *et al.* (1986).	Original paper from Malaysia but used in a recent paper for Fiji	AG biomass: D_{max} = 24 cm BG biomass: D_{max} = 33 cm
Camptostemon schultzii	-	$0.251W_D(DBH)^{2.46}$	$0.199W_D^{0.899}DBH^{2.22}$	0.42	Komiyama *et al.* (2005) Common equation.	Common equation	AG biomass: D_{max} = 49 cm BG biomass: D_{max} = 45 cm
Ceriops australis	-	$0.320DBH^{2.056}$	$0.158DBH^{1.951}$	0.85	Comley and McGuiness 2005	Northern QLD	AG biomass: D_{max} = 18 cm BG biomass: D_{max} = 8 cm
Ceriops tagal	-	$0.189DBH^{2.34}$	$0.199W_D^{0.899}DBH^{2.22}$	0.85	Clough and Scott (1989) Komiyama *et al.* (2005) Common equation.	Northern QLD	AG biomass: D_{max} = 18 cm BG biomass: D_{max} = 45 cm
Ceripos decandra	-	$0.189DBH^{2.34}$	$0.199W_D^{0.899}DBH^{2.22}$	0.85	Clough and Scott (1989) Komiyama *et al.* (2005) Common equation.	Northern QLD	AG biomass: D_{max} = 18 cm BG biomass: D_{max} = 45 cm
Cynometra iripa	-	0.251*wood density*$DBH^{2.46}$	$0.199W_D^{0.899}DBH^{2.22}$	0.80	Komiyama et al. (2005) Common equation.	Common equation	AG biomass: D_{max} = 49 cm BG biomass: D_{max} = 45 cm
Dolichandrone spathacea	-	0.251*wood density*$DBH^{2.46}$	$0.199W_D^{0.899}DBH^{2.22}$	0.43	Komiyama et al. (2005) Common equation	Common equation	AG biomass: D_{max} = 49 cm BG biomass: D_{max} = 45 cm
Excoecaria agallocha	-	$0.251W_D(DBH)^{2.46}$	$0.199W_D^{0.899}DBH^{2.22}$	0.750	T_{AGB}: Komiyama *et al.* (2005) Common equation. W_R: Komiyama *et al.* (2005) Common equation.	Common equation	AG biomass: D_{max} = 49 cm BG biomass: D_{max} = 45 cm
Heritiera littoralis	-	0.251*wood density*$DBH^{2.46}$	$0.199W_D^{0.899}DBH^{2.22}$	0.89	Komiyama et al. (2005) Common equation	Common equation	AG biomass: D_{max} = 49 cm BG biomass: D_{max} = 45 cm
Lumnitzera littorea	-	$0.251W_D(DBH)^{2.46}$	$0.199W_D^{0.899}DBH^{2.22}$	0.74	Komiyama *et al.* (2005) Common equation. Komiyama *et al.* (2005) Common equation.	Common equation	AG biomass: D_{max} = 49 cm BG biomass: D_{max} = 45 cm
Lumnitzera racemosa	-	$0.184DBH^{2.384}$	$0.199W_D^{0.899}DBH^{2.22}$	0.74	Kangkuso, A., Jamili, J., Septiana, A., Raya, R., Sahidin, I., Rianse, U., Rahim, S., Alfirman, A., Sharma, S. and Nadaoka, K.,	Indonesia	AG biomass: Unknown BG biomass: D_{max} = 45 cm

Mangrove species	Prop Roots Biomass (*Rhizophora* spp.)	Total Above-ground (AG) Biomass (kg)	Total Below-ground (BG) Biomass (kg)	Wood density (g/cm^3)	References	Origin	Max DBH (cm) for allometric equation
					2016. Allometric models and above-ground biomass of Lumnitzera racemosa Willd. forest in Rawa Aopa Watumohai National Park, Southeast Sulawesi, Indonesia. *Forest science and technology*, *12*(1), pp.43-50.		
Rhizophora stylosa, Rhizophora samoensis	$0.0209DBH^{2.55}$	$\sum(0.128*DBH^{\wedge 2.60})$ + prop roots biomass	$W_R = 0.00974(DBH^2H)^{1.05}$ $H = DBH/(0.02DBH+0.678)$	0.94	Komiyama *et al.* (2008) original ref. Fromard *et al*. 1998. BG Komiyama *et al*. (2008) original ref. Ong *et al.* (2004)	AG - Micronesia BG – Northern Australia	AG and Prop root biomass D_{max} = N/A Below-ground D_{max} = 40 cm
Rhizophora apiculata	-	$0.235DBH^{2.42}$	$0.00698DBH^{2.61}$	0.88	Ong et al. (2004)		AG biomass: D_{max} = 28 cm BG biomass: D_{max} = 28 cm
Rhizophora X lamarckii	-	$0.128*DBH^{2.60}$	$W_R = 0.00974(DBH^2H)^{1.05}$ $H = DBH/(0.02DBH+0.678$	0.84	Komiyama (2008) originally Fromard et al (1998)	Common equation	AG and Prop root biomass D_{max} = N/A Below-ground D_{max} = 40 cm
Rhizophora mucronata	-	$0.1587DBH^{2.383}$	$0.064DBH^{2.194}$	0.84	Bersaldo, M. J. I. (2023). Biomass Estimates Using Species Specific Allometry in Reforested Mangrove Areas of Malita, Davao Occidental, Philippines.	Philippines	
Sonneratia alba	-	$0.3841DBH^{2.101}*\rho$	$0.199W_D^{0.899}DBH^{2.22}$	0.47	Modified from Cole et al. (1999), Kauffman and Cole (2010)	Micronesia	AG biomass: D_{max} = 323 cm BG biomass: D_{max} = 45 cm
Sonneratia caseolaris	-	$0.258DBH^{2.287}$	0.230DBH^0.740	0.53	Kusama et al. (2018)	Papua Province, Indonesia	AG biomass: D_{max} = 20 cm BG biomass: D_{max} = 45 cm
Sonneratia gungai	-	$0.3841DBH^{2.101}*\rho$	$0.199W_D^{0.899}DBH^{2.22}$	0.47	Modified from Cole et al. (1999), Kauffman and Cole (2010)	Micronesia	AG biomass: D_{max} = 323 cm BG biomass: D_{max} = 45 cm
Sonneratia lanceolata	-	$0.3841DBH^{2.101}*\rho$	$0.199W_D^{0.899}DBH^{2.22}$	0.47	Modified from Cole et al. (1999), Kauffman and Cole (2010)	Micronesia	AG biomass: D_{max} = 323 cm BG biomass: D_{max} = 45 cm
Scyphiphora hydrophylacea	-	0.251*wood density*$DBH^{2.46}$	$0.199W_D^{0.899}DBH^{2.22}$	0.69	Komiyama et al. (2005)	Common equation	AG biomass: D_{max} = 49 cm BG biomass: D_{max} = 45 cm

Mangrove species	Prop Roots Biomass (*Rhizophora* spp.)	Total Above-ground (AG) Biomass (kg)	Total Below-ground (BG) Biomass (kg)	Wood density (g/cm^3)	References	Origin	Max DBH (cm) for allometric equation
Xylocarpus granatum	-	$0.1832DBH^{2.21}$	$0.199W_D^{0.899}DBH^{2.22}$	0.541	AG - Tarlan (2008); Komiyama *et al.* (2005) Common equation.	AG – Indonesia	AG biomass: D_{max} = 41 cm BG biomass: D_{max} = 45 cm
Xylocarpus moluccensis	-	$0.1832DBH^{2.21}$	$0.199W_D^{0.899}DBH^{2.22}$	0.541	AG - Tarlan (2008); Komiyama *et al.* (2005) Common equation.	AG – Indonesia	AG biomass: D_{max} = 41 cm BG biomass: D_{max} = 45 cm
Terrestrial trees Mangroves where DBH max has been reached for both species specific and common equations*		W_D * exp(-1.499 + 2.148ln(DBH)+0.207(ln(DBH))^2 – 0.0281(ln(DBH))^3)	TAGB * 0.24	NA	Chave et al. (2005)		AG biomass: D_{max} = 158 cm
Dead trees Status 2 (defoliated and most limbs remain)	NA	T_{AGB} = Species specific allometric equations *0.15	Species specific allometric equations	species specific	Howard, J., Hoyt, S., Isensee, K., Pidgeon, E., Telszewski, M. (eds.) (2014). Coastal Blue Carbon: Methods for assessing carbon stocks and emissions factors in mangroves, tidal salt marshes, and seagrass meadows. Conservation International, Intergovernmental Oceanographic Commission of UNESCO, International Union for Conservation of Nature. Arlington, Virginia, USA.	T_{AGB} is multiplied by 0.15 based on the assumption that Status 2 trees retain most of their woody biomass. Commonly, a total of 10–20% of biomass (accounting for both leaves and some branches) is subtracted. A median of 15% was chosen.	-
Dead trees Status 3 (main trunk snapped or most limbs lost)	NA	T_{ABG} = Above-ground biomass *0.70	Species specific allometric equations	species specific	Kangkuso, A., Jamili, J., Septiana, A., Raya, R., Sahidin, I., Rianse, U., Rahim, S., Alfirman, A., Sharma, S. and Nadaoka, K., 2016. Allometric models and above-ground biomass of Lumnitzera racemosa Willd. forest in Rawa Aopa Watumohai	T_{AGB} uses the estimated proportion of 70% biomass based on Kangkuso et al. (2016) study.	-

Mangrove species	Prop Roots Biomass (*Rhizophora* spp.)	Total Above-ground (AG) Biomass (kg)	Total Below-ground (BG) Biomass (kg)	Wood density (g/cm³)	References	Origin	Max DBH (cm) for allometric equation
					National Park, Southeast Sulawesi, Indonesia. *Forest science and technology*, *12*(1), pp.43-50.		

3.5.2 Soil organic carbon calculations

Total SOC stock (Mg C ha^{-1}) was calculated using the formula:

$$SOC\ (Mg\ C\ ha^{-1}) = Carbon\ Concentration\ (\%) \times Bulk\ Density\ (g\ cm^{-3}) \times Soil\ Depth\ (cm)$$

This integrates carbon concentration with soil physical properties to estimate carbon per unit area. For each site, SOC was calculated for each depth interval and summed to represent the total SOC to the maximum sampled depth (≤1 m). The mean SOC per depth was derived by averaging values from up to three replicate plots per site. Not all sites had three replicates for every depth due to field constraints (e.g., sandy sediments, inundation, shallow bedrock, crocodile risk).

Although sampling was limited to 1 m, this depth is widely accepted in blue carbon assessments because most SOC in mangrove and seagrass ecosystems is concentrated within the upper meter. Studies show that >90% of SOC is typically within this depth, with 30–50% often in the top 20 cm, especially in younger or dynamic systems. Therefore, where sampling did not reach 1 m, estimates may be conservative—except in sand-dominated sediments, where SOC is inherently low.

A subset of soil samples from 190 sites across all countries was laboratory analysed for carbon concentration (CC%). The laboratory data were then used to develop a predictive relationship between CC% and bulk density (BD):

$$CC\% = 3.0418 \times BD^{-1.293}\ (R^2=0.77)$$

The high coefficient of determination ($R^2 = 0.77$) indicates a strong relationship between CC% and BD, making this equation a robust and widely accepted surrogate for estimating carbon concentrations where direct laboratory analysis is not feasible for every soil sample. This approach represents the majority of sites in this study.

Note: This report presents only field-based SOC data for measured depths; no extrapolation to greater depths was applied here. Extrapolated SOC estimates for national-scale assessments are provided in the subsequent report in this series. [35]

[35] Alluvium Group, 2025, Blue Carbon Ecosystems of the South Pacific: National Carbon Stock Estimates for Fiji, Papua New Guinea, Solomon Islands, and Vanuatu, report prepared by Alluvium Group for the MACBLUE Project, Brisbane, Australia.

FIJI

4 Fiji carbon assessments

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4.1 Fiji study sites

Seagrass meadows and mangrove forests were surveyed across three major islands in Fiji, including Vanua Levu, Viti Levu and Ovalau. The survey locations for both mangroves and seagrass are shown in Figure 11, including: Rewa, Ovalau-Moturiki, and Vanua Levu. A total of 20 mangrove sites and 10 seagrass sites were surveyed across a diversity of geomorphological settings and land-use conversion gradients in order to capture representative data for these dynamic ecosystems. This is because different processes dominate, such as tides, river discharge, temperature, precipitation, and evapotranspiration, in different geomorphological settings, influencing the soil chemistry and mangrove ecosystem.

The locations and sites of these surveys are shown in detail in Figure 11 to Figure 16. For more site details, refer to site photos and names in Appendix A of the Stage 3 Seagrass and Mangroves Ecosystem Reports for Fiji, Papua New Guinea, Solomon Islands, and Vanuatu.

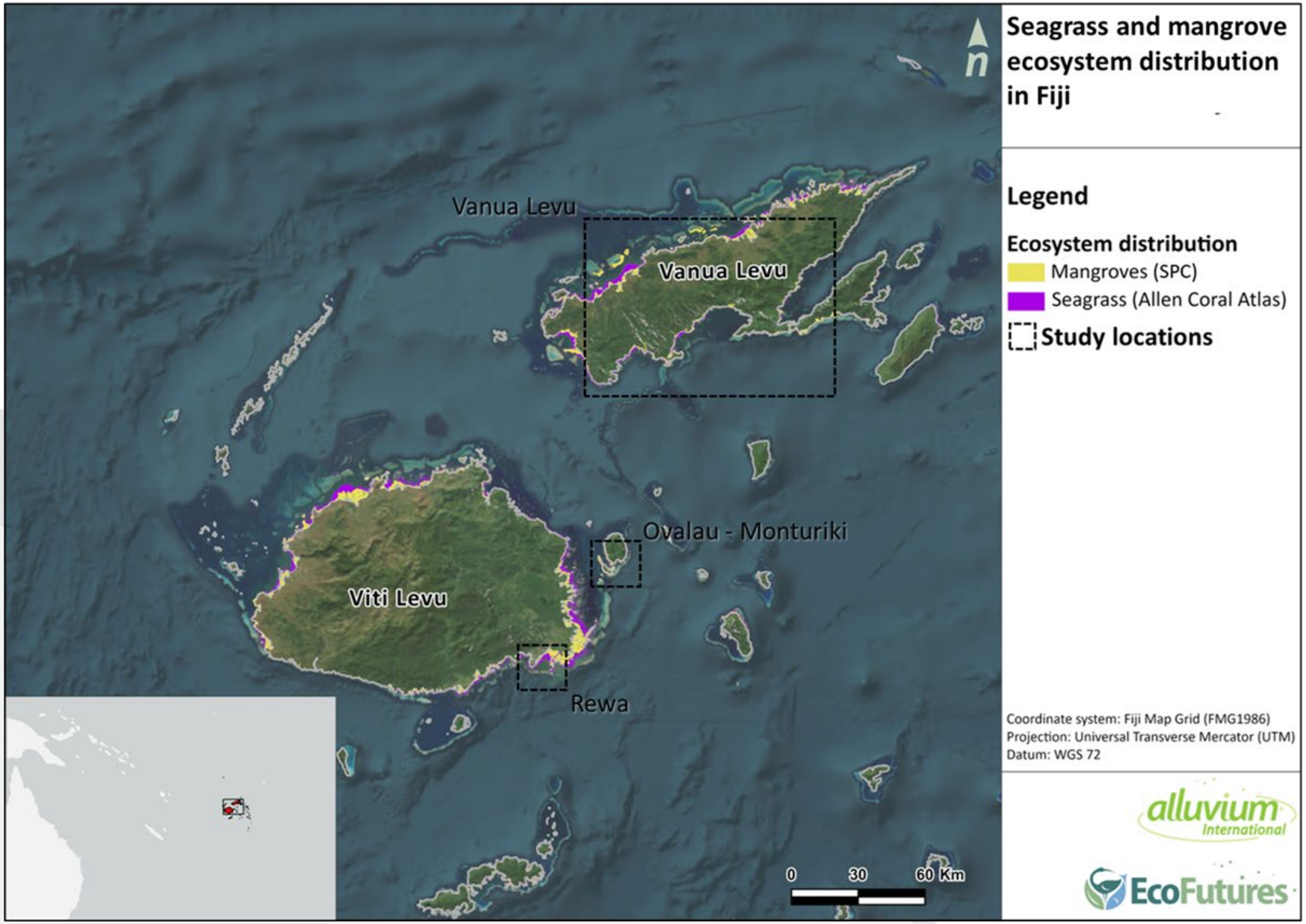

Figure 111. Seagrass and mangrove ecosystem distribution and assessment locations in Fiji. For the purpose of this study, several study sites across three study locations were grouped for analysis, specifically: Rewa, Ovalau-Moturiki, and Vanua Levu. The location of individual study sites are shown in the Figures below.

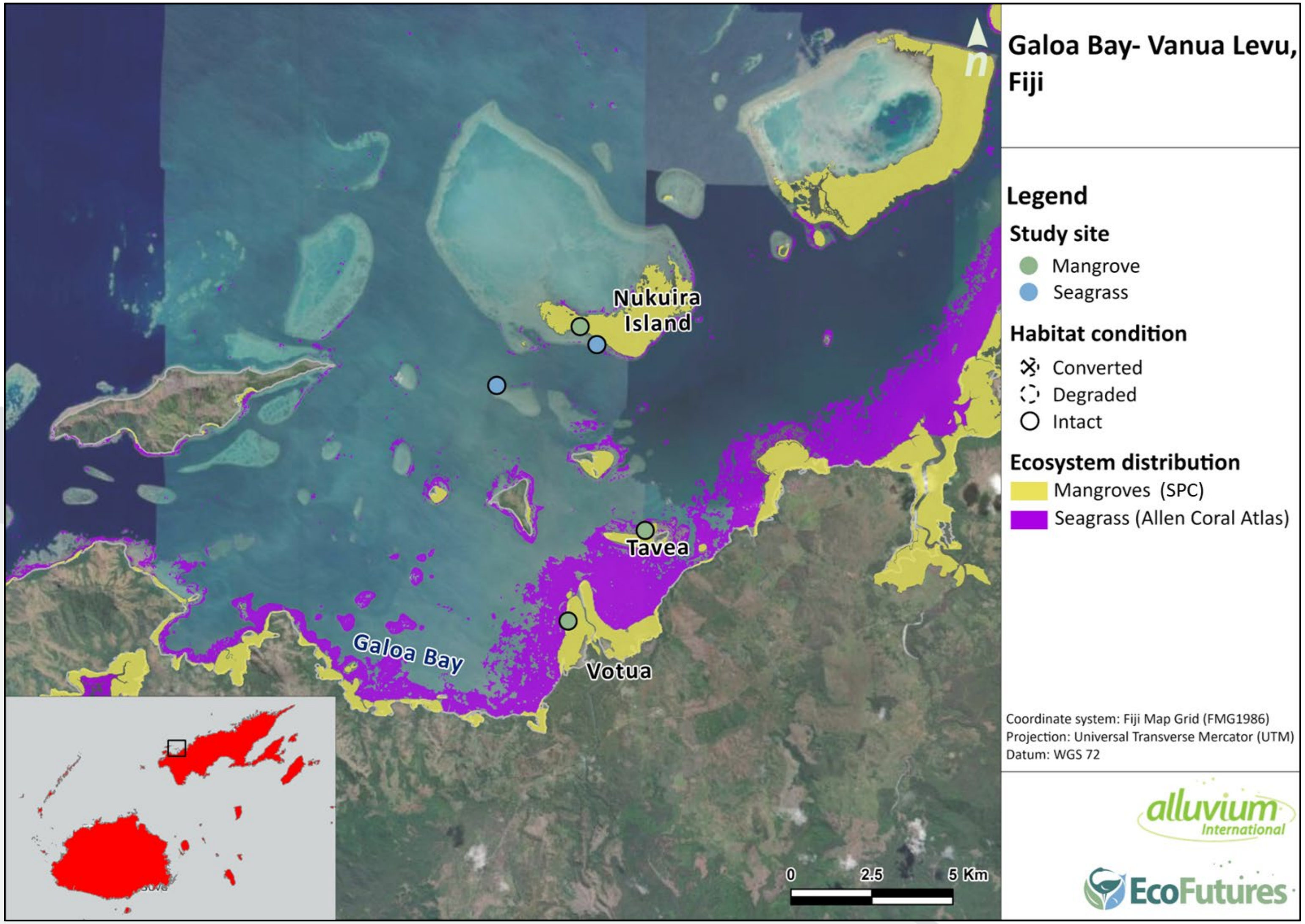

Figure 112. Seagrass and mangrove ecosystem distribution and survey sites at Galoa Bay, Vanua Levu. At this location there were three (3) intact mangrove sites, two (2) intact seagrass sites assessed.

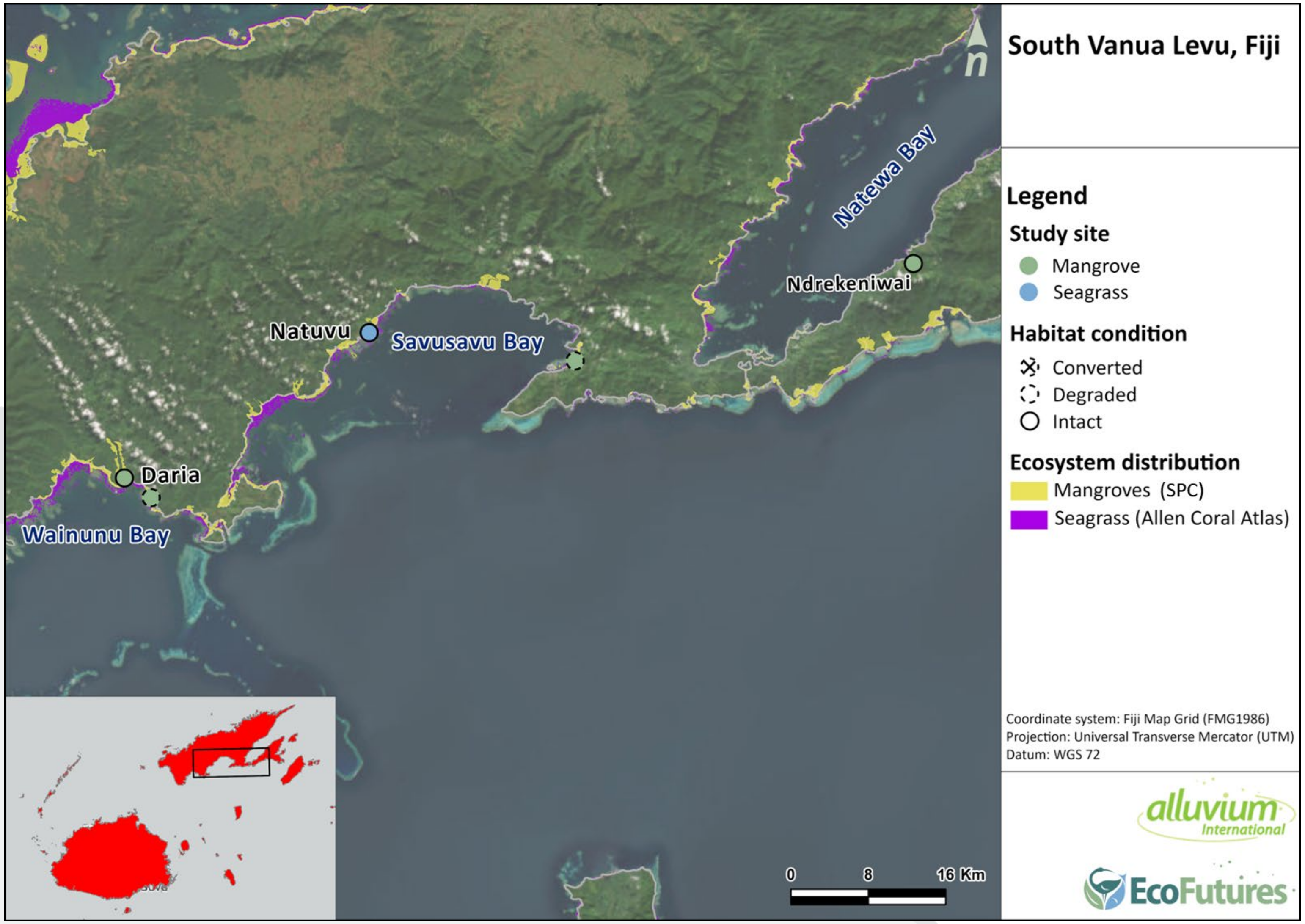

Figure 113. Seagrass and mangrove ecosystem distribution and survey sites at South Vanua Levu. At this location there were three (3) intact mangrove sites, two (2) degraded mangrove sites, and one (1) intact seagrass site assessed.

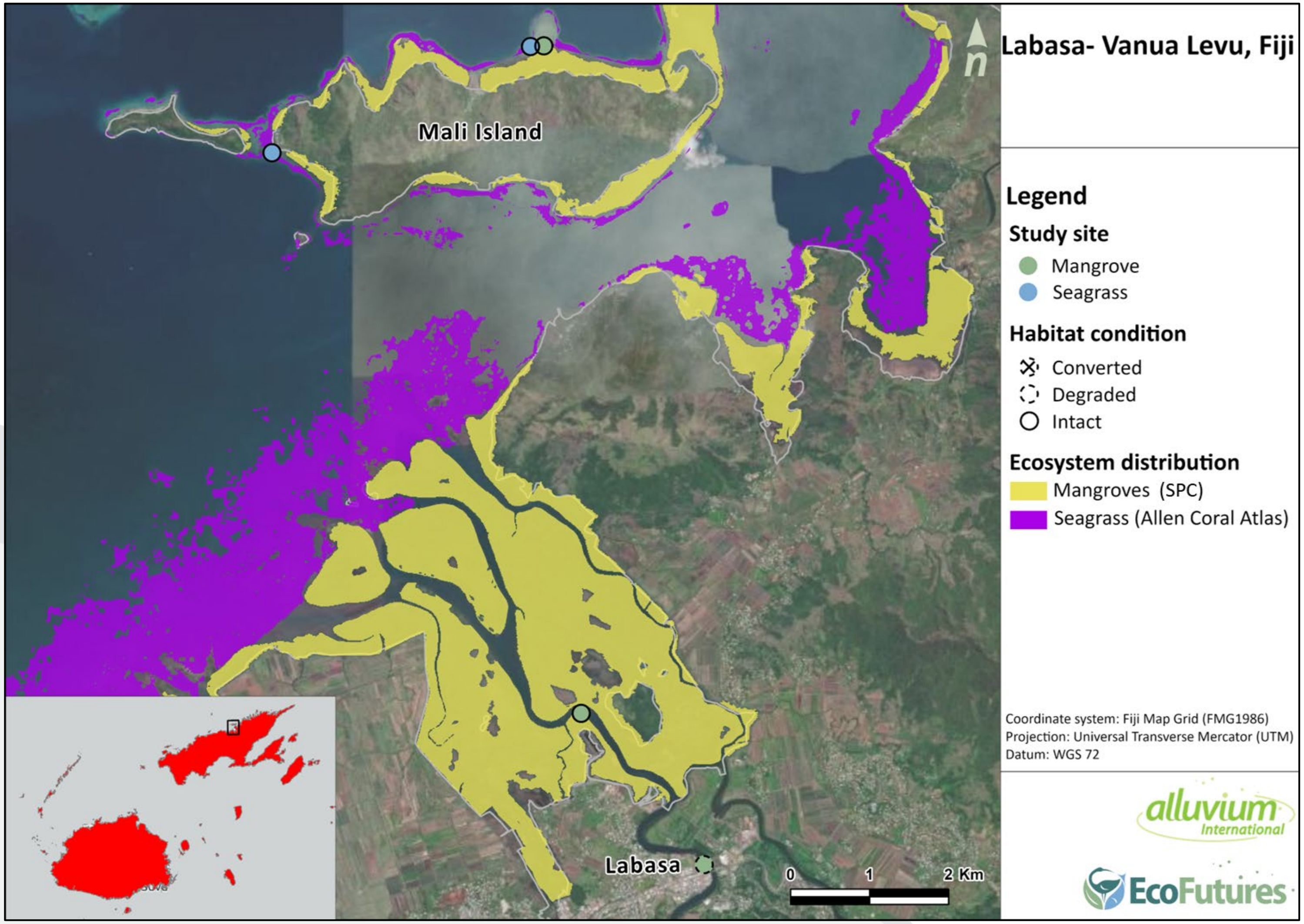

Figure 114. Seagrass and mangrove ecosystem distribution and survey sites at Labasa, Vanua Levu. At this location there were two (2) intact mangrove sites, and two (2) intact seagrass sites assessed.

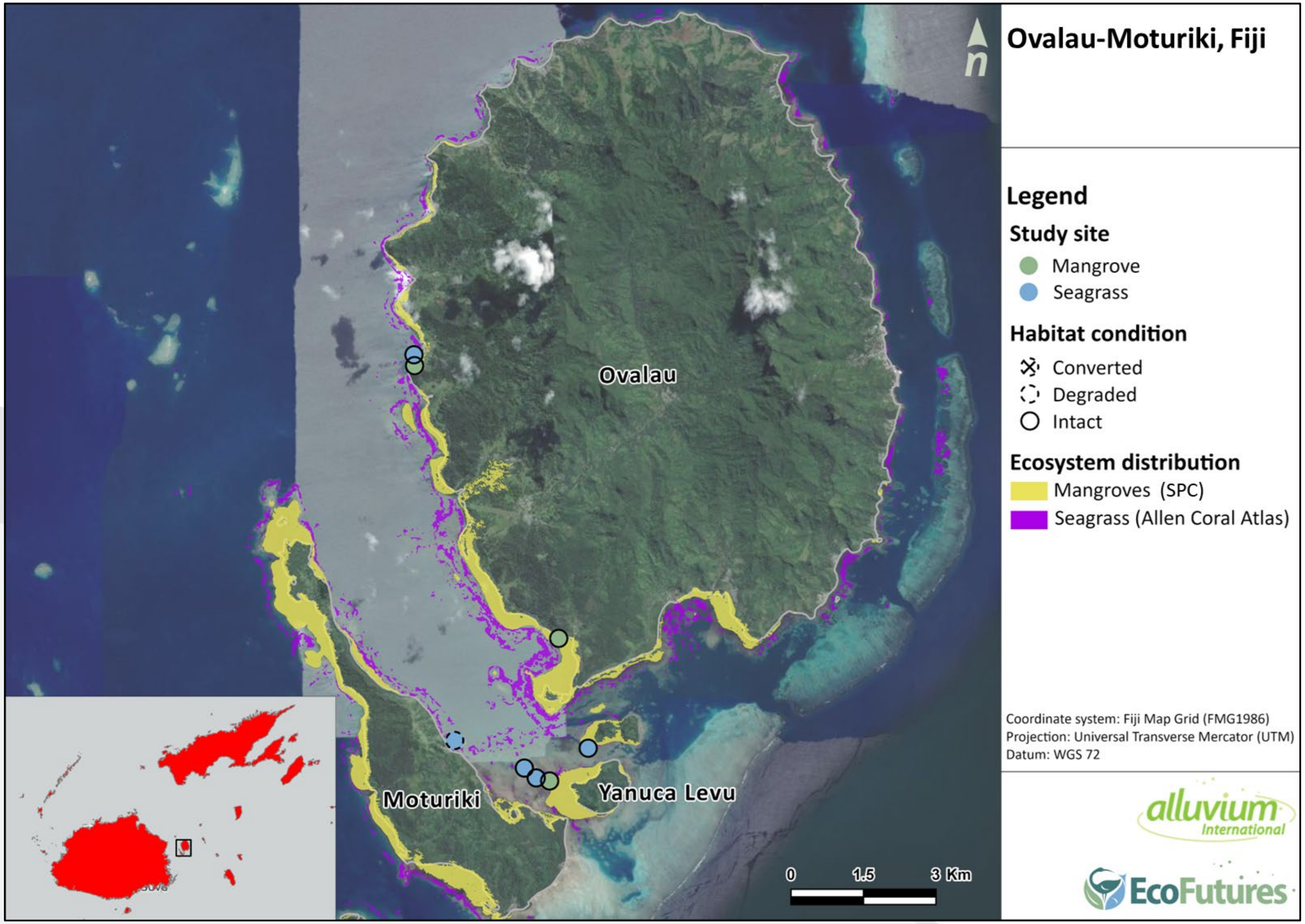

Figure 115. Seagrass and mangrove ecosystem distribution and survey sites at Ovalau-Moturiki. At this location there were three (3) intact mangrove sites, four (4) intact seagrass sites and one (1) degraded seagrass site assessed.

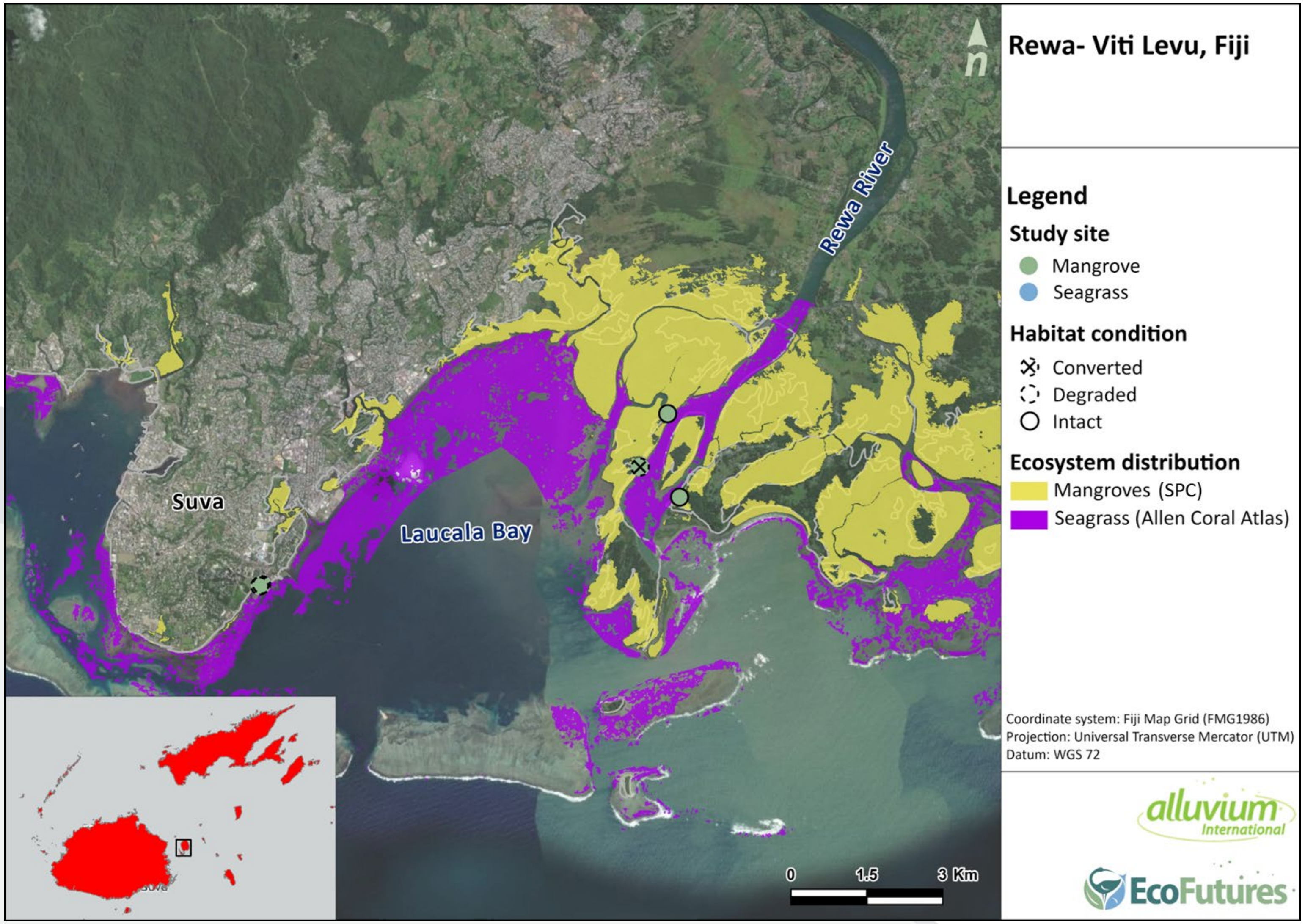

Figure 116. Seagrass and mangrove ecosystem distribution and survey sites at Rewa, Viti Levu. In this location there were two (2) intact mangrove sites, one (1) degraded mangrove site and one (1) converted mangrove site assessed.

4.2 Fiji carbon assessment results – Seagrass

This results section for seagrass ecosystems presents only soil organic carbon (SOC) measurements, reflecting the study's focus on the dominant carbon pools in blue carbon ecosystems. Above and below-ground biomass carbon is not considered a significant component of the total ecosystem carbon pool in seagrass meadows.

4.2.1 Soil organic carbon

Sampling was limited to the upper 50 cm of the sediment profile due to field constraints, with some sites only being sampled at the surface in the upper 15 cm. This is a common limitation in seagrass carbon assessments as they are typically logistically challenging environments, with inundation typically affecting the integrity of soil cores.

For all sites across Fiji SOC at seagrass sites ranged from 1% to 12%, and 38 Mg C ha^{-1} to 172 Mg C ha^{-1}. The mean SOC content was relatively similar in seagrass sites at Ovalau-Moturiki and Vanua Levu (164 Mg C ha^{-1}, and 140 Mg C ha^{-1}, respectively) (Figure 17, Figure 18, and Figure 19). There was low variation in soil organic carbon between the depth categories 0-15 cm, 15-30 cm and 30-50 cm, with relatively similar mean values at all depths, noting not all depths were sampled at all sites.

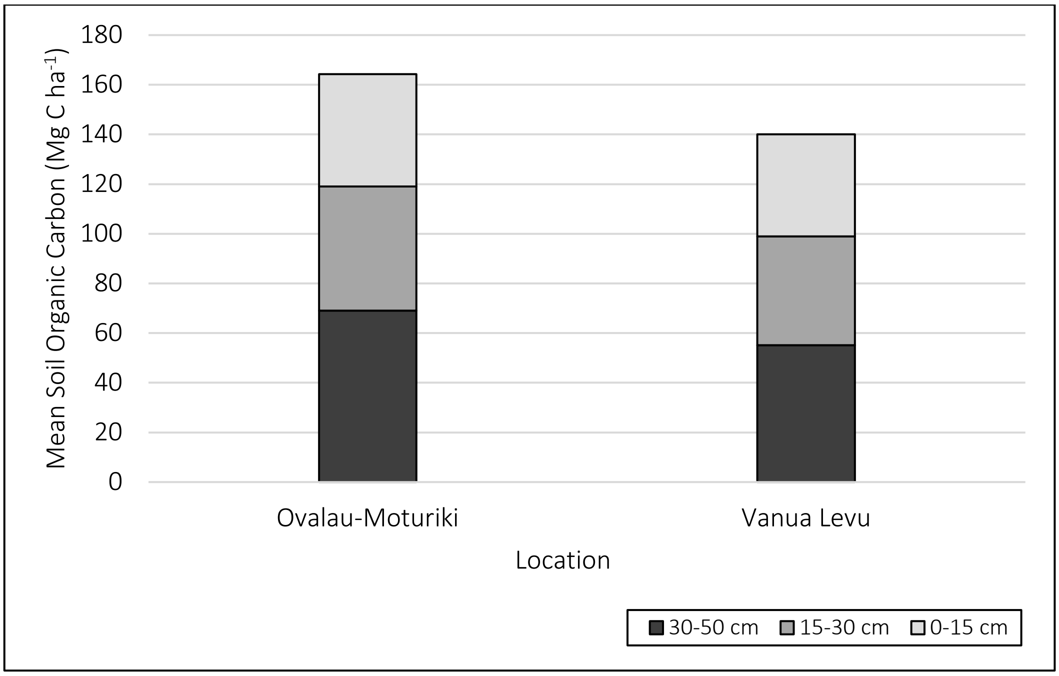

Figure 117. Mean total soil organic carbon at seagrass sites at various depths (cm) across two locations in Fiji.

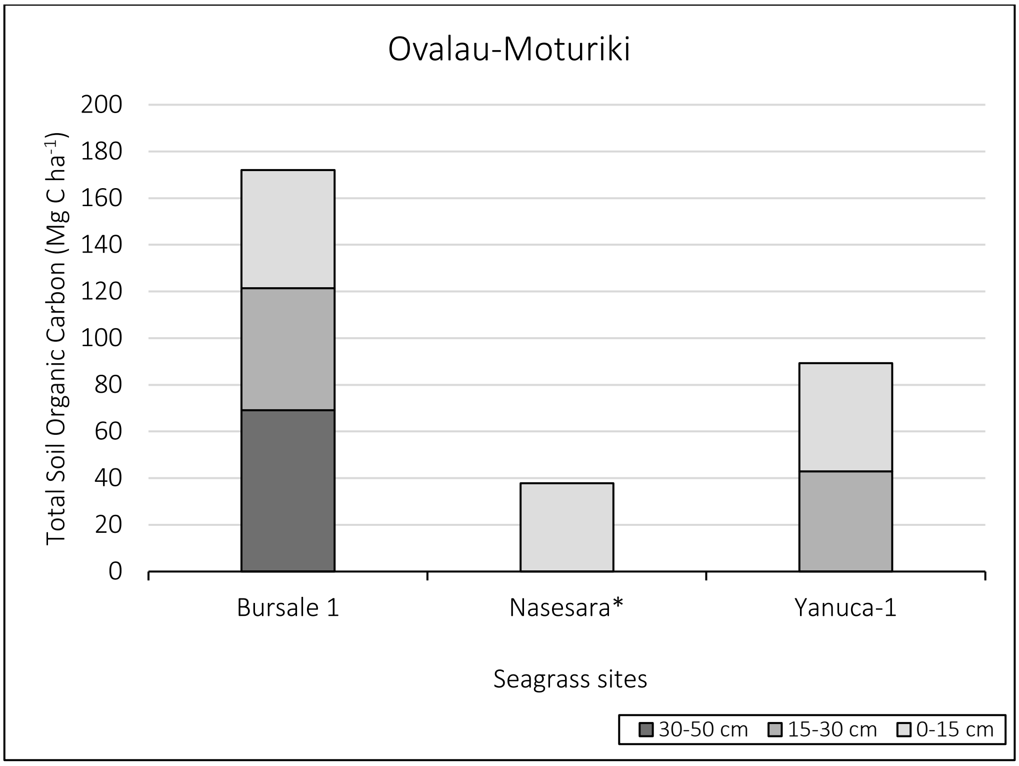

Figure 118. Seagrass soil organic carbon at various depths (cm) at the three sites in the location Ovalau-Moturiki, Fiji. The asterisk (*) indicates a degraded site.

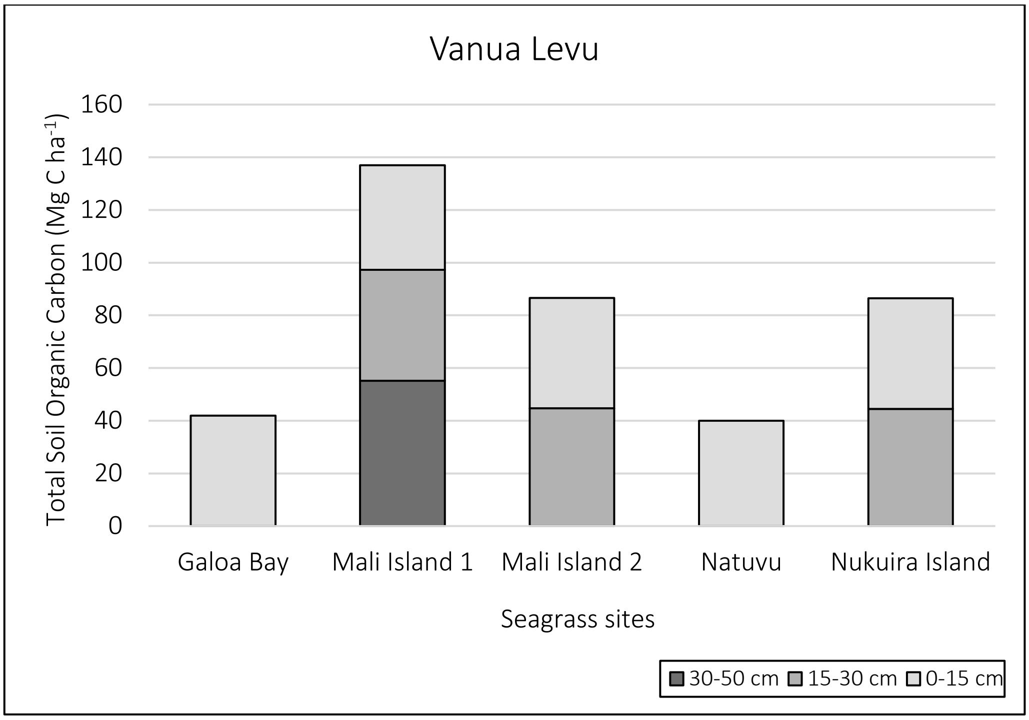

Figure 119. Seagrass soil organic carbon at various depths (cm) at the five seagrass sites in the location Vanua Levu, Fiji.

4.3 Fiji carbon assessment results – Mangroves

This results section for mangrove ecosystems is systematically divided into several subsections to provide a comprehensive analysis of the data. Initially, species density is examined across various locations, offering insights into the geographical distribution of species. Subsequent subsections focus on the comparative analysis of above-ground (AG) and below-ground (BG) biomass and tree carbon, evaluated across different locations and land use conversion categories. These comparisons help understand the spatial variations in carbon stock distribution and their implications for carbon storage and ecosystem dynamics.

4.3.1 Species density

In Rewa, *Rhizophora samoensis* was the dominant species with a mean density of 5,357 trees ha^{-1} (Figure 20). This was followed by *Bruguiera gymnorhiza* and *Hibiscus tiliaceus* (terrestrial) which had mean densities of 803 trees ha^{-1} (± 207 SE) and 591 trees ha^{-1}, respectively (Figure 20). All other species had a tree density <500 trees ha^{-1}.

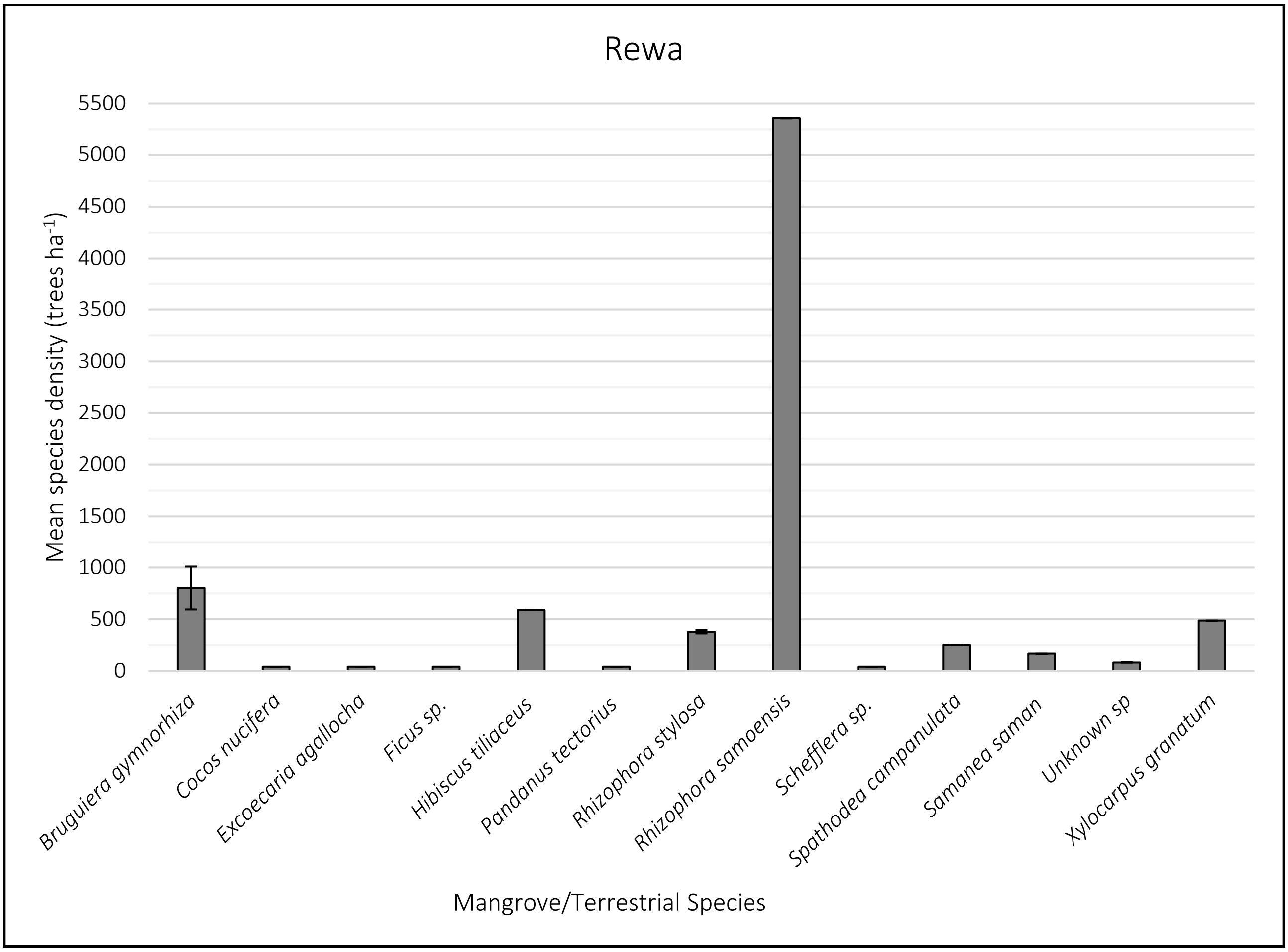

Figure 20. Bar graph showing the mean density of mangrove species (± SE) in Rewa. *Rhizophora samoensis* exhibited the highest density at 5357 trees ha^{-1}, followed by *Bruguiera gymnorhiza* and *Hibiscus tiliaceus* with densities of 803 and 591 trees ha^{-1}, respectively. All other species at this location <500 trees ha^{-1}.

In Ovalau-Moturiki, *Bruguiera gymnorhiza* had the highest density of 1,582 trees ha^{-1} (± 462 SE), followed by *Rhizophora stylosa* 1,139 trees ha^{-1} (± 351 SE) (Figure 21). *Lumnitzera littorea* had the lowest density at this location with 759 trees ha^{-1}.

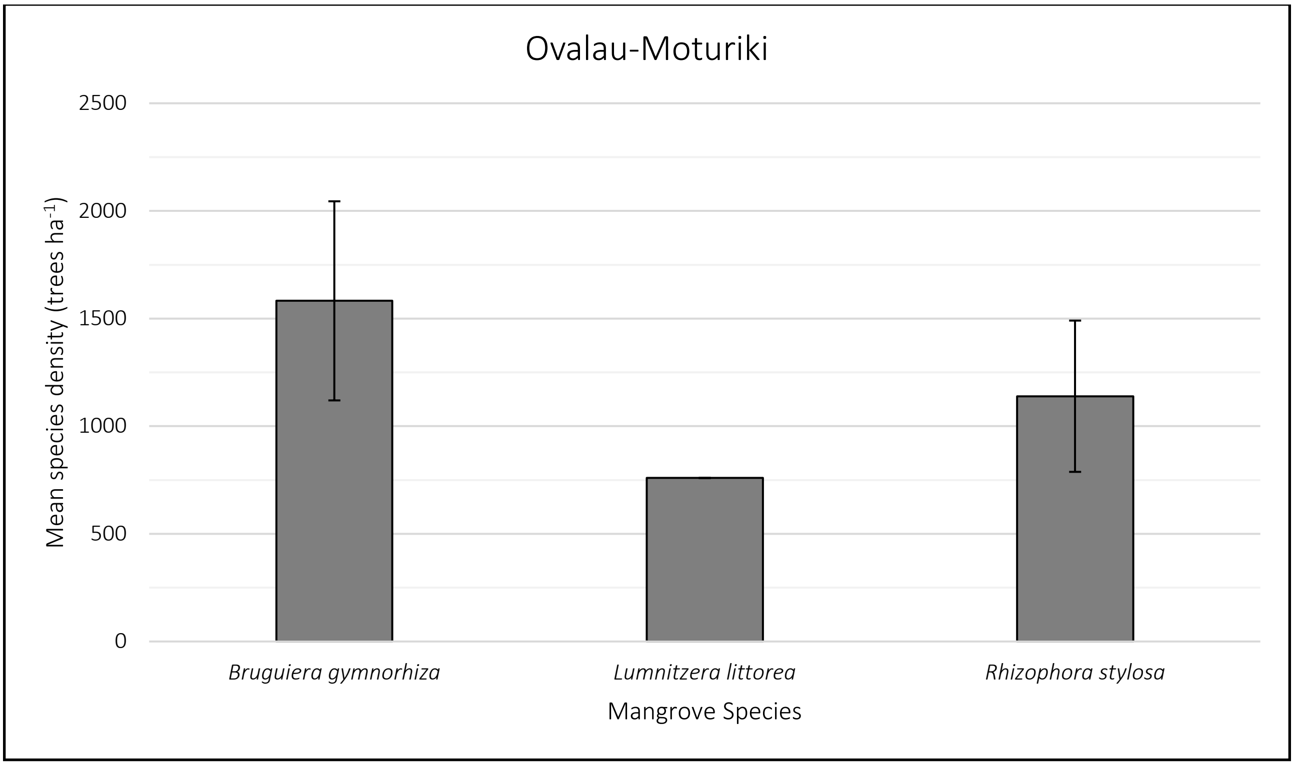

Figure 20. Bar graph showing the mean density of mangrove species (± SE) in Ovalau-Moturiki. *Bruguiera gymnorhiza* exhibited the highest density at 1582 trees ha^{-1}, followed by *Rhizophora stylosa* (1139 trees ha^{-1}) and *Lumnitzera littorea* (759 trees ha^{-1}).

In Vanua Levu, *Rhizophora stylosa* and *Bruguiera gymnorhiz*a had the highest density across the sites, with 1,413 (± 166 SE) and 1,026 trees ha^{-1} (± 178 SE), respectively (Figure 22). Notably, *Rhizophora stylosa* is highly effective in carbon storage due to its extensive stilt roots, substantial above-ground biomass and high wood densities. These stilt roots not only stabilize the soil and prevent erosion but also trap carbon-rich sediments, while the dense above-ground biomass stores significant amounts of carbon, contributing greatly to blue carbon sequestration. *Excoecaria agallocha* had a tree density of 580 trees ha^{-1} (± 48 SE), while all other species had a tree density <130 trees ha^{-1} (Figure 22). *Excoecaria agallocha* is generally considered a lower contributor to total carbon stocks compared to species like *Rhizophora stylosa* or *Sonneratia alba*, particularly in terms of above-ground biomass.

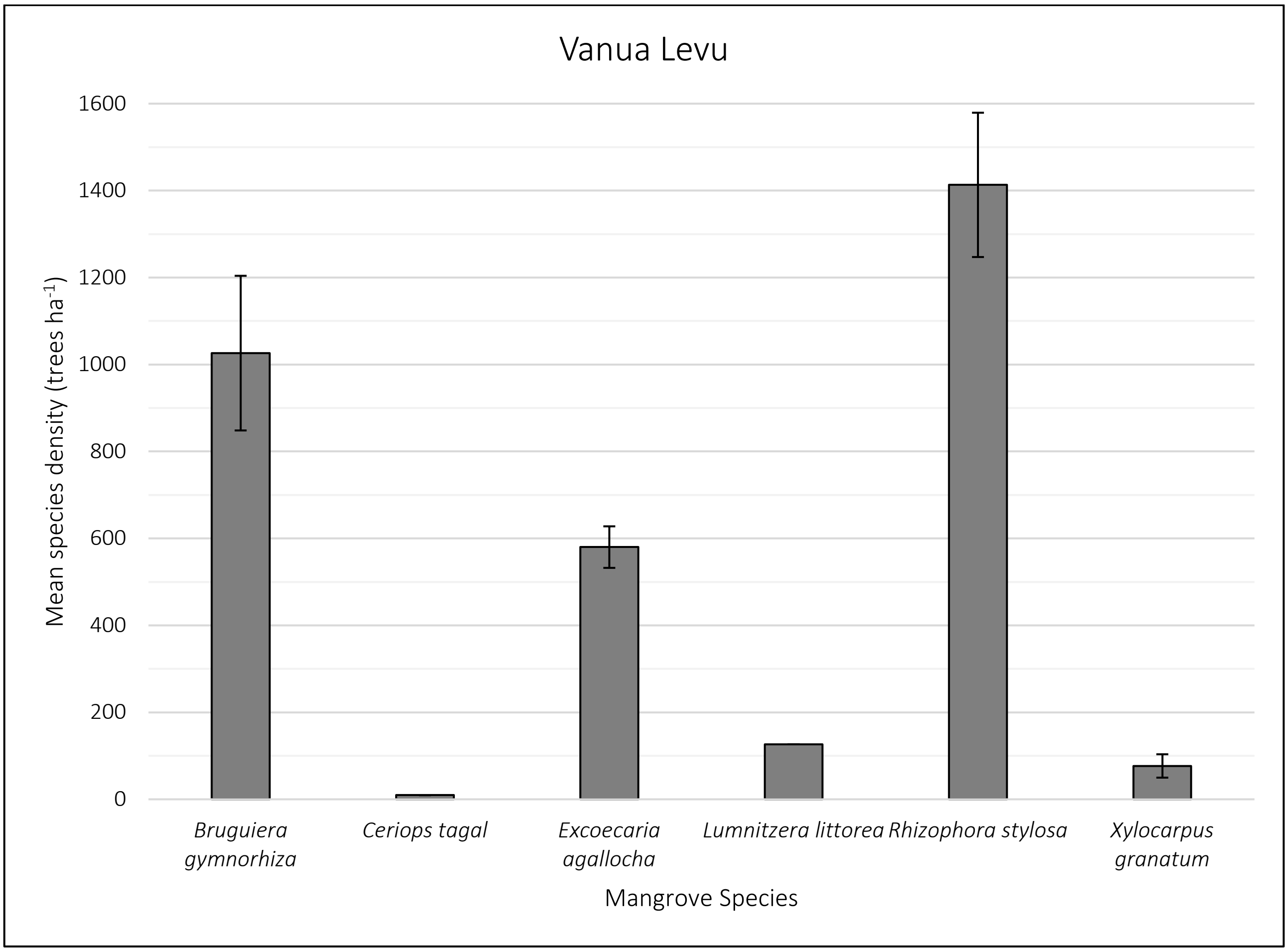

Figure 21. Bar graph showing the mean density of mangrove species (± SE) in Vanua Levu. *Rhizophora stylosa* (1413 trees ha^{-1}) and *Bruguiera gymnorhiza* (1026 trees ha^{-1}) had the highest densities. *Excoecaria agallocha* had 580 trees ha^{-1}, while all other species had a density <130 trees ha^{-1}. Error bars represent the standard error of the mean.

4.3.2 Above-ground and below-ground tree carbon storage

As shown in Figure 23, tree carbon storage (TCS) refers to the amount of carbon stored within trees, which can be stored above-ground (in their trunks, stems, foliage, aerial roots and prop roots) and below-ground (in their roots). Total TCS refers to the sum of the carbon stored in trees both above-ground (AG) and below-ground (BG).

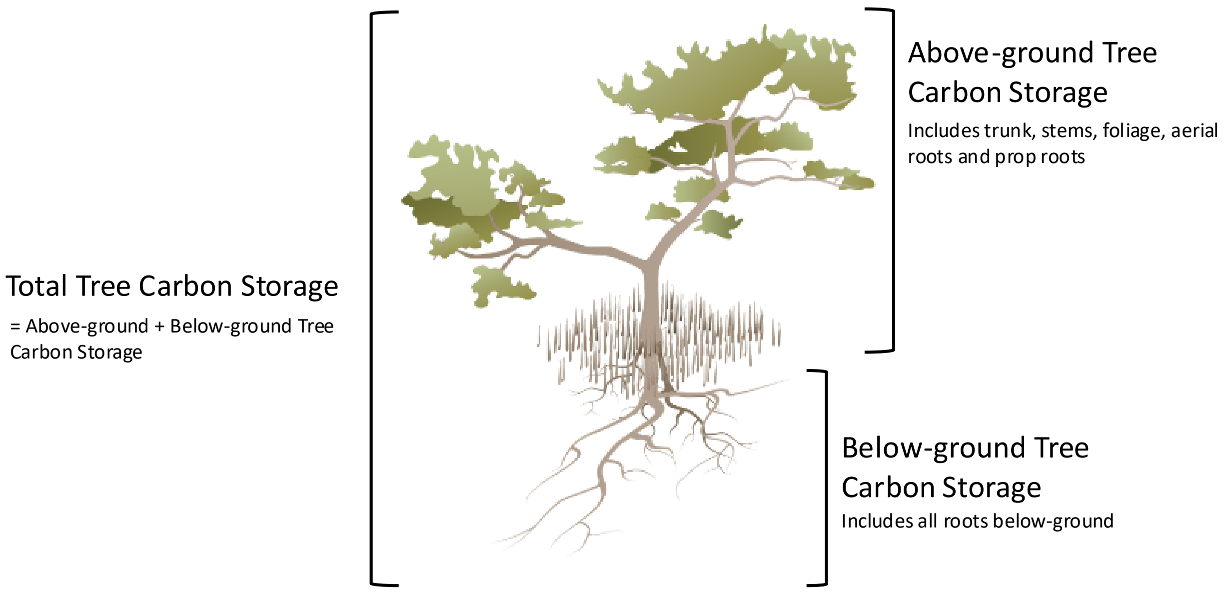

Figure 22. Illustration of total tree carbon storage stored in trees both above and below-ground.

Upper and lower estimates for total TCS were calculated for each site across Fiji and compared between locations (Figure 14). In this section, we report the lower estimates unless otherwise stated. Total live TCS for sites assessed across Fiji ranged from 23 Mg C ha^{-1} to 430 Mg C ha^{-1} (Figure 26, Figure 27, and Figure 28).

Across the sampling locations, Vanua Levu had the displayed highest mean live TCS at 142 Mg C ha^{-1} (± 44 SE), followed by Rewa with 113 Mg C ha^{-1} (± 32 SE) and Ovalau-Moturiki with 74 Mg C ha^{-1} (± 36 SE) (Figure 24). Although Vanua Levu showed the highest mean value, the differences in TCS among locations are likely not statistically significant, as indicated by the overlapping standard errors. The relatively high TCS in Vanua Levu may be related to species composition, particularly the high density of *Rhizophora stylosa*.

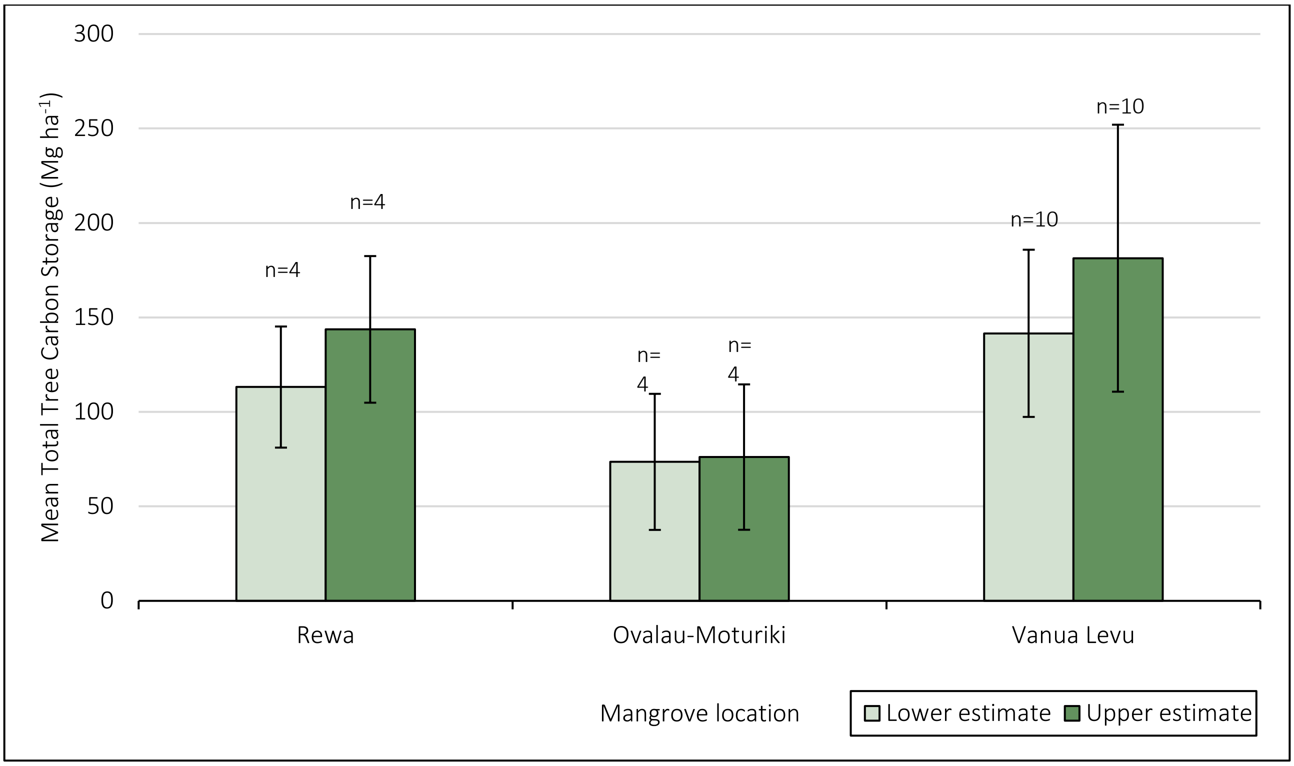

Figure 23. Mean tree carbon storage (± SE) in Fiji. Vanua Levu had the highest mean carbon storage at 142 Mg C ha^{-1}, followed by Rewa (113 Mg C ha^{-1}) and Ovalau-Moturiki (74 Mg C ha^{-1}). Error bars represent the standard error of the mean. The "lower estimate" uses species-specific allometric equations (where available) for all trees, while the "upper estimate" applies the general equation from Chave et al. (2005) for trees exceeding the maximum DBH specified in species-specific models.

Across the three locations in Fiji, Vanua Levu had the highest mean above-ground (AG) TCS at 112 Mg C ha^{-1} (± 35 SE), followed by Rewa with 83 Mg C ha^{-1} (± 23 SE) and Ovalau-Moturiki with 57 Mg C ha^{-1} (± 29 SE) (Figure A). Rewa showed the highest below-ground (BG) carbon storage at 30 Mg C ha^{-1} (± 14 SE), while Vanua Levu and Ovalau-Moturiki had below-ground values of 29 Mg C ha^{-1} (± 9 SE) and 16 Mg C ha^{-1} (± 8 SE), respectively (Figure 25). Although mean values varied among locations, the overlapping standard errors suggest these differences are not statistically significant.

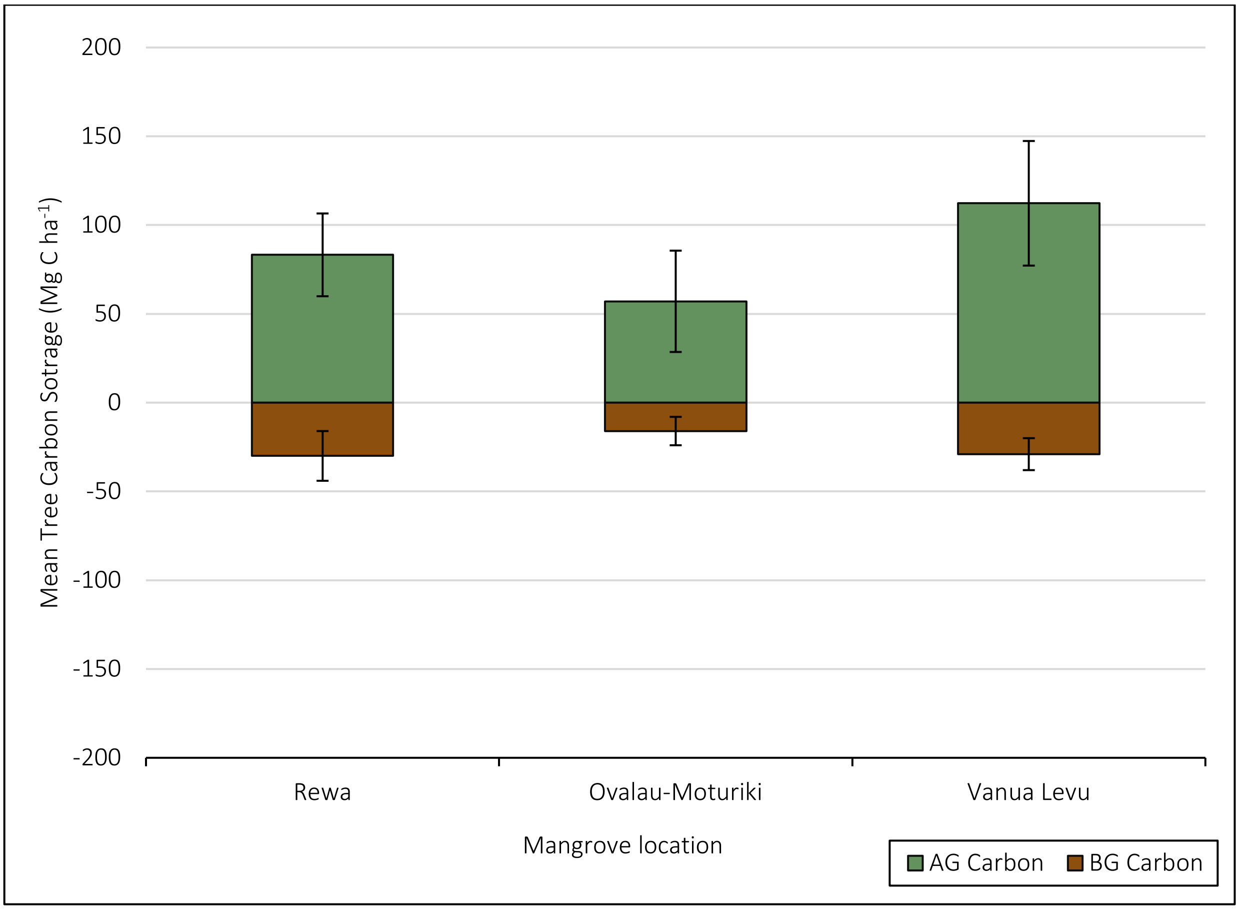

Figure 24. Above-ground (AG) and below-ground (BG) mangrove tree carbon storage in Fiji: Vanua Levu had the highest AG carbon storage (112 Mg C ha^{-1}), followed by Rewa (83 Mg C ha^{-1}) and Ovalau-Moturiki (57 Mg C ha^{-1}). Rewa had the highest BG carbon storage (30 Mg C ha^{-1}), followed by Vanua Levu (29 Mg C ha^{-1}) and Ovalau-Moturiki (16 Mg C ha^{-1}). Error bars represent the standard error.

There was significant variation in AG and BG tree carbon storage between sites at each location. Higher levels were typically found in river deltas such as Rewa River, Labasa River and Daria River (196-430 Mg C ha^{-1}). The few degraded and restoration sites that were assessed were found to have relatively low tree carbon stocks (23-115 Mg C ha^{-1}), as did smaller island sites slightly offshore of the mainland, such as Tavea, Mali, and Nukuira Islands (27-46 Mg C ha^{-1}).

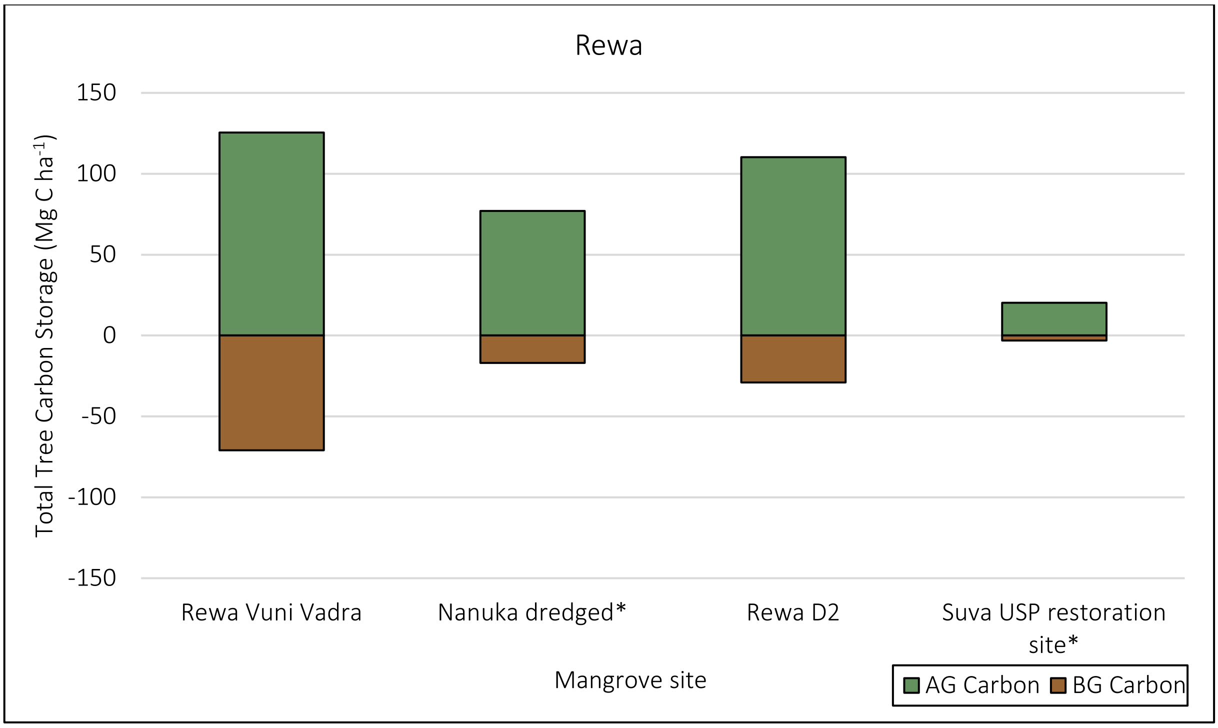

Figure 25. Above-ground (AG) and below-ground (BG) mangrove total tree carbon storage at each mangrove assessment site for the Rewa location. *Two assessment sites were not classified as intact mangrove systems and were associated with low levels of live Tree Carbon Storage; these were the degraded dredged site at Nanuka and the USP restoration site in Suva.

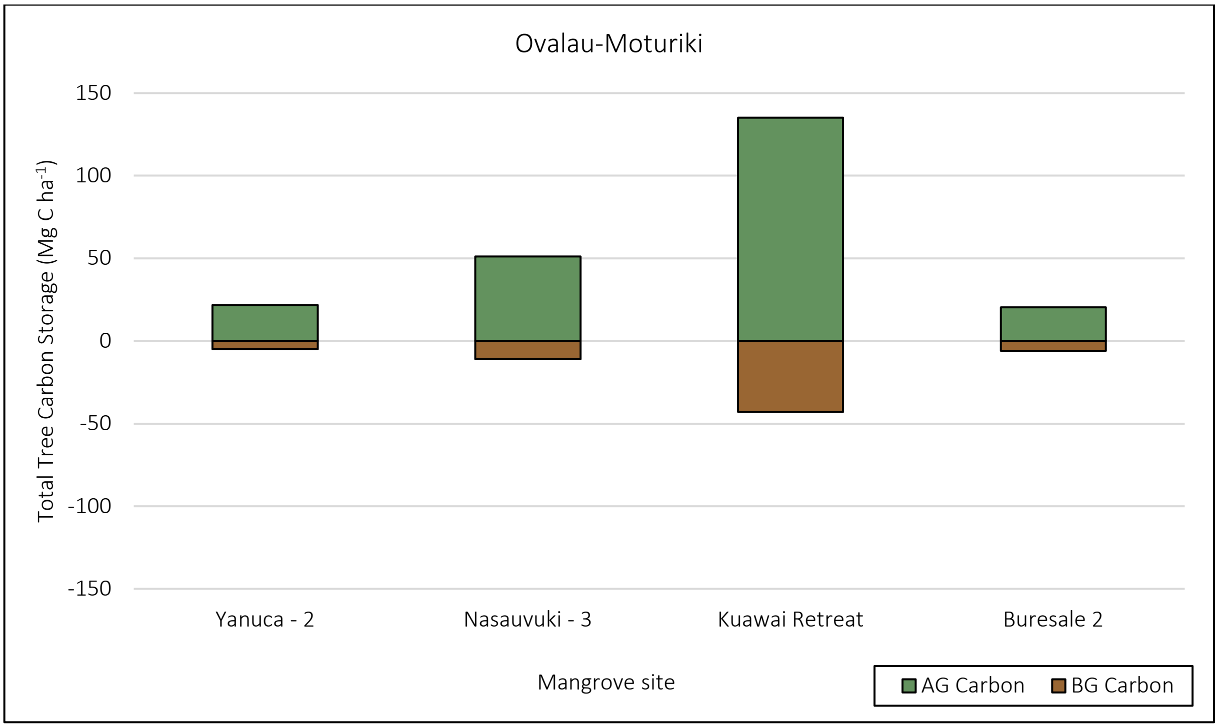

Figure 26. Above-ground (AG) and below-ground (BG) mangrove total tree carbon storage at each mangrove assessment site for the Ovalau-Moturiki location.

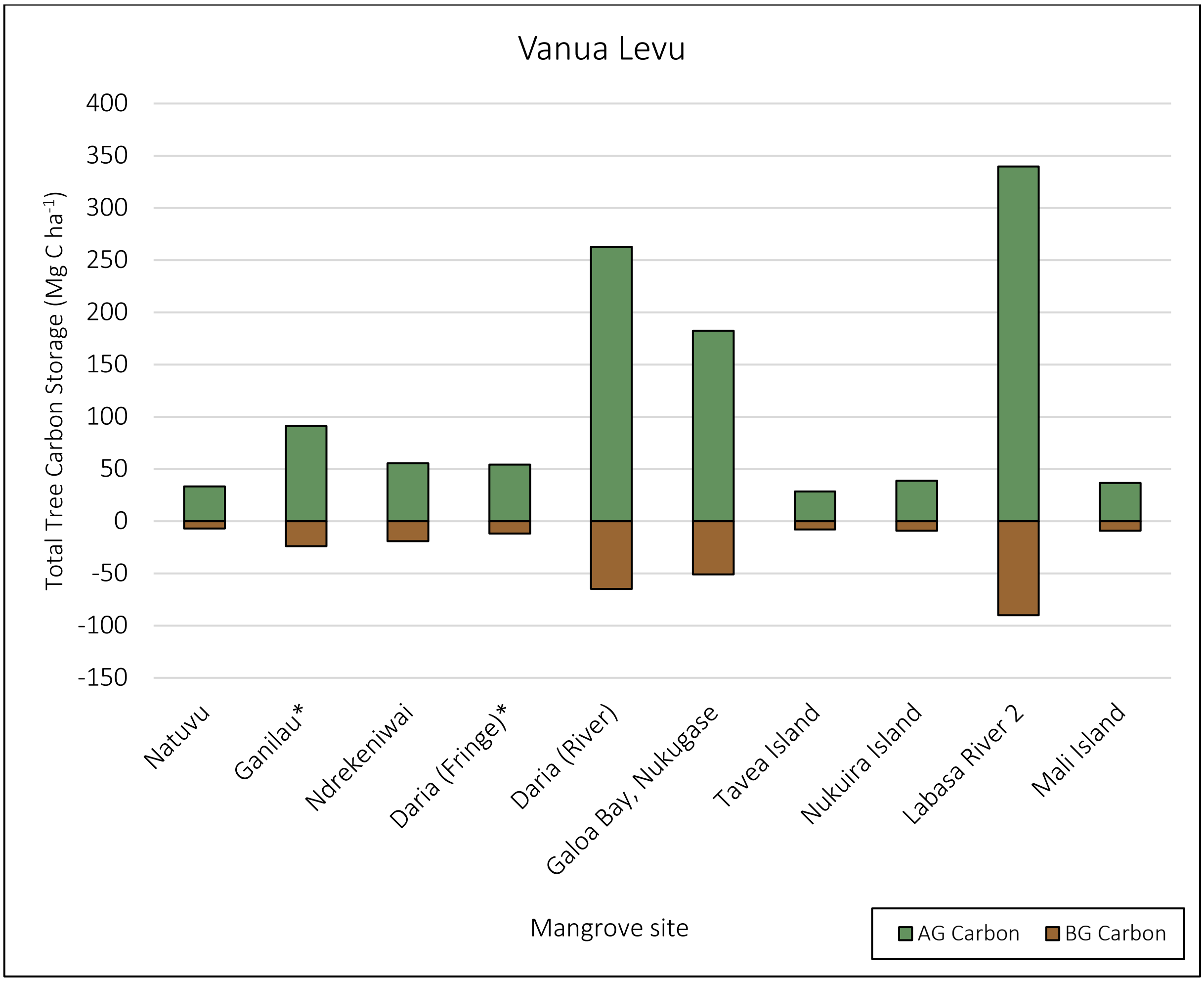

Figure 27. Above-ground (AG) and below-ground (BG) mangrove total tree carbon storage at each mangrove assessment site for the Vanua Levu location. *Two assessment sites were not classified as intact mangrove systems these were the degraded sites Ganilau and Daria (Fringe).

4.3.3 Soil organic carbon

Mangrove soil organic carbon (SOC) sampling in Fiji represents the first meter of the sediment profile at most sites. However, due to field constraints, challenging conditions, or shallow bedrock at some locations, obtaining deeper samples was not always possible, therefore, the results from those sites represent only the top 50 cm or less of the soil profile. Sampling depths at each site are represented in Figure 30, Figure 31 and Figure 32.

For all sites across Fiji SOC at mangrove sites ranged from 1% to 28%, and 46 to 397 Mg C ha^{-1}. Figure 20, Figure 21, and Figure 22 summarise SOC storage at each mangrove assessment site and demonstrate the variability between sites at different depths. SOC storage varied significantly between sites, reflecting the differences in soil properties and organic matter inputs. These differences suggest spatial variability in SOC potential, possibly influenced by site-specific factors such as mangrove species, land use history, and soil texture. Higher SOC storage was observed at sites such as Kawai, Rewa and Labasa Rivers, which may indicate more favourable conditions for carbon accumulation or reduced rates of organic matter decomposition. Similarly, sites dominated by a high density of *Rhizophora stylosa*, such as Nukuira Island and Mali Island, were also found to have higher SOC levels.

When averaged across sites, the mean total SOC stock was similar between the three locations, Vanua Levu (338 Mg C ha^{-1}), Rewa (334 Mg C ha^{-1}), and Ovalau-Moturiki (356 Mg C ha^{-1}) (Figure 29).

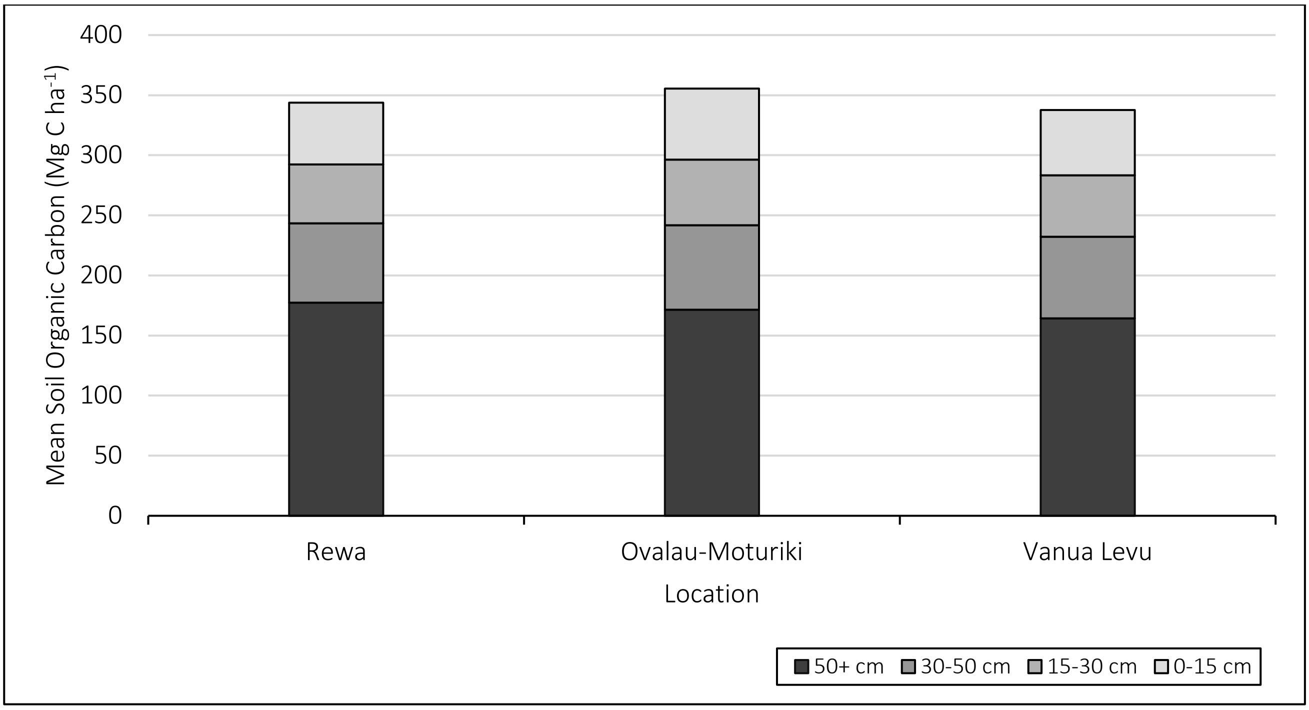

Figure 28. Mean total soil organic carbon storage (Mg C ha^{-1}) (SOC) at different soil depths in Fiji survey locations. Mean SOC was similar across Vanua Levu (338 Mg C ha^{-1}), Rewa (334Mg C ha^{-1}), and Ovalau-Moturiki (356 Mg C ha^{-1}).

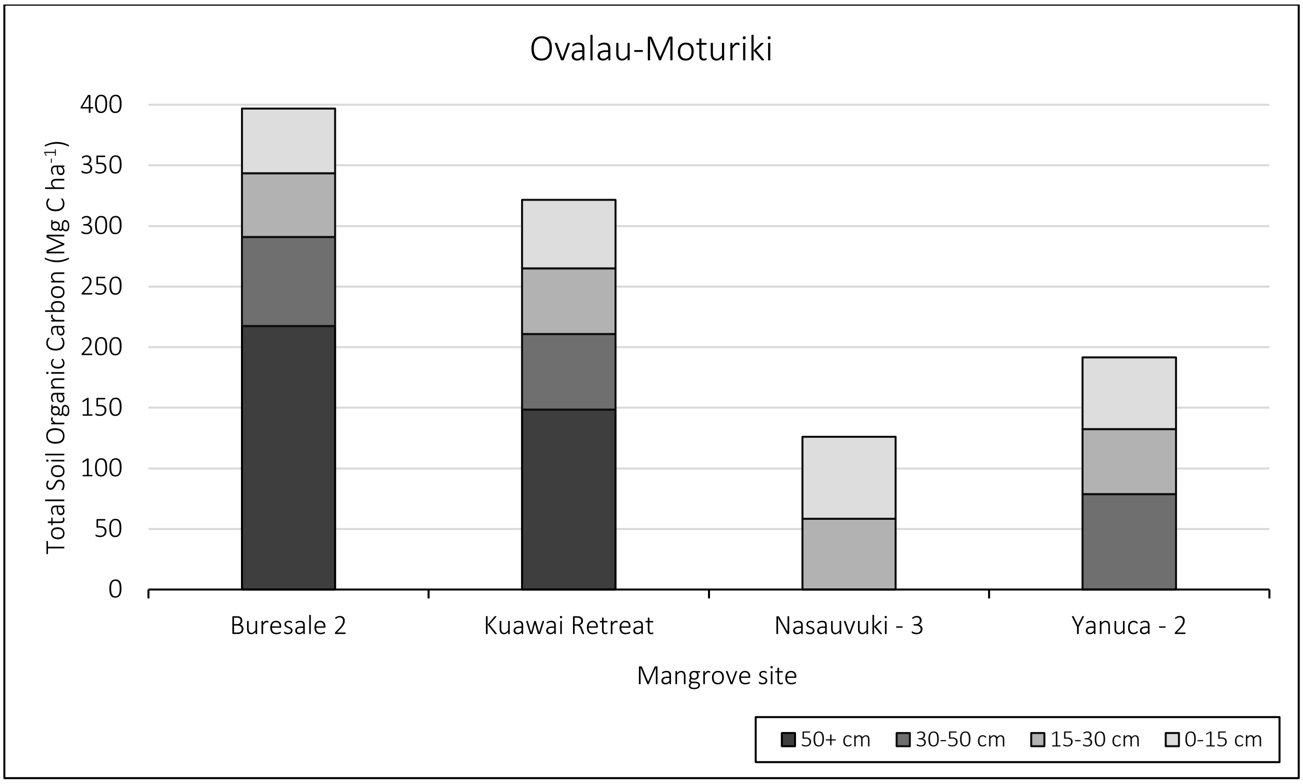

Figure 29. Mangrove soil organic carbon at different soil depths at the four sites in Ovalau-Moturiki, Fiji.

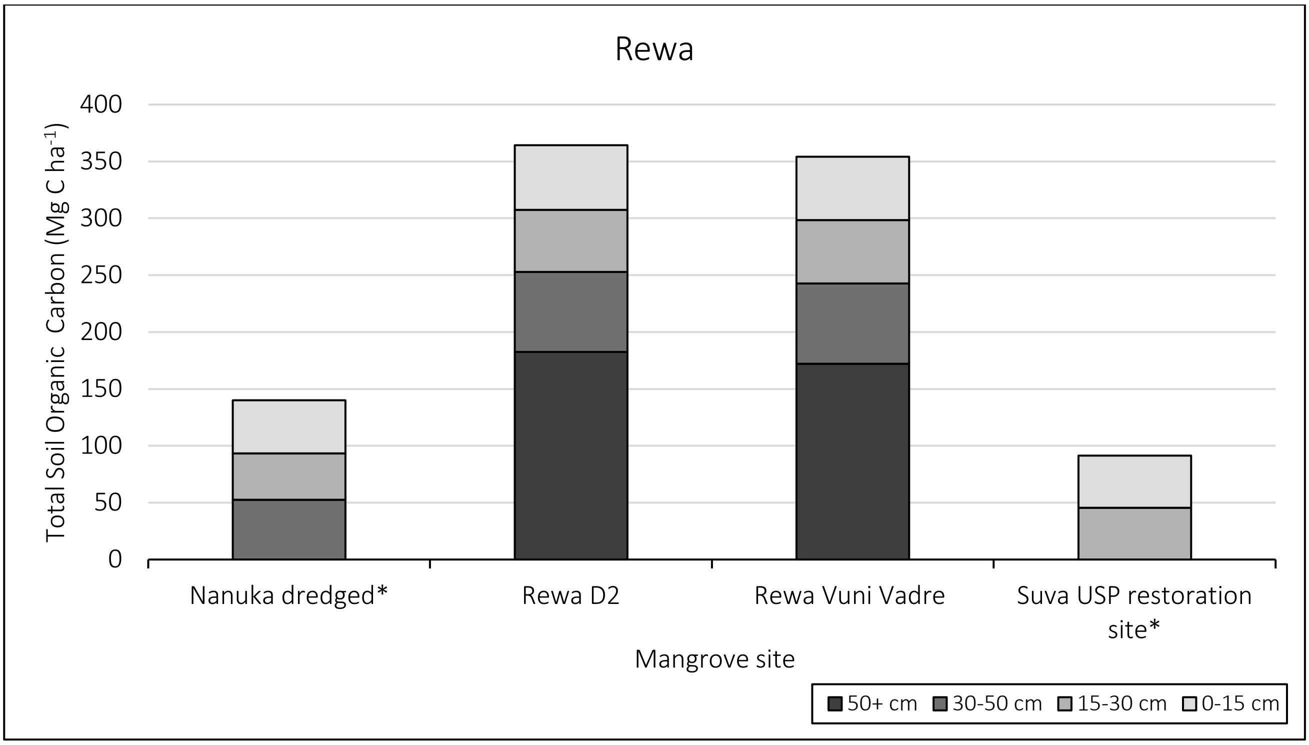

Figure 30. Mangrove soil organic carbon at different soil depths at the five sites in location Rewa, Fiji. An asterisk (*) is indicative of a degraded site.

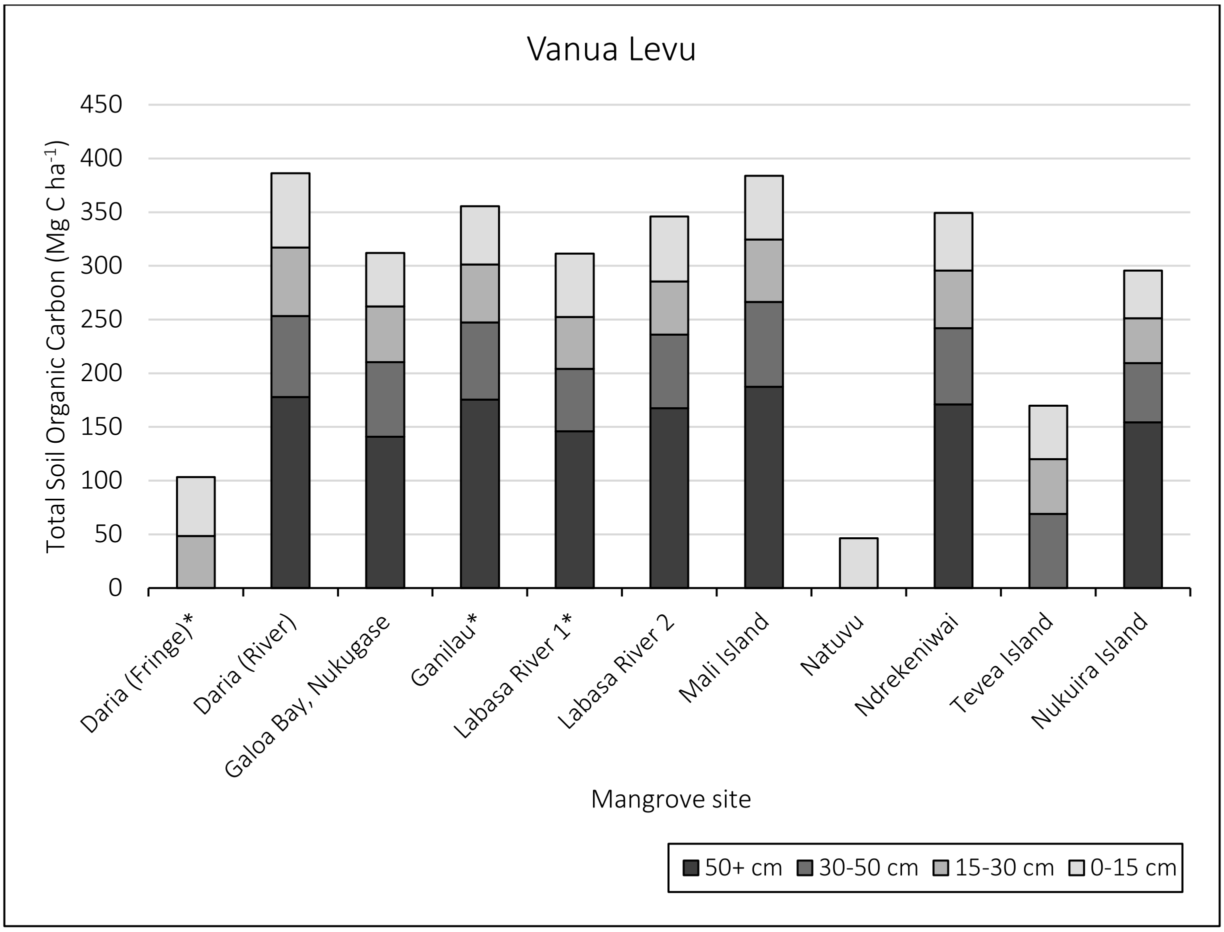

Figure 31. Mangrove soil organic carbon at different soil depths at the 11 sites in Vanua Levu, Fiji. An asterisk (*) is indicative of a degraded site.

4.3.4 Total ecosystem carbon

Mean total ecosystem carbon stocks (TECS) varied little across the three study locations, with Vanua Levu demonstrating slightly higher mean values and Ovalau-Moturiki exhibiting the lowest (Figure 33). While differences in the mean values was observed, these differences may not be statistically significant.

Across Vanua Levu, mean TECS were approximately 709 Mg C ha^{-1}. The majority of this carbon was stored as soil organic carbon (SOC), contributing approximately 338 Mg C ha^{-1}. Smaller proportions were stored in live tree carbon storage (TCS), 112 Mg C ha^{-1} above-ground and 29 Mg C ha^{-1} below-ground. In comparison, dead TCS contributed only minimally to overall TECS (Figure 33).

In Rewa, mean TECS were approximately 669 Mg C ha^{-1}. The greatest contributor was SOC, accounting for 344 Mg C ha^{-1}. Live TCS contributed slightly less, with 83 Mg C ha^{-1} above-ground and 30 Mg C ha^{-1} below-ground. Dead TCS made only a minor contribution to TECS (Figure 33).

Ovalau-Moturiki exhibited the lowest mean TECS, at 611 Mg C ha^{-1}. As with other locations, SOC was the largest component, accounting for 356 Mg C ha^{-1}. Live TCS contributed 55 Mg C ha^{-1} above-ground and 15 Mg C ha^{-1} below-ground. Dead TCS contributed minimally (Figure 33).

Across all sites, SOC was the predominant carbon pool, accounting for 70% to 83% of the mean TECS. Above-ground TCS was the next largest contributor, while below-ground TCS and dead TCS pools represented relatively minor components (Figure 33).

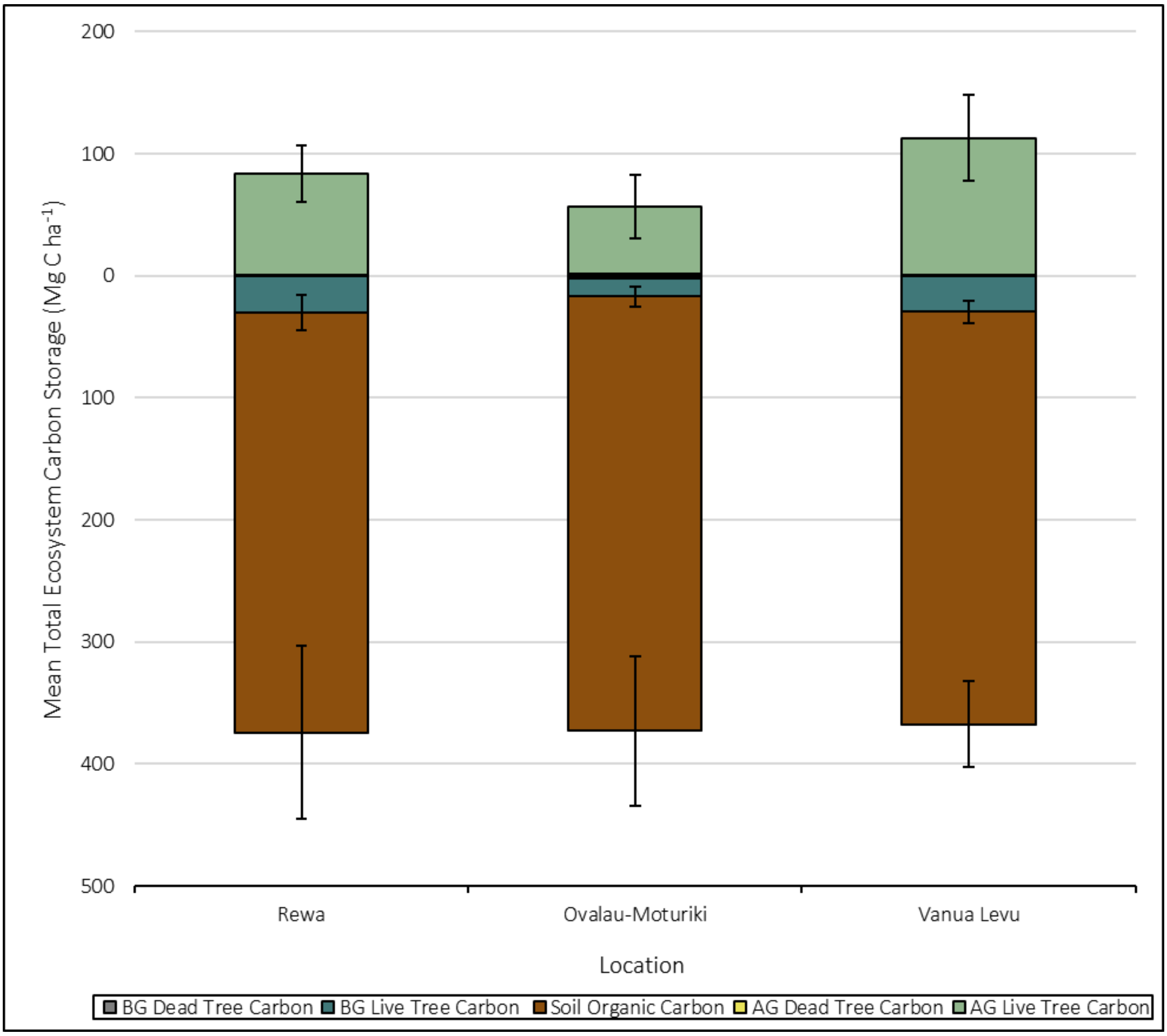

Figure 32. Mean total ecosystem carbon stocks (TECS) across three locations in Fiji partitioned by carbon pools: soil organic carbon, above-ground (AG) and below-ground (BG) live tree carbon, and dead tree carbon. The mean TECS were similar between locations, Vanua Levu (709 Mg C ha^{-1}), Rewa (669 Mg C ha^{-1}), and Ovalau-Moturiki (611 Mg C ha^{-1}). Soil organic carbon contributed the most to TECS. Error bars represent standard error of the mean.

4.4 Summary

The seagrass and mangrove ecosystems of Fiji provide essential services like biodiversity enhancement, coastal protection, carbon sequestration, food production, as well as sources of firewood and construction materials. To our knowledge, this carbon assessment was the largest for Fiji, covering eight (8) seagrass sites and 19 mangrove sites, across locations including Ovalau-Moturiki and Vanua Levu, where previous carbon assessments have not focused. As expected, the results were similar to past studies focused on Viti Levu and found that carbon storage vary between seagrass and mangrove systems across the archipelago, with some sites found to have high and significant carbon storage. In line with the Blue Carbon literature, high carbon stocks were typically found associated with major rivers (Labasa, Rewa, and Daria Rivers) and mangrove forests dominated by high-density *Rhizophora stylosa*. Seagrass soil organic carbon was higher than expected based on past literature and may reflect differences in methods. Overall, the results emphasize Fiji's seagrass and mangrove ecosystems as significant carbon sinks.

Key findings:

Seagrass ecosystems

- The total soil organic carbon (SOC) varied little between seagrass sites in the surface layers (0 – 15 cm), ranging from 38 to 51 Mg C ha^{-1}. Sampling to depths greater than 15 cm was challenging, which limited our ability to capture the full vertical profile of SOC. This limitation likely results in an underestimation of total carbon stocks, as deeper sediment layers in seagrass meadows may store additional carbon. However, the limited deeper samples collected showed similar variability to surface layers. Past studies of seagrass ecosystems from Fiji[36], Indonesia[37] and Palau[38] found levels ranging from 0.32 to 65.8 Mg C ha^{-1}, as such these results are within an expected range for island nations in Melanesia.
- The moderate to high SOC levels in the Fiji seagrass sites, relative to past Melansia studies, may relate to the dominant and mixed species seagrass communities. As described in the Ecosystem Assessments report for this project[39], the sites in this study found *Halodule* spp. dominant at 90% of sites, with *Halophila ovalis* and *Syringodium isoetifolium* also present at 60% of sites. These species, especially when mixed, can create dense, structurally complex meadows that trap more organic matter. Other factors leading to higher SOC levels, could include Fiji's sediment characteristics, seagrass sites' proximity to functional mangrove forests and coral reefs, and disturbance and pollution levels compared to assessments from other countries.

Mangrove ecosystems

- There are limited studies to compare our results with, however, a past study by Cameronet al (2021) assessed sites across Viti Levu (Ba, Rewa, and Nadroga-Navosa) and found total ecosystem carbon stocks (TECS), with a SOC sampling depth of 1.5 m, varies between 132.8 to 772.8 Mg C ha^{-1}.[40] While there were significant differences in the methods between our studies, our study found similar values compared to Cameron et al, with mean TECS for each location estimates at: Vanua Levu 706 Mg C ha^{-1}, Rewa 669 Mg C ha^{-1}, and Ovalau–Moturiki 611 Mg C ha^{-1}.

[36] Singh, S., Lal, M. M., Southgate, P. C., Wairiu, M., & Singh, A. (2022). Blue carbon storage in Fijian seagrass meadows: First insights into carbon, nitrogen and phosphorus content from a tropical southwest Pacific Island. *Marine Pollution Bulletin, 183*, Article 113432. https://doi.org/10.1016/j.marpolbul.2022.113432

[37] Stankovic, M., Mishra, A. K., Rahayu, Y. P., Lefcheck, J., Murdiyarso, D., Friess, D. A., ... & Prathep, A. (2023). Blue carbon assessments of seagrass and mangrove ecosystems in South and Southeast Asia: Current progress and knowledge gaps. *Science of the Total Environment*, *904*, 166618.

[38] Kauffman, J. B., Heider, C., Cole, T. G., Dwire, K. A., & Donato, D. C. (2011). Ecosystem carbon stocks of Micronesian mangrove forests. *Wetlands, 31*(2), 343–352. https://doi.org/10.1007/s13157-011-0148-9

[39] Alluvium Group, 2025, Blue Carbon Ecosystems of the South Pacific: Ecosystem Assessments in Fiji, Papua New Guinea, Solomon Islands, and Vanuatu, report prepared by Alluvium Group for the MACBLUE Project, Brisbane, Australia.

[40] Cameron, M. J., Lovelock, C. E., & Adame, M. F. (2021). Carbon stocks of mangrove forests in Fiji: Implications of soil depth and land use. Forest Ecology and Management, 482, 118879. https://doi.org/10.1016/j.foreco.2020.118879

- Cameron et al reported SOC ranges between 1.76 to 10.83 %C and 83.9 to 490.3 Mg C ha^{-1}. Our study found similar ranges with SOC concentrations from 1 %C to 28 %C and carbon stocks ranging from 46 to 397 Mg C ha^{-1}.
- Across all sites, SOC was the dominant carbon pool, accounting for 70% to 83% of the mean TECS.
- The highest TECS were typically found in association with major rivers (Labasa, Rewa, Daria Rivers) and mangrove forests dominated by high density of *Rhizophora stylosa*.

PAPUA NEW GUINEA

5 Papua New Guinea carbon assessments

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5.1 Papua New Guinea study sites

Seagrass meadows and mangrove forests were surveyed across five (5) locations in Papua New Guinea (PNG). The survey locations for both seagrass and mangrove are shown in Figure 34, including Western, Central, Milne Bay, West New Britain and New Ireland Provinces. A total of 24 mangrove sites and 17 seagrass sites were surveyed across a diversity of geomorphological settings in order to capture representative data for these dynamic ecosystems. Locations and sites are shown in detail in Figure 34 to Figure 39.

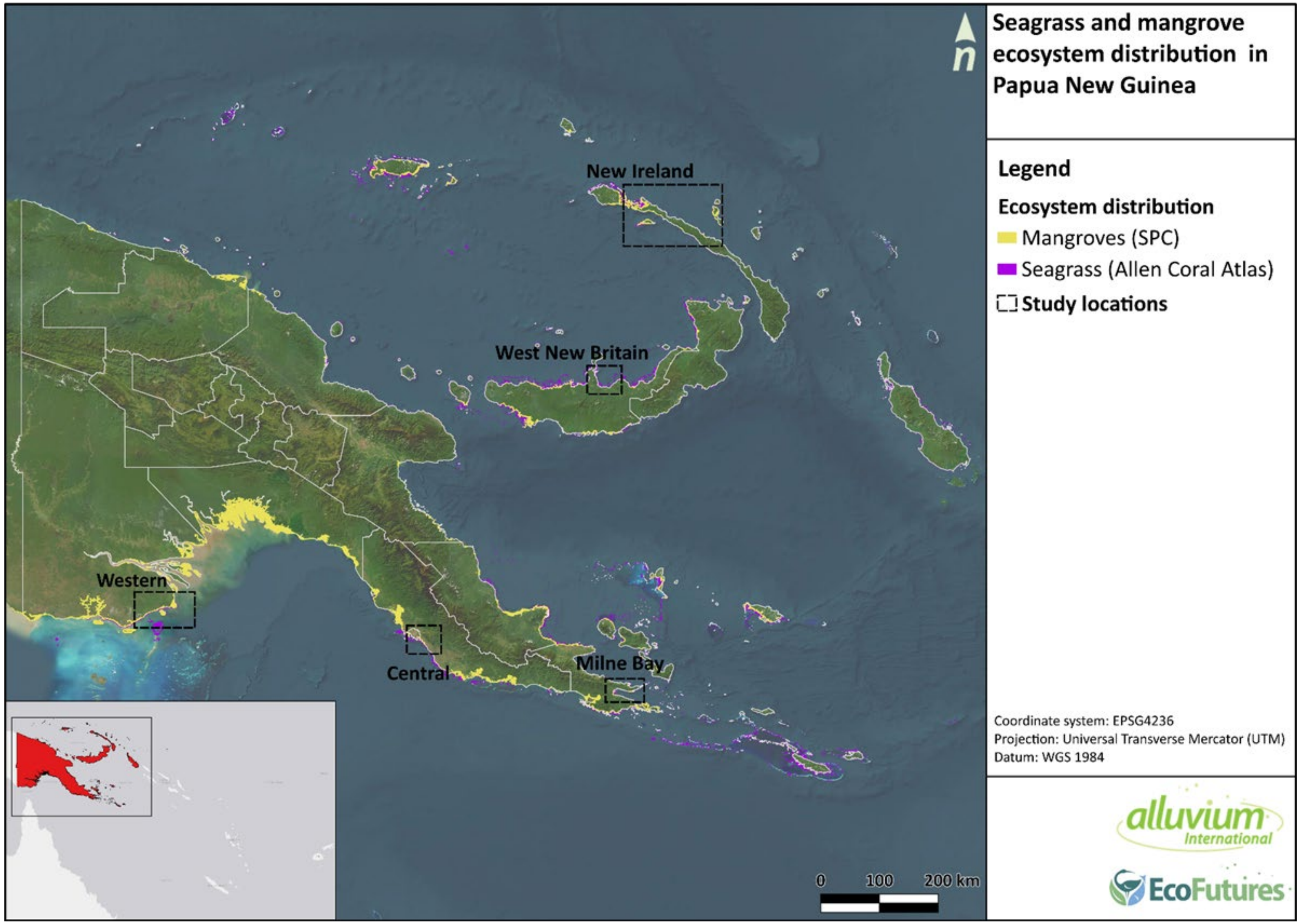

Figure 34. Seagrass and mangrove ecosystem distribution and survey locations in Papua New Guinea.

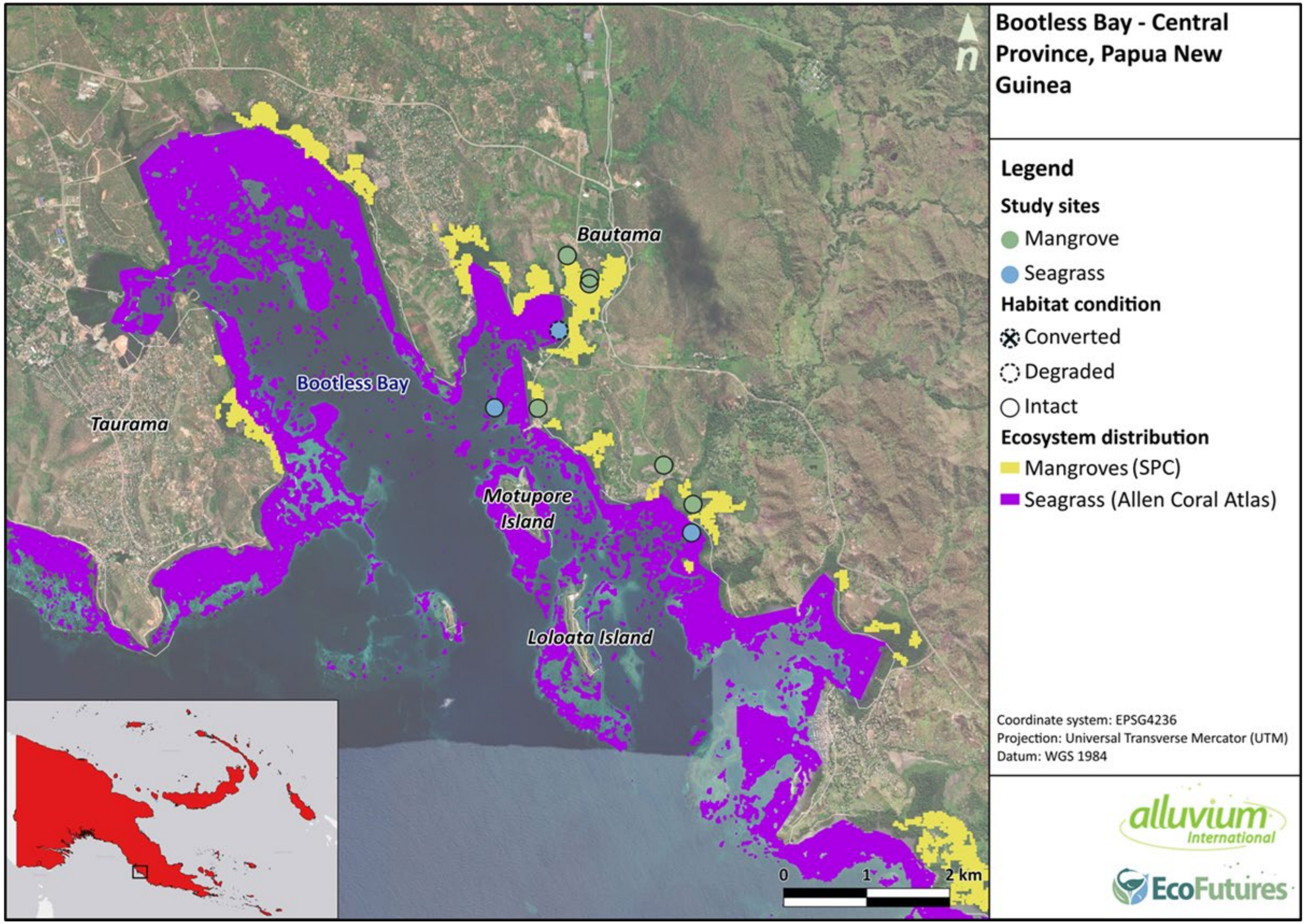

Figure 35. Seagrass and mangrove ecosystem distribution and survey sites in Central Province, in the area of Bootless Bay. At this location there were six (6) intact mangrove sites, two (2) intact seagrass sites and one (1) degraded seagrass site.

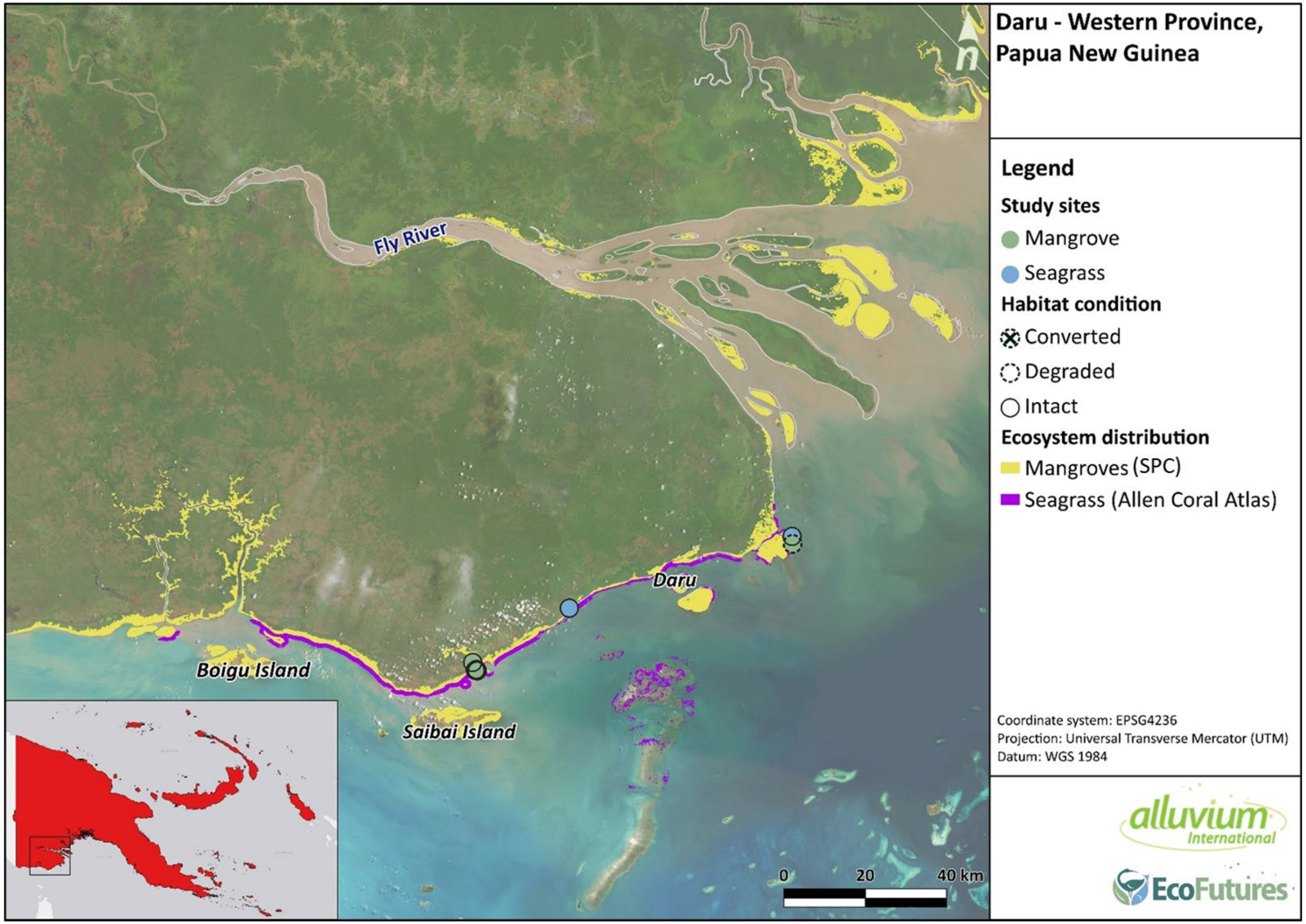

Figure 336. Seagrass and mangrove ecosystem distribution and survey sites in Western Province in the coastal areas surrounding Daru. At this location were four (4) intact and one (1) degraded mangrove side as well as two (2) intact seagrass sites.

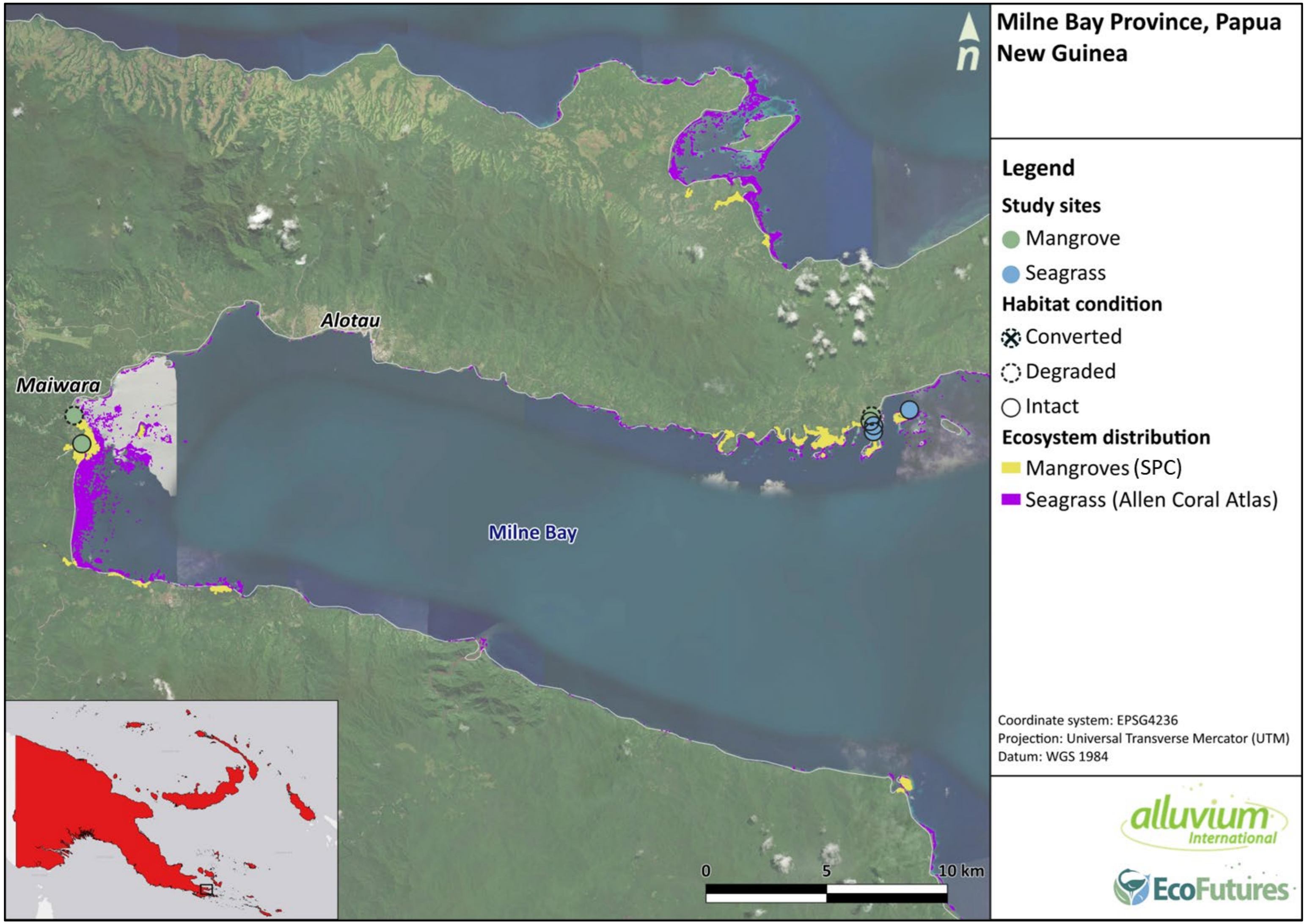

Figure 37. Seagrass and mangrove ecosystem distribution and survey sites in Milne Bay Province. At this location there were two (2) degraded and two (2) intact mangrove sites and three (3) intact seagrass sites.

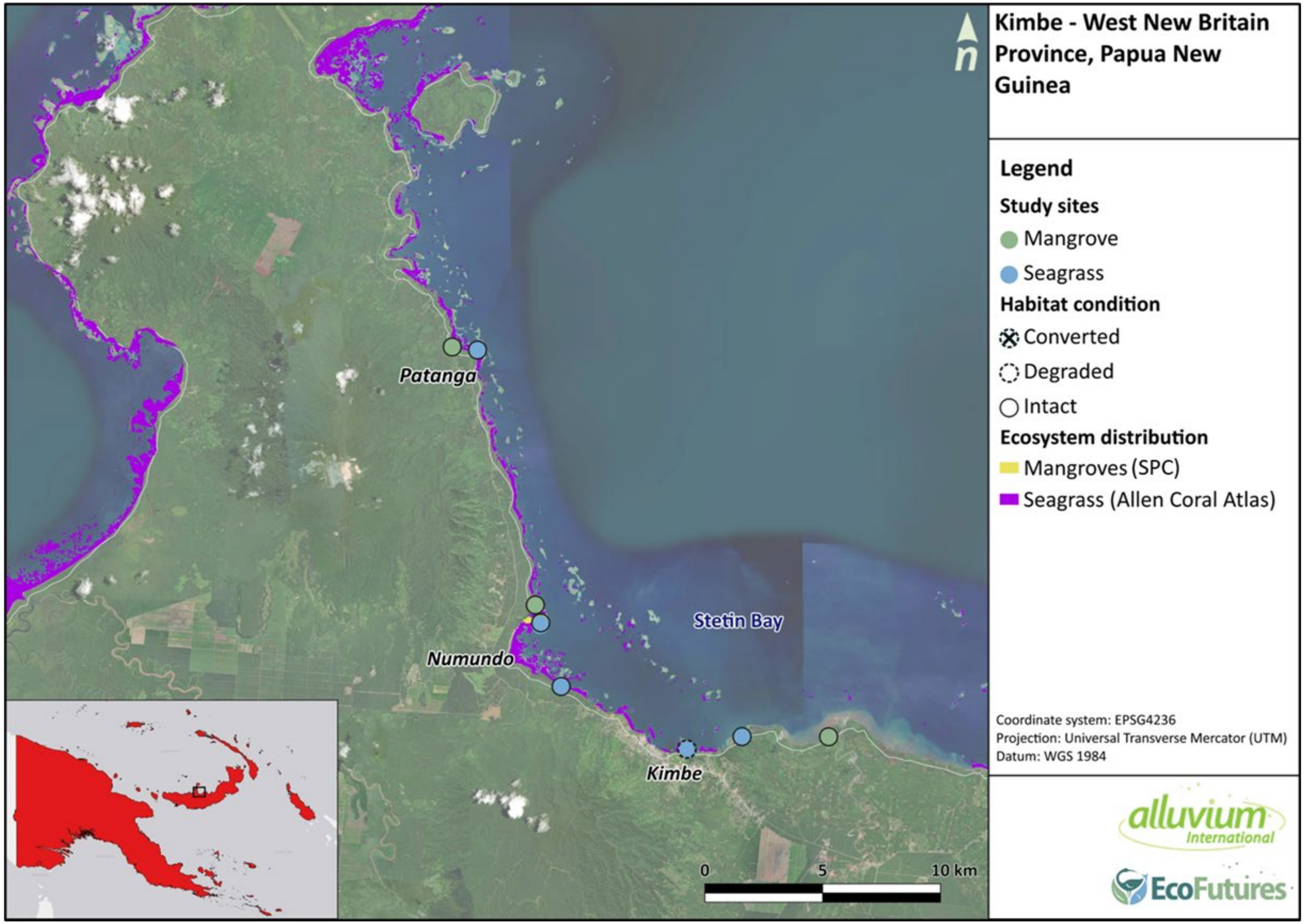

Figure 38. Seagrass and mangrove ecosystem distribution and survey sites in West New Britain Province in the coastal areas surrounding Kimbe. At this location were three (3) intact and one (1) degraded seagrass sites and four (4) intact mangrove sites.

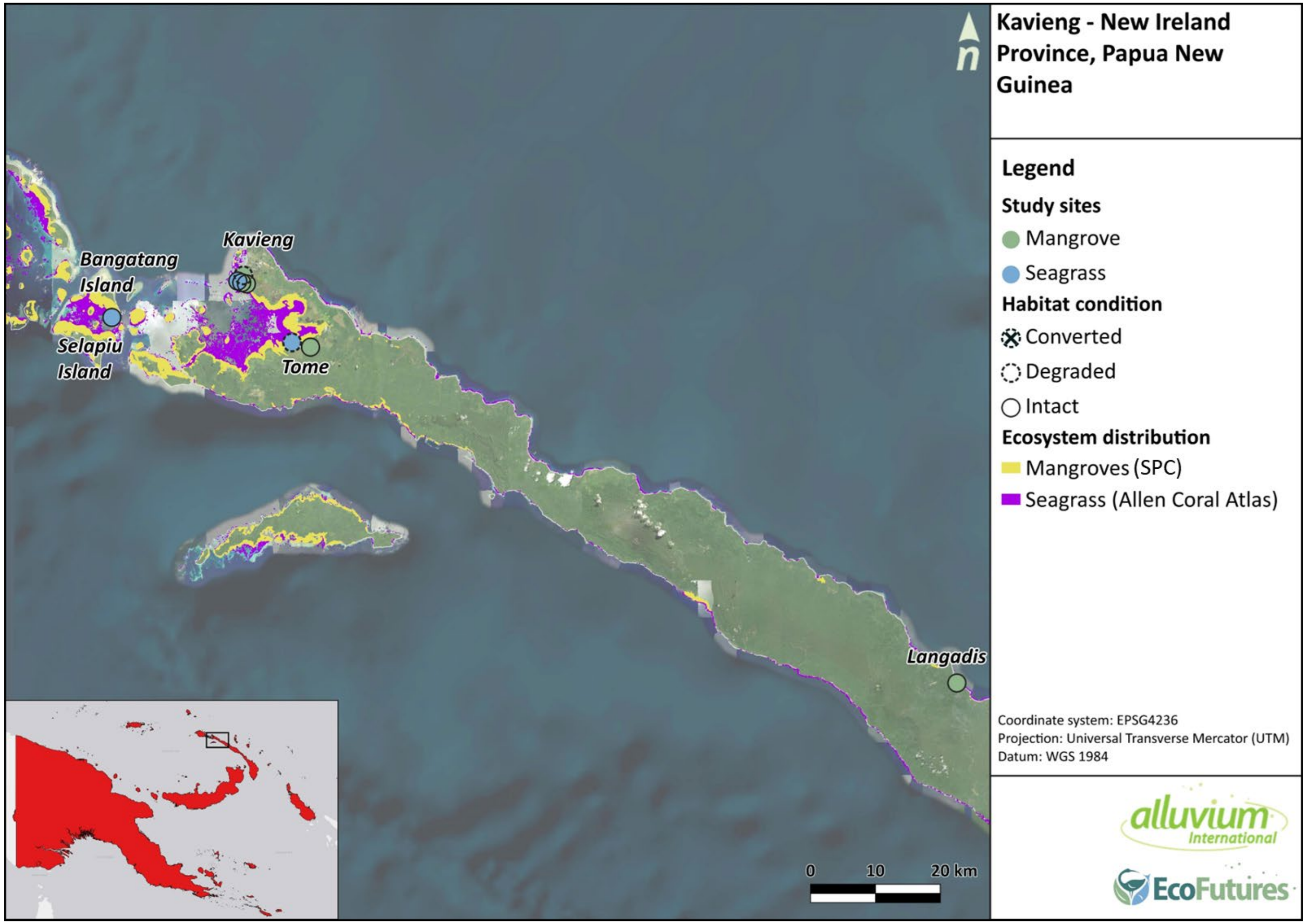

Figure 39. Seagrass and mangrove ecosystem distribution and survey sites in New Ireland Province. At this location were one (1) degraded and four (4) intact mangrove sites and one (1) degraded and two (2) intact seagrass sites.

5.2 Papua New Guinea carbon assessment results – Seagrass

This results section for seagrass ecosystems presents only Soil Organic Carbon measurements in megagrams of carbon per hectare (Mg C ha^{-1}), reflecting the study's focus on the dominant carbon pools in blue carbon ecosystems. Above-ground and below-ground biomass carbon is not considered a significant component of the total ecosystem carbon stock in seagrass meadows.

5.2.1 Soil organic carbon

Sampling depths were limited, and samples varied between the top 15 to 100 cm of the soil profile, primarily due to field constraints, with most sites only accessing the top 15 cm of the soil profile. This is a common limitation in seagrass carbon assessments as they are logistically challenging environments, with inundation typically affecting the integrity of soil cores. This limitation likely results in an underestimation of soil carbon stocks, as deeper sediment layers in seagrass meadows may store additional carbon.

The mean SOC content had relatively low variability within each depth interval across the different locations at different depths (Figure 40). At the 0-15 cm depth interval, the mean SOC ranged from approximately 43 to 49 Mg C ha^{-1}. Results were similarly consistent at the 15-30 cm depth interval, with SOC ranging from approximately 42 to 48 Mg C ha^{-1}. Noting that soil samples were not accessible at all depths across all sites.

Across all 17 seagrass sites assessed, Soil Organic Carbon (SOC) varied significantly, with concentrations ranging from approximately 1% to 9%, and stocks ranging from 42 to 338 Mg C ha^{-1}. Soil Organic Carbon stocks varied between sites reflecting differences in soil properties, organic matter inputs and rates of organic matter decomposition. Figure 41 to Figure 45 summarise SOC stocks at each seagrass assessment site and demonstrate the variability between sites at different depths.

The highest SOC stocks were recorded at sites in West New Britain, where seagrass sediments were deep with minimal sand, and typically dominated by dense Enhaulus meadows. Despite being slightly degraded due to adjacent urban land uses, the Liamo Reef Resort site obtained the highest SOC at 338 Mg C ha^{-1}, other study sites within the West New Britain location obtained similarly high results (140-302 Mg C ha^{-1}).

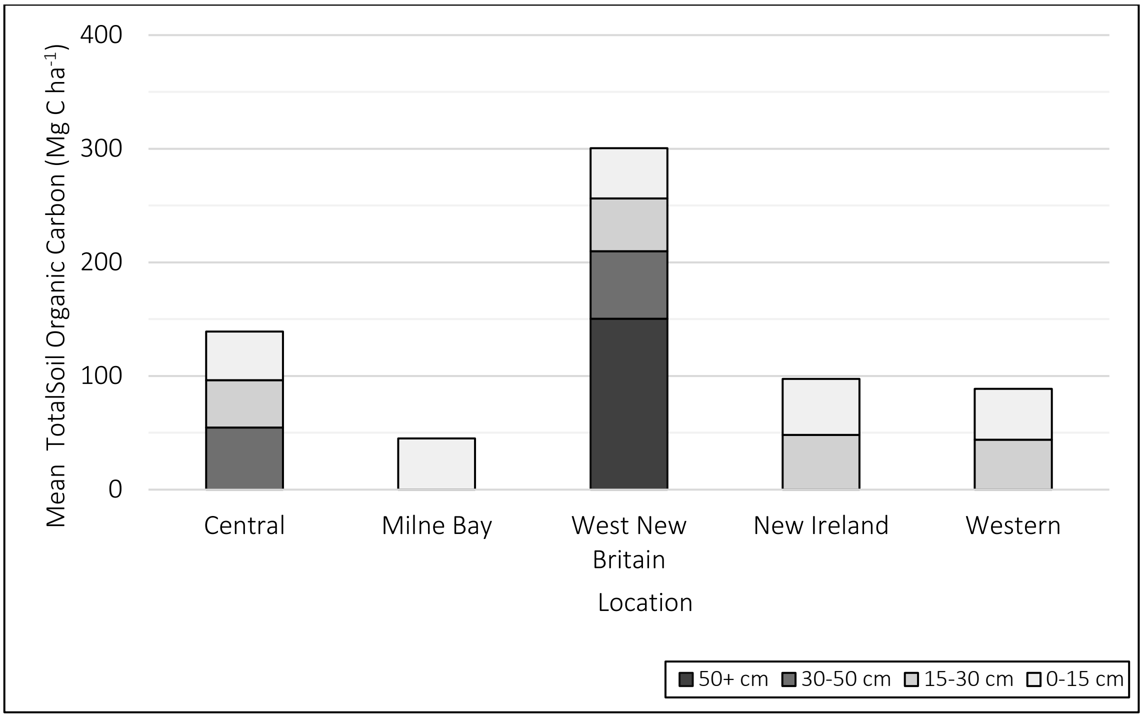

Figure 40. Mean total soil organic carbon (SOC) in seagrass meadows at different soil depths across five survey locations in Papua New Guinea. The highest mean total SOC was measured in West New Britain (301 Mg C ha^{-1}). Mean SOC was relatively consistent across each of the depth intervals for each location.

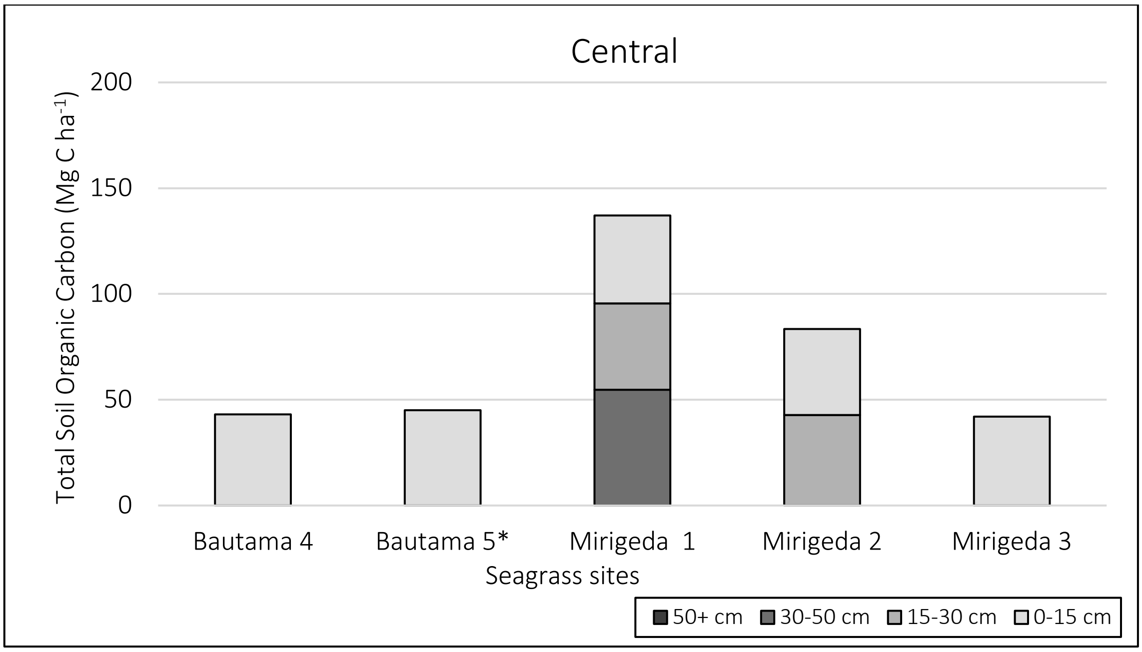

Figure 41. Seagrass soil organic carbon (SOC) at different soil depths at the four seagrass sites in Central Province, Papua New Guinea. The asterisk (*) is indicative of a degraded site. The highest total SOC was obtained from site Mirigeda 1 (137 Mg C ha^{-1}). Total SOC was relatively consistent across each of the depth intervals for each location (41-45 Mg C ha^{-1} at 0-15 cm and 41-43 Mg C ha^{-1} at 15-30 cm).

Figure 42. Seagrass soil organic carbon (SOC) at different soil depths at the three seagrass sites in Milne Bay, Papua New Guinea. Total SOC was highly consistent at 0-15 cm depths, ranging from 44-45 Mg C ha^{-1}.

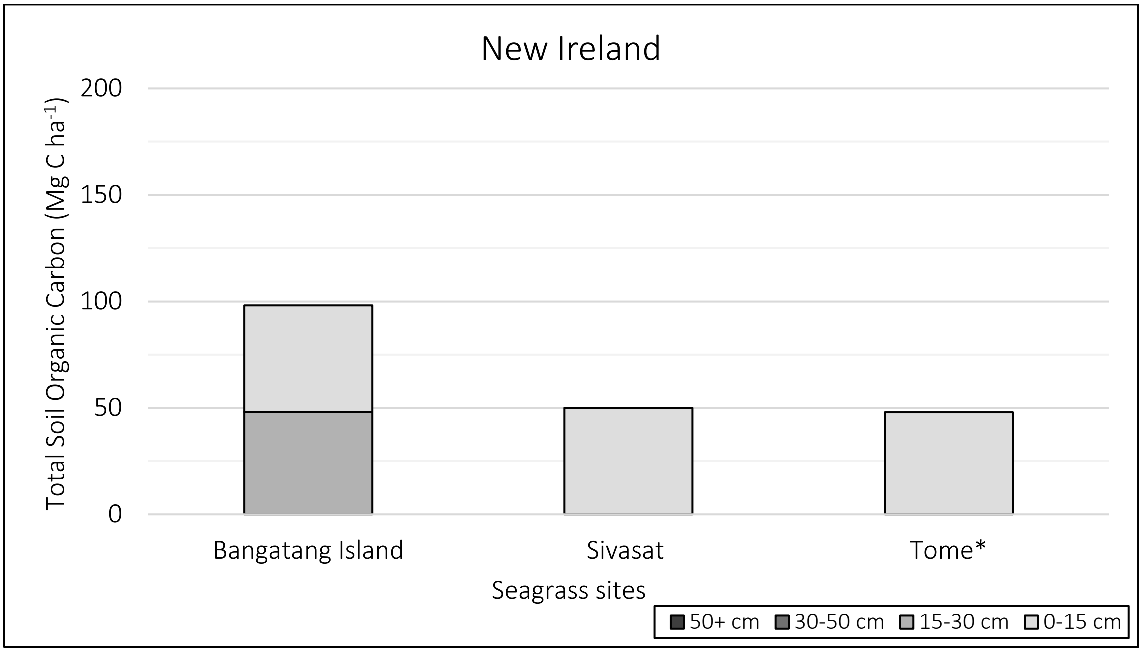

Figure 34. Seagrass soil organic carbon (SOC) at different soil depths at the three seagrass sites in New Ireland, Papua New Guinea. The asterisk (*) is indicative of a degraded site. The highest total SOC was obtained at Bangatang Island (98 Mg C ha^{-1}). Across all sites, SOC was highly consistent at 0-15 cm depths, ranging from 48-50 Mg C ha^{-1}.

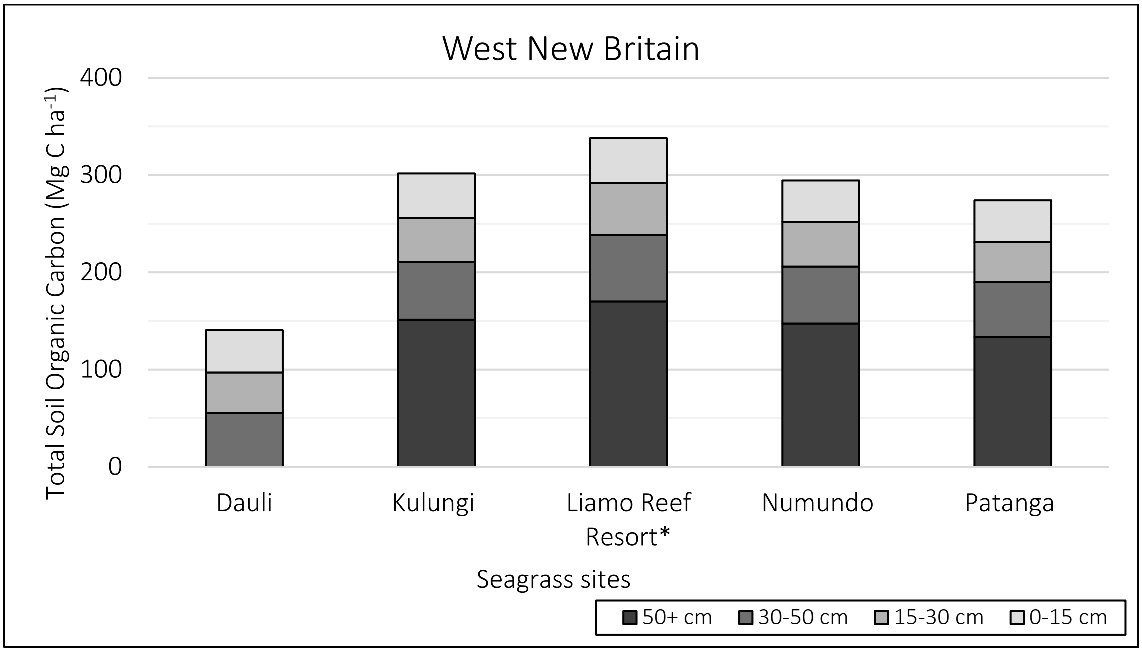

Figure 35. Seagrass soil organic carbon (SOC) at different soil depths at the five seagrass sites in West New Britain, Papua New Guinea. The asterisk (*) is indicative of a degraded site. SOC was obtained at all depth intervals for most sites, due to Enhalus dominated seagrass meadows with deep sediments and minimal sand. Total SOC ranged from 140-338 Mg C ha^{-1}.

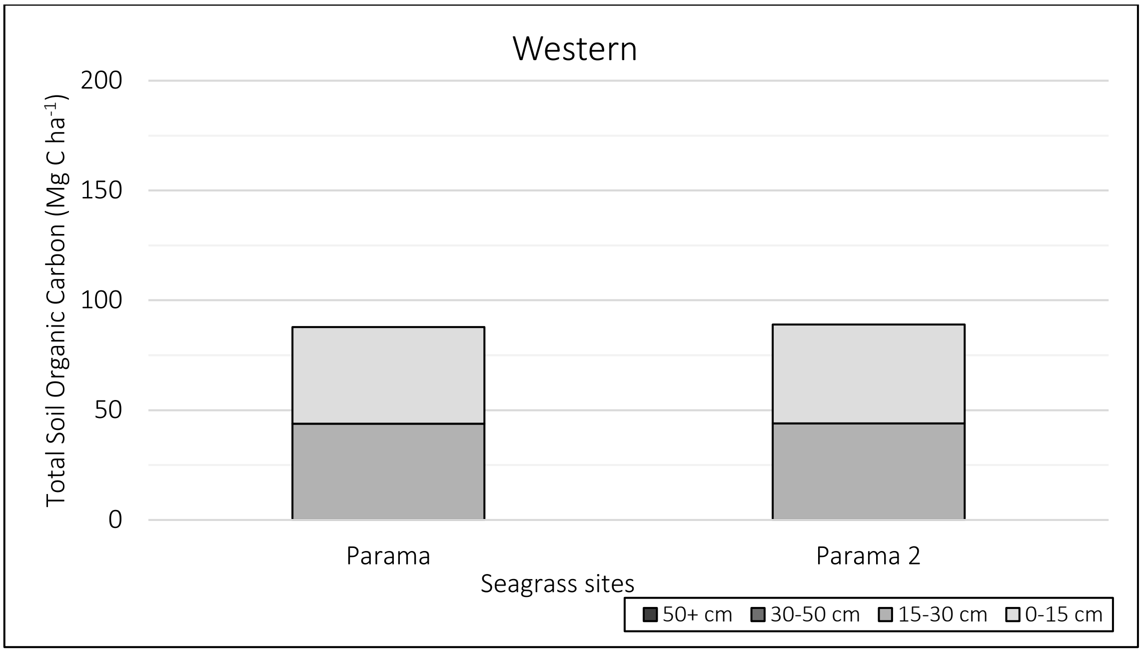

Figure 45. Seagrass soil organic carbon (SOC) at different soil depths at the two seagrass sites in Western Province, Papua New Guinea. Total SOC was highly consistent at 0-30 cm depths, ranging from 88-89 Mg C ha^{-1}.

5.3 Papua New Guinea carbon assessment results – Mangroves

This results section for mangrove ecosystems is systematically divided into several subsections to provide a comprehensive analysis of the data. Initially, species density is examined across various locations, offering insights into the geographical distribution of species. Subsequent subsections focus on the comparative analysis of carbon stored in trees both above and below-ground, evaluated across different locations and land use conversion categories. These comparisons help understand the spatial variations in carbon stock distribution and their implications for carbon storage and ecosystem dynamics.

5.3.1 Species density

The mean species density (mean ± standard error) was measured in trees per hectare (trees ha^{-1}) across six (6) mangrove sites in the Central Province. Mangrove species with the highest tree densities at this location were *Avicennia alba* (1,621 ± 1,333 trees ha^{-1}), *Avicennia marina* (1,341 ± 792 trees ha^{-1}), and *Rhizophora stylosa* (1,333 trees ha^{-1}), despite *R. stylosa* only being recorded at one site (Figure 46). All other mangrove species had tree densities less than 800 trees ha^{-1}.

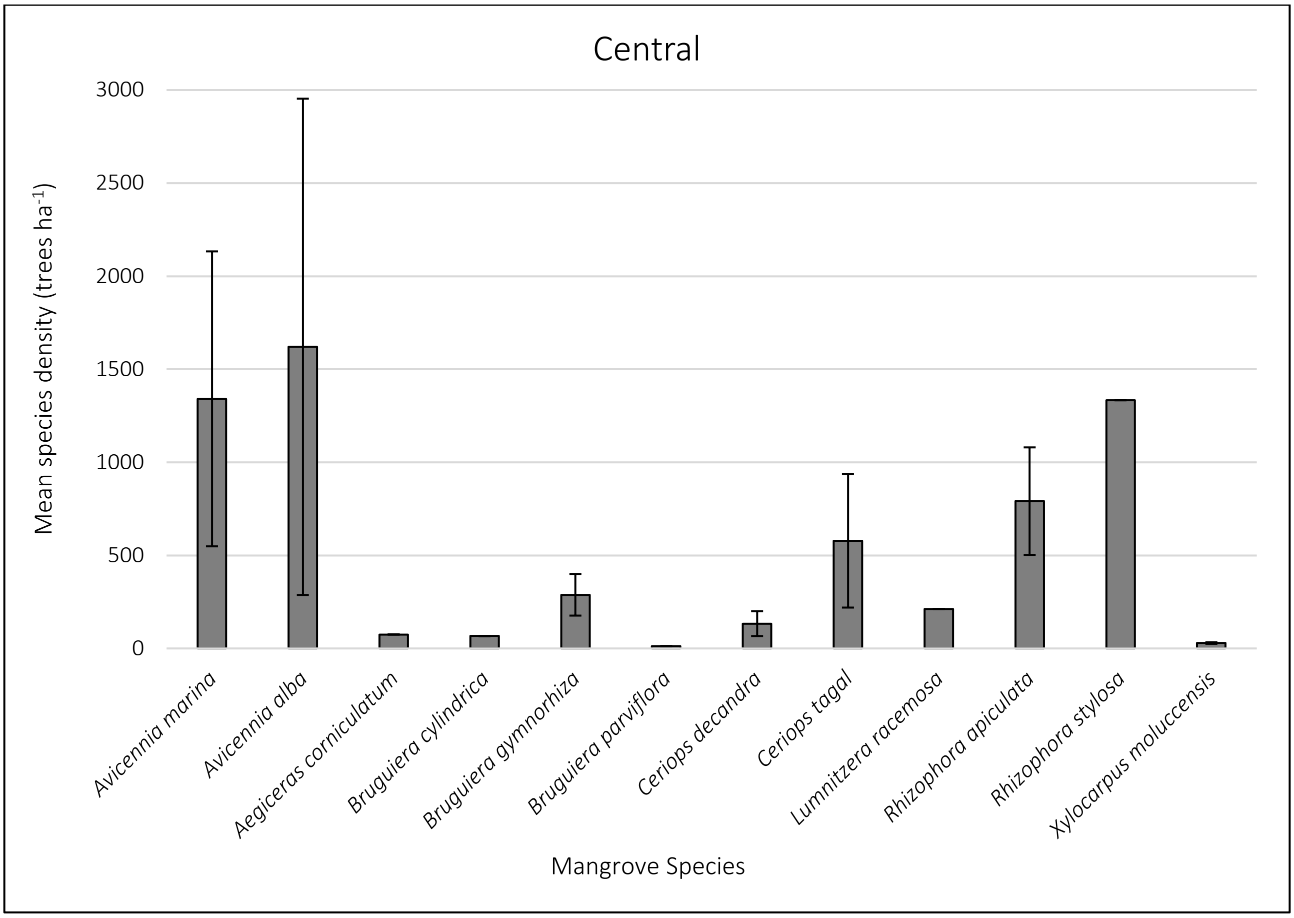

Figure 36. Bar graph showing the mean density of mangrove species (± SE) in Central. Species with the highest densities were *Avicennia alba* (1,621 ± 1,333 trees ha^{-1}), *Avicennia marina* (1,341 ± 792 trees ha^{-1}), and *Rhizophora stylosa* (1,333 trees ha^{-1}). All other species at this location < 800 trees ha^{-1}. Error bars represent the standard error of the mean. For species observed only at one site in this location, error bars are absent.

In Milne Bay, across the four (4) mangrove sites assessed, *Ceriops decandra* had the highest density of 350 trees ha^{-1}, followed by *Rhizophora stylosa* with 253 ± 57 trees ha^{-1} (Figure 47). *Avicennia marina*, *Dolichandrone spathacea* and *Sonneratia caseolaris* all had the same tree density of 150 trees ha^{-1} each. *Bruguiera gymnorhiza* had slightly fewer trees, with 138 trees ha^{-1} (Figure 47). All other species had tree densities less than 70 trees ha^{-1} each (Figure 47).

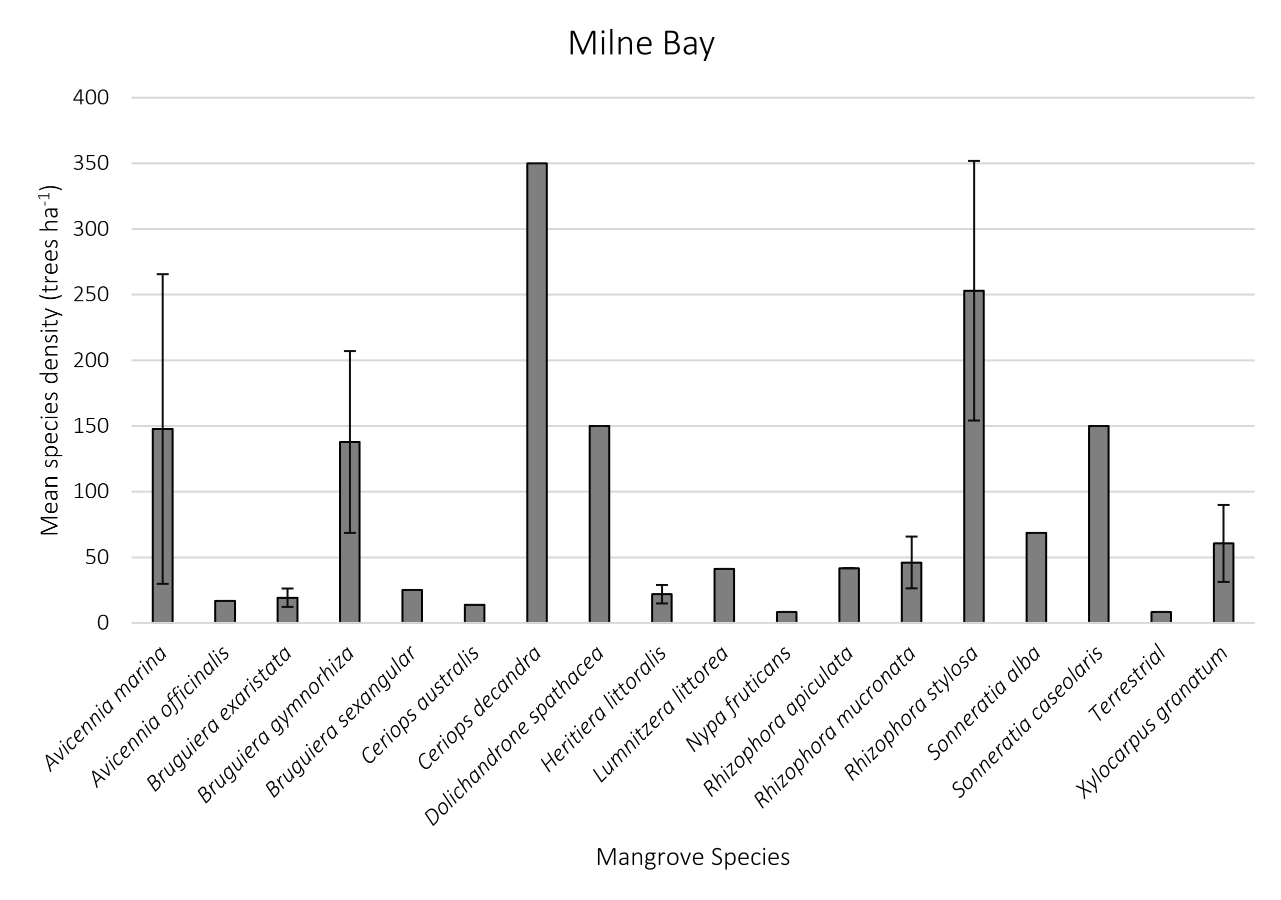

Figure 47. Bar graph showing the mean density of mangrove species (± SE) in Milne Bay. *Ceriops decandra* exhibited the highest density at 350 trees ha^{-1}, followed by *Rhizophora stylosa* (253 trees ha^{-1}). All other trees were ≤150 tree ha^{-1}. Error bars represent the standard error of the mean. For species observed only at one site in this location, error bars are absent.

In West New Britain, across the four (4) mangrove sites assessed, *Rhizophora stylosa* had the highest density across the sites, with 428 ± 166 trees ha^{-1} (Figure 48). *Rhizophora stylosa* is highly effective in carbon storage due to its extensive stilt roots and substantial above-ground biomass. These stilt roots not only stabilise the soil and prevent erosion but further trap carbon-rich sediments, while the above-ground biomass stores significant amounts of carbon, contributing greatly to blue carbon sequestration. This was followed by *Bruguiera gymnorhiza* with 274 ± 56 trees ha^{-1} and *Cerebra manghas* with 88 trees ha^{-1} (Figure 48). All other species had densities of less than 70 trees ha^{-1} (Figure 48).

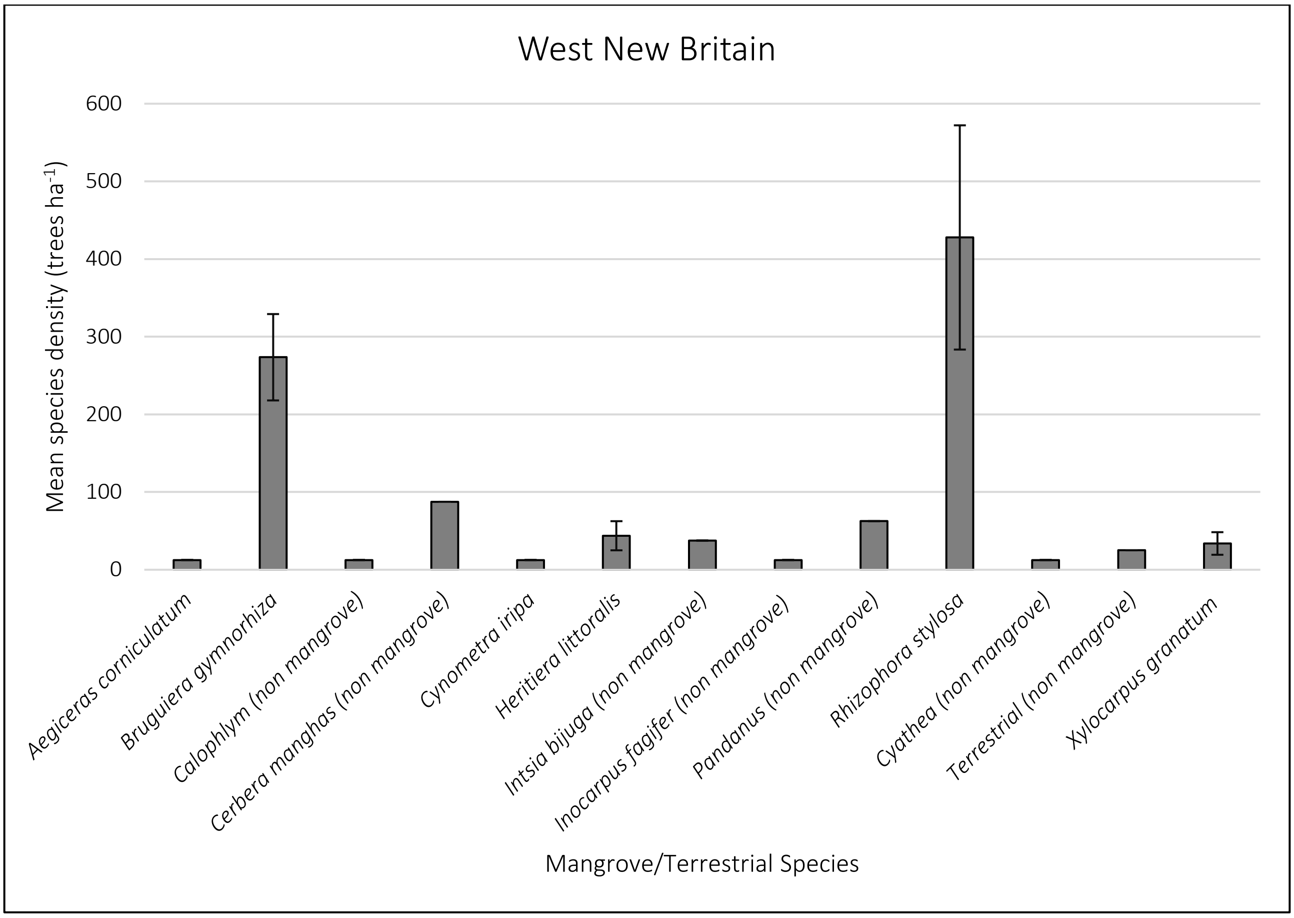

Figure 37. Bar graph showing the mean density of mangrove species (± SE) in West New Britain. *Rhizophora stylosa* had the highest tree density (428 trees ha^{-1}), followed by *Bruguiera gymnorhiza* (274 trees ha^{-1}). All other species had a density <100 trees ha^{-1}. Error bars represent the standard error of the mean. For species observed only at one site in this location, error bars are absent.

In New Ireland, across the five (5) mangrove sites assessed, the highest tree densities were observed for *Bruguiera gymnorhiza* and *Rhizophora stylosa* with densities of 299 ± 114 trees ha^{-1} and 294 ± 39 trees ha^{-1}, respectively. This was followed by *Xylocarpus granatum* (236 ± 219 trees ha^{-1}) and *Lumnitzera littorea* (187 ± 169 trees ha^{-1}) (Figure 49). By comparison, *Xylocarpus moluccensis* and *Excoecaria agalollocha* had the lowest species densities at this location, with densities of 70 ± 56 trees ha^{-1} and 67 trees ha^{-1} (Figure 49).

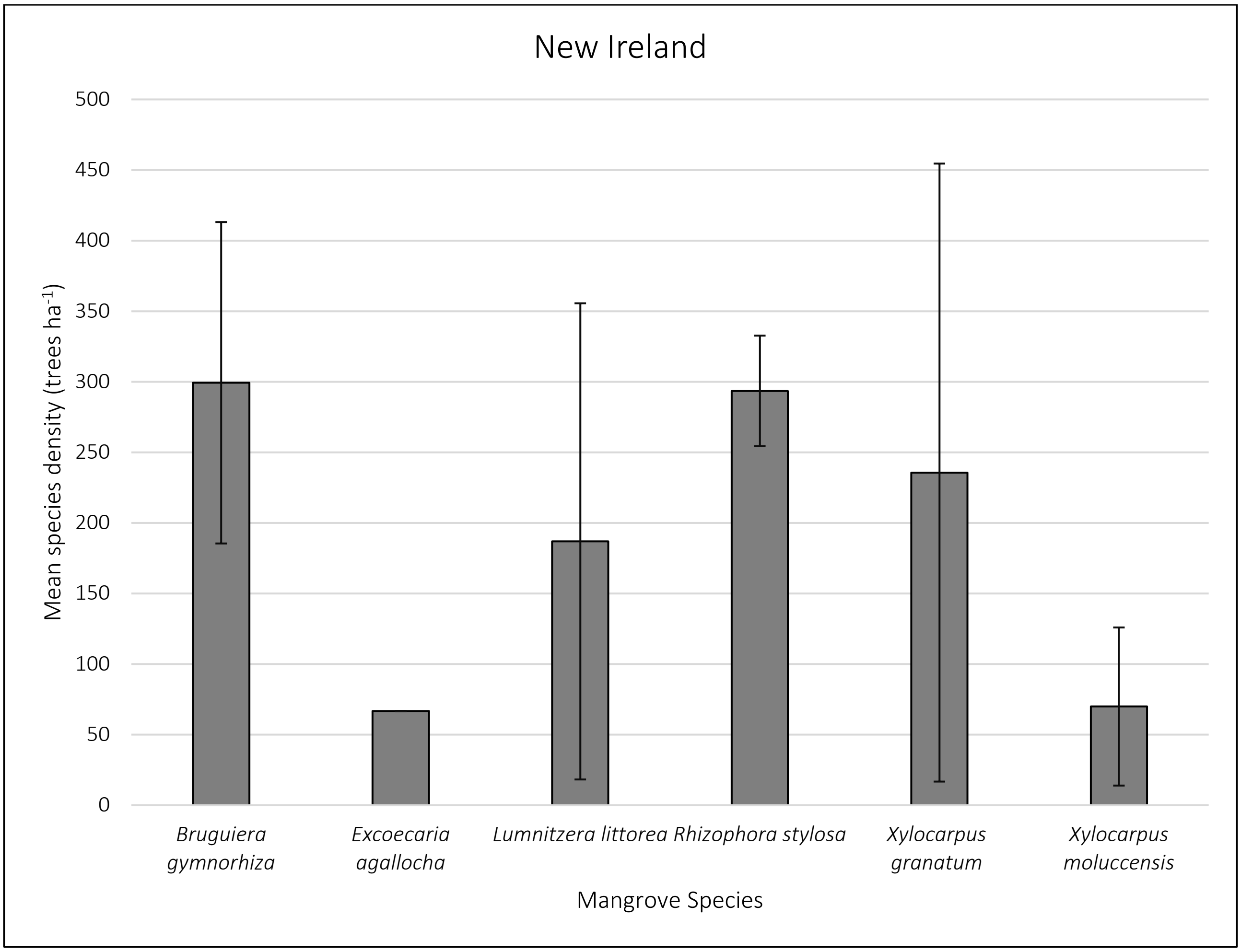

Figure 49. Bar graph showing the mean density of mangrove species (± SE) in New Ireland. *Bruguiera gymnorhiza* had the highest tree density (299 trees ha^{-1}), followed by *Rhizophora stylosa* (924 trees ha^{-1}), *Xylocarpus granatum* (236 trees ha^{-1}) and *Lumnitzera littorea* (187 trees ha^{-1}). All other species had a density <100 trees ha^{-1}. Error bars represent the standard error of the mean. For species observed only at one site in this location, error bars are absent.

In the Western Province, across the five (5) mangrove sites assessed, *Avicennia marina* var. *marina* had the highest tree density of 600 trees ha^{-1}, despite only being observed at one site. *Bruguiera cylindrica* and *Rhizophora stylosa* had similarly high tree densities (and variability) at this location, with densities of 505 ± 448 trees ha^{-1} and 503 ± 315 trees ha^{-1}, respectively (Figure 50). *Rhizophora apiculata* had a density of 432 ± 82 trees ha^{-1}, while *Scyphipora hydrophylacea* had a density of 338 trees ha^{-1} (Figure 50). All other species had densities of less than 220 trees ha^{-1} (Figure 50).

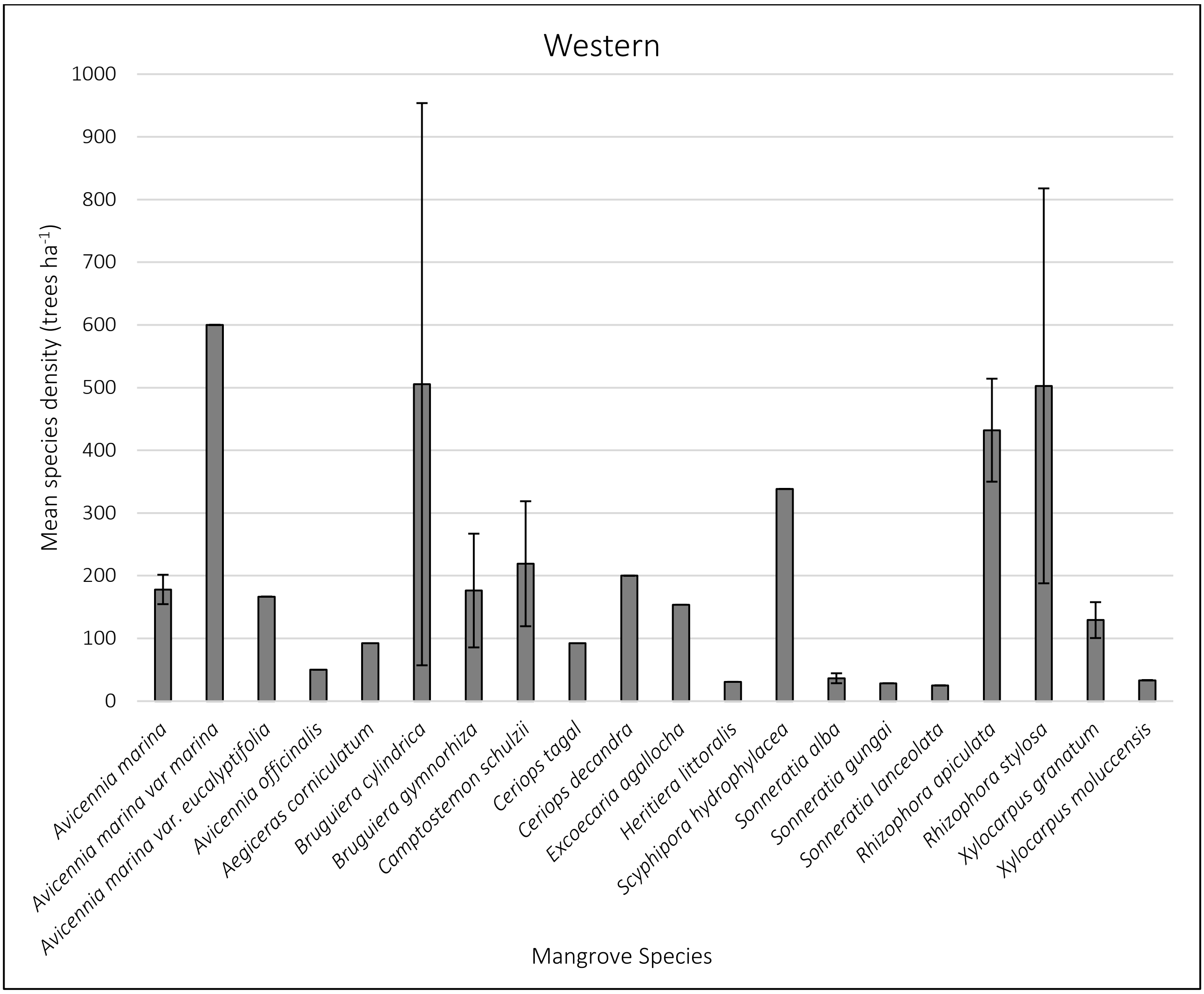

Figure 38. Bar graph showing the mean density of mangrove species (± SE) in New Ireland. *Avicennia marina* var. *marina* had the highest tree density (600 trees ha^{-1}), followed by *Bruguiera cylindrica* (505 trees ha^{-1}), *Rhizophora stylosa* (503 trees ha^{-1}), *Rhizophora apiculata* (432 trees ha^{-1}) and *Scyphipora hydrophylacea* (338 trees ha^{-1}). All other species had a density < 220 trees ha^{-1}. Error bars represent the standard error of the mean. For species observed only at one site in this location, error bars are absent.

5.3.2 Above-ground and below-ground tree carbon storage

As shown in Figure 51, tree carbon storage (TCS) refers to the amount of carbon stored within trees, which can be stored above-ground (in their trunks, stems, foliage, aerial roots and prop roots) and below-ground (in their roots). Total TCS refers to the sum of the carbon stored in trees both above-ground (AG) and below-ground (BG).

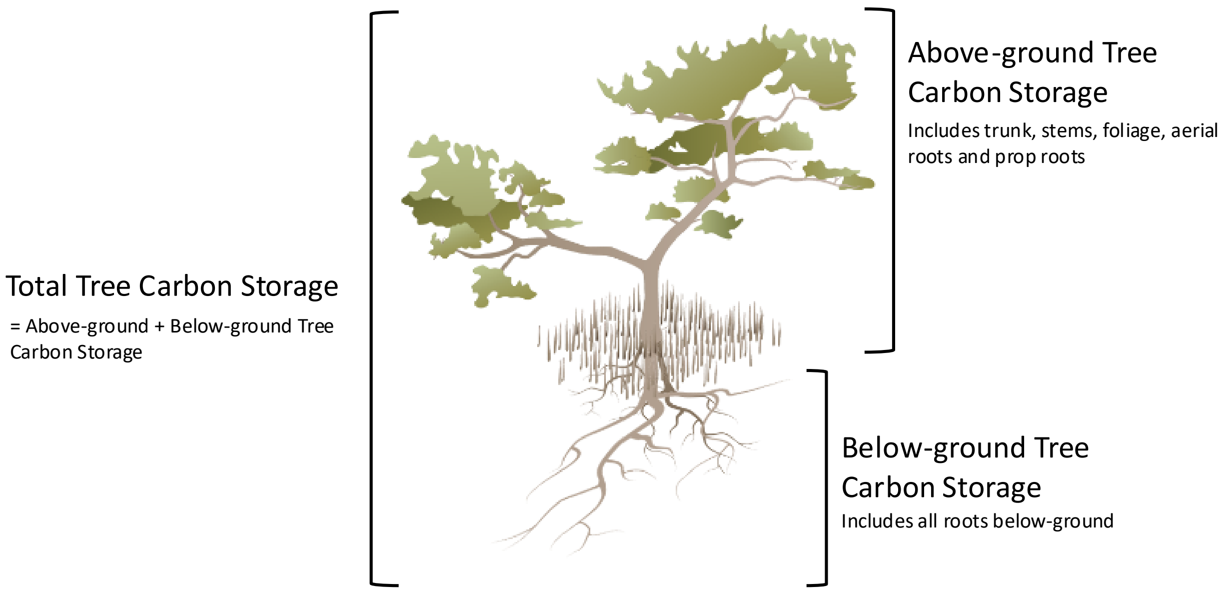

Figure 51. Illustration of total tree carbon storage stored in trees both above and below-ground.

Upper and lower estimates for the mean total TCS were calculated in megagrams of carbon per hectare (Mg C ha^{-1}) for each study location (Figure 52 and Figure 53) and study site (Figure 54 to Figure 58) across PNG. In this section, we report the lower estimates unless otherwise stated, as shown in detail in Figure 52.

The mean total TCS was calculated for each study location and is presented as mean ± standard error. Across the study locations, the mangrove forests in New Ireland, West New Britain, and Western Provinces were found to have the highest mean total TCS, with values of 352 ± 58 Mg C ha^{-1}, 350 ± 85 Mg C ha^{-1}, and 303 ± 69 Mg C ha^{-1}, respectively (Figure 52). In contrast, mangrove forests in Central and Milne Bay exhibited substantially lower mean total TCS, at 180 ± 39 Mg C ha^{-1} and 121 ± 31 Mg C ha^{-1}, respectively (Figure 52).

High mean total TCS may be related to species composition, as most locations with elevated TCS also had significant densities of *Rhizophora stylosa* across multiple sites. By comparison, Milne Bay had the lowest densities of *R. stylosa*, while only one site in Central Province contained this species, which may explain the lower total TCS values being observed in these two locations (Figure 52).

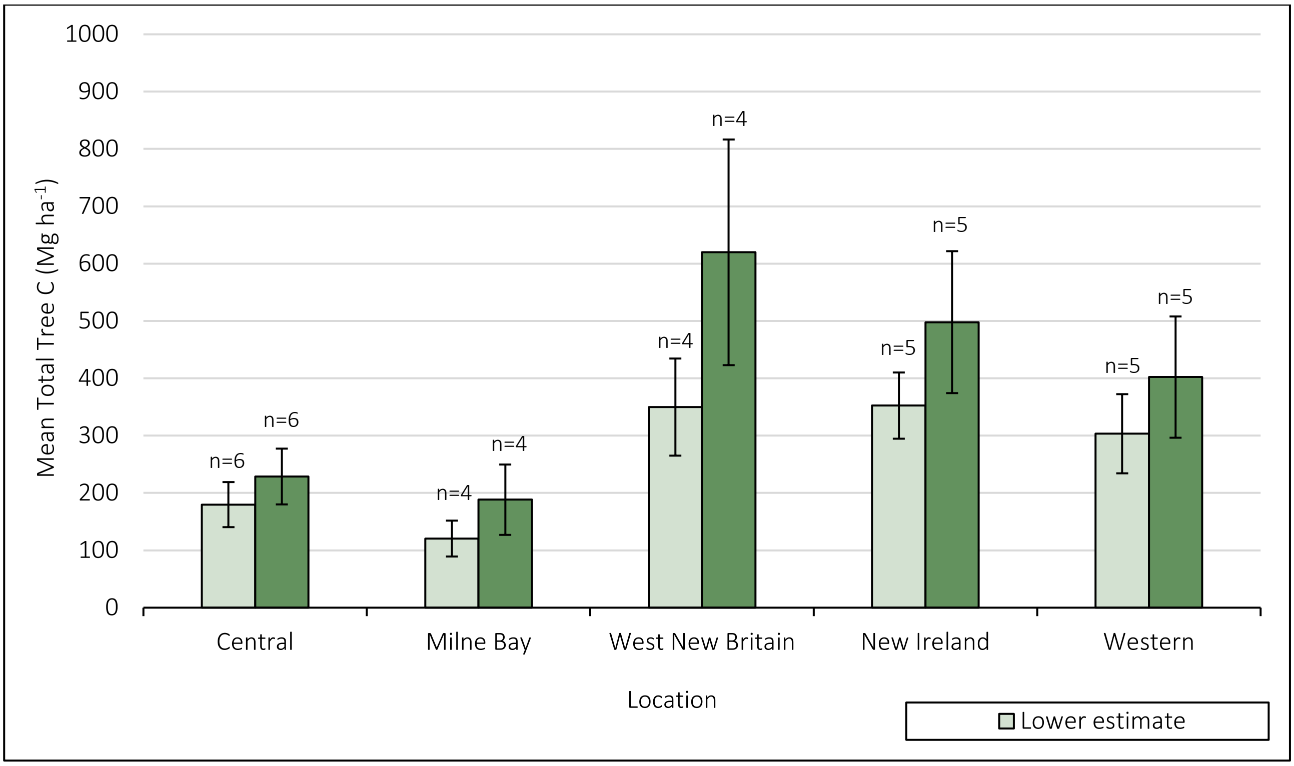

Figure 52. Mean tree carbon storage (± SE) in Papua New Guinea. New Ireland had the highest carbon storage at 352 Mg C ha^{-1}, followed by West New Britain (350 Mg C ha^{-1}), Western (303 Mg C ha^{-1}), Central (180 Mg C ha^{-1}) and Milne Bay (121 Mg C ha^{-1}). Error bars represent the standard error of the mean.

Across the five (5) survey locations in PNG, the highest mean AG tree carbon storage levels were found in New Ireland, West New Britain and Western with values of 281 ± 47 Mg C ha^{-1}, 278 ± 67 Mg C ha^{-1}, and 254 ± 61 Mg C ha^{-1}, respectively. Central and Milne Bay Provinces had significantly lower AG tree carbon storage (Figure 53). Below-ground tree carbon storage followed a similar pattern, with New Ireland, West New Britain and Western also having the highest values and Central and Milne Bay had the lowest (Figure 53).

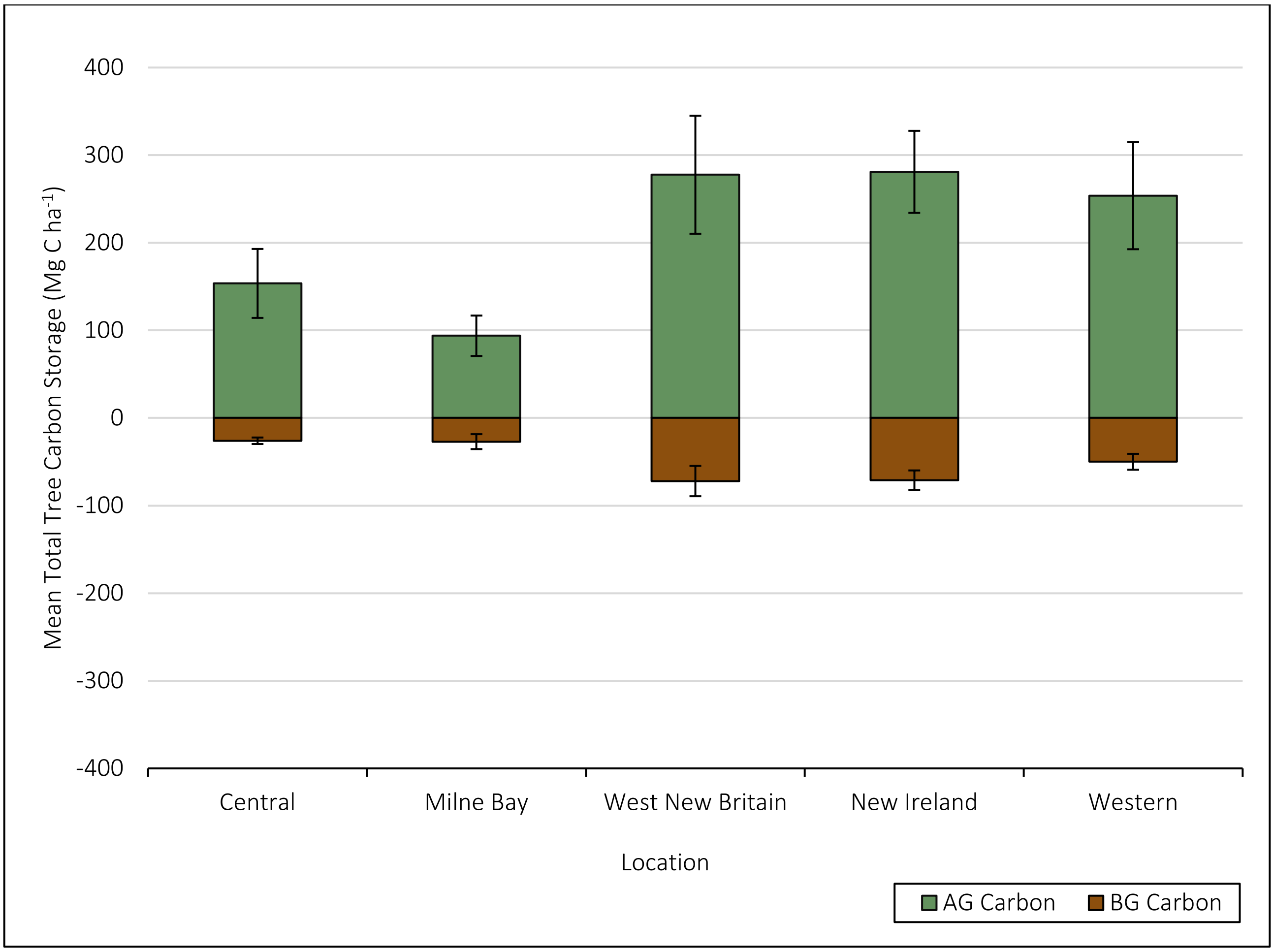

Figure 53. Above-ground (AG) and Below-ground (BG) tree carbon storage in Papua New Guinea: New Ireland had the highest AG tree carbon storage (281 Mg C ha^{-1}), followed by West New Britain (278 Mg C ha-^{1}), Western (254 Mg C ha-^{1}), Central (154 Mg C ha^{-1}) and Milne Bay (94 Mg C ha^{-1}). West New Britain had a very similar BG tree carbon storage of 72 and 71 Mg C ha^{-1}, respectively. This was followed by Western (50 Mg C ha^{-1}), Milne Bay (27 Mg C ha^{-1}) and Central (26 Mg C ha^{-1}). Error bars represent the standard error.

Total live TCS for sites assessed across PNG ranged from 52 to 544 Mg C ha^{-1}. There was significant variation in AG and BG tree carbon storage between sites at each location (Figure 54, Figure 55, Figure 56, Figure 57, and Figure 58). Higher total TCS levels were typically found in river deltas such as Paho River (Figure 58) and Dargi River (Figure 56), which were 595 and 544 Mg C ha^{-1}, respectively. The few degraded sites that were assessed were found to have relatively lower total TCS, with values ranging from approximately 51 to 172 Mg C ha^{-1}.

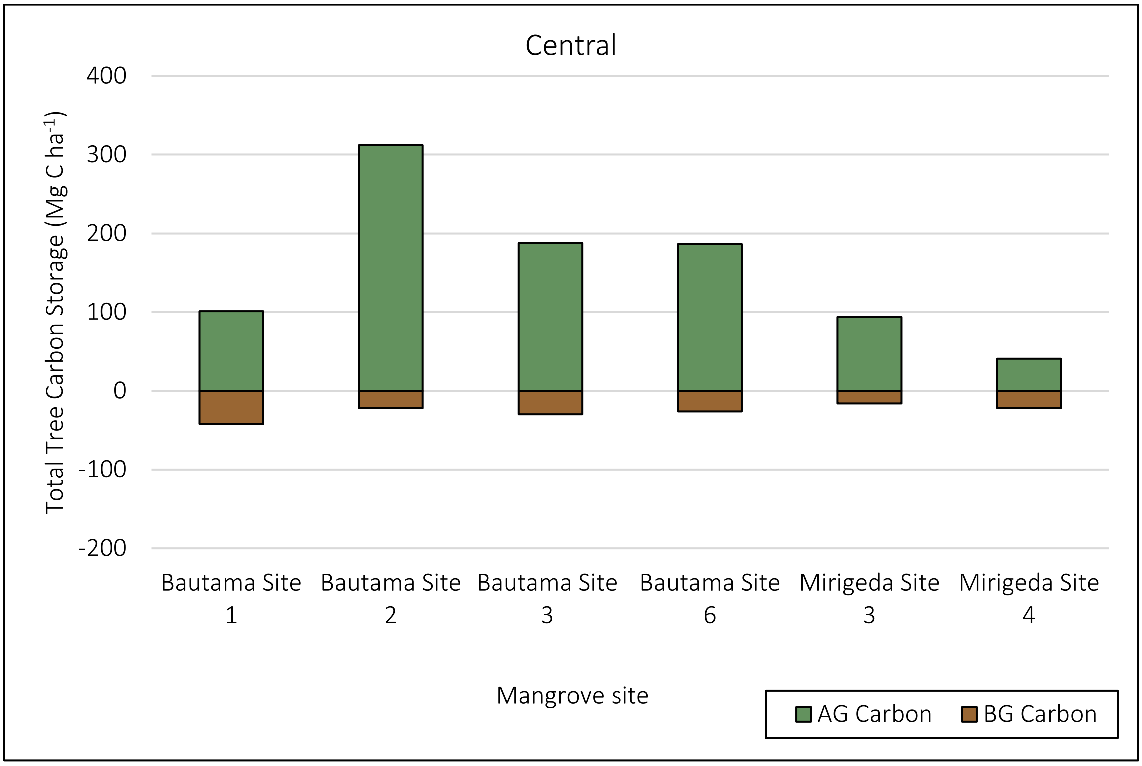

Figure 39. Above-ground (AG) and below-ground (BG) mangrove tree carbon storage at each mangrove assessment site for assessment sites in Central province. Bautama Sites 1-3 were located in the Seven Day Adventist mangrove restoration site.

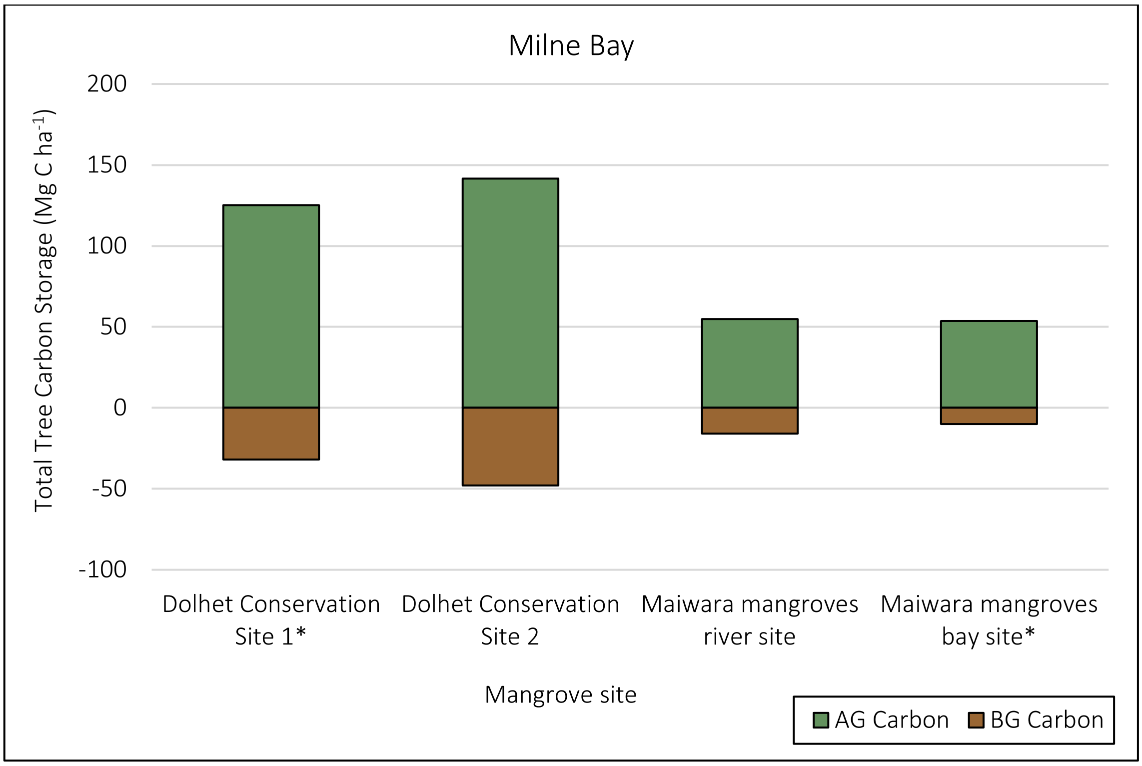

Figure 55. Above-ground (AG) and below-ground (BG) mangrove tree carbon storage at each mangrove assessment site for assessment sites in Milne Bay province. The asterisk (*) is indicative of a degraded site, these sites had current and historic wood harvesting pressures (notably a majority of Milne Bay assessment sites were exposed to wood harvesting pressures).

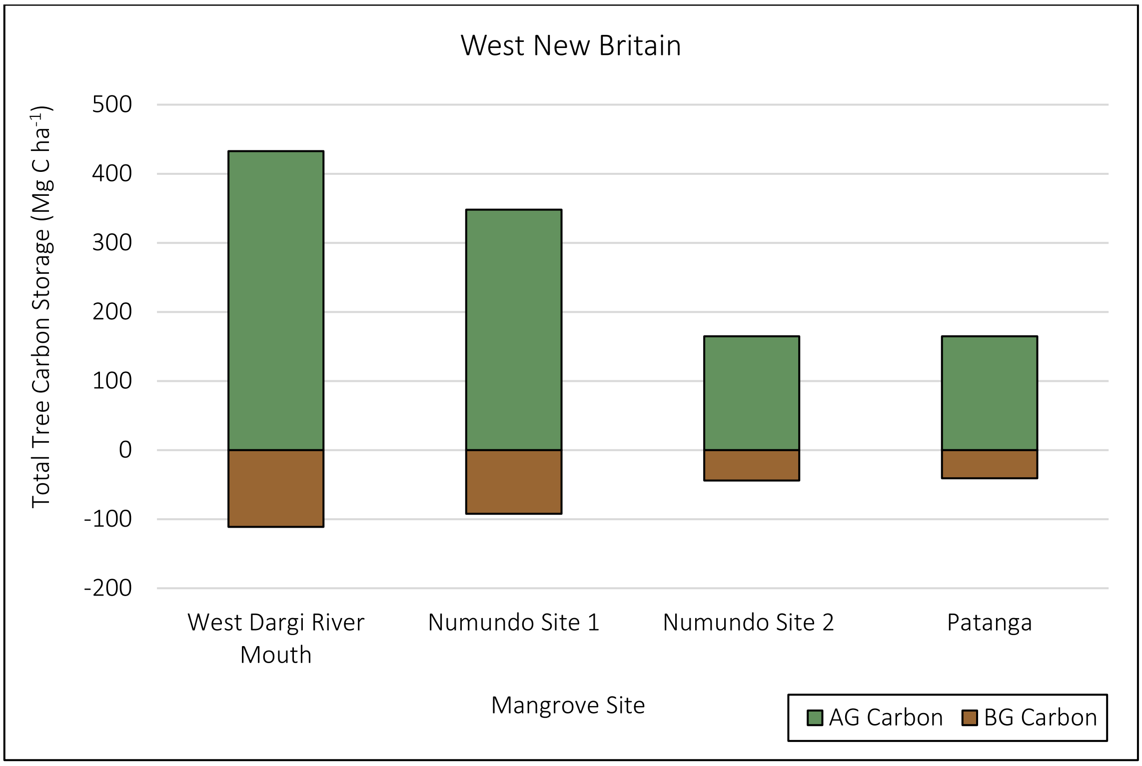

Figure 56. Above-ground (AG) and below-ground (BG) mangrove tree carbon storage at each mangrove assessment site for assessment sites in West New Britain province.

Figure 57. Above-ground (AG) and below-ground (BG) mangrove tree carbon storage at each mangrove assessment site for assessment sites in New Ireland province. The asterisk (*) is indicative of a degraded site, it was cleared of most mangrove trees in 2023 for a road development that didn't go ahead, this site was associated with the lowest carbon levels for this location.

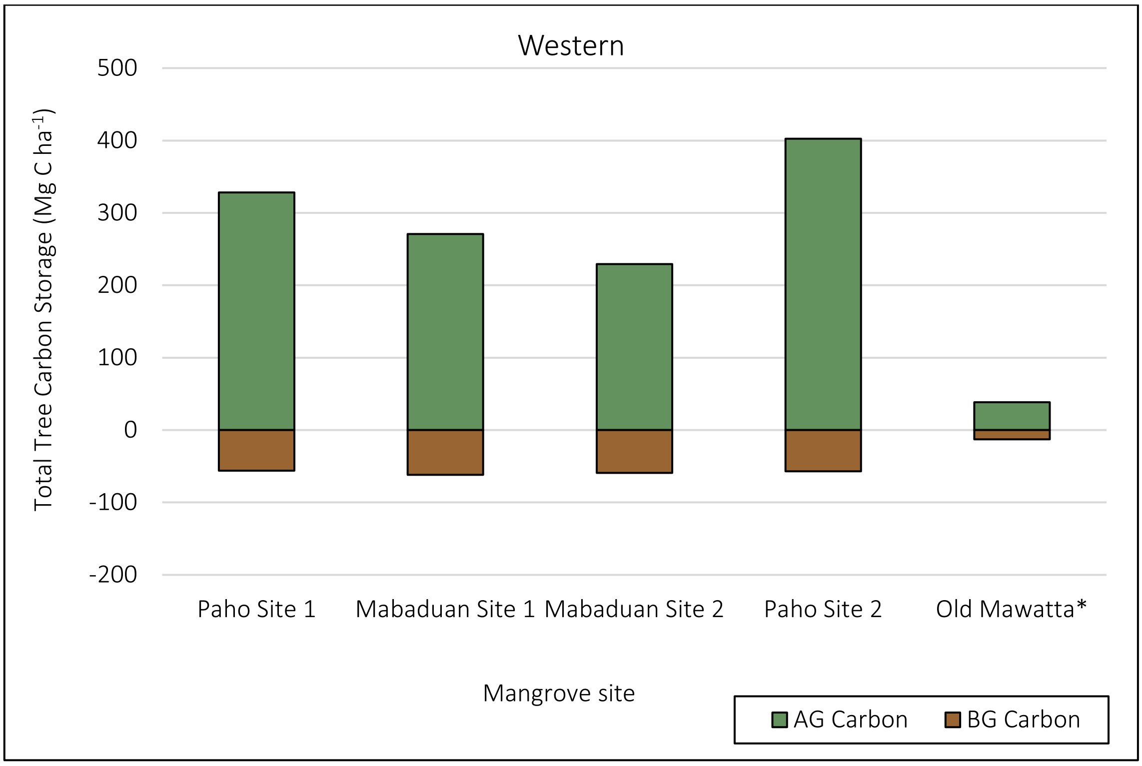

Figure 58. Above-ground (AG) and below-ground (BG) mangrove tree carbon storage at each mangrove assessment site for assessment sites in Western province. The asterisk (*) is indicative of a degraded site, it was significantly degraded to due to pressures associated with adjacent palm oil plantation and erosion, this site had the lowest carbon levels for this location.

5.3.3 Soil organic carbon

Mangrove soil organic carbon (SOC) sampling in PNG represents the first meter of the sediment profile at most sites and were calculated in megagrams of carbon per hectare (Mg C ha^{-1}) and compared across locations (Figure 59). However, due to field constraints and challenging conditions at some locations, obtaining deeper samples was not always possible, therefore, the results from those sites represent only the top 50 cm or less of the soil profile. Sampling depths at each site are represented between Figure 60 and Figure 64.

At the location level, total SOC varied across the five (5) study locations in PNG, reflecting differences in soil properties and organic matter inputs. Among these locations, New Ireland had the highest total SOC at 434 Mg C ha^{-1}, followed by Central with 386 Mg C ha^{-1}, and Milne Bay with 344 Mg C ha^{-1}. Total SOC was found to be slightly lower in the Western Province (333 Mg C ha^{-1}) and West New Britain (331 Mg C ha^{-1}). These differences suggest spatial variability in carbon storage potential, possibly influenced by site-specific factors such as mangrove species, land use history, and soil texture. The higher SOC stock observed in New Ireland and Central Provinces may indicate more favourable conditions for carbon accumulation or reduced rates of organic matter decomposition.

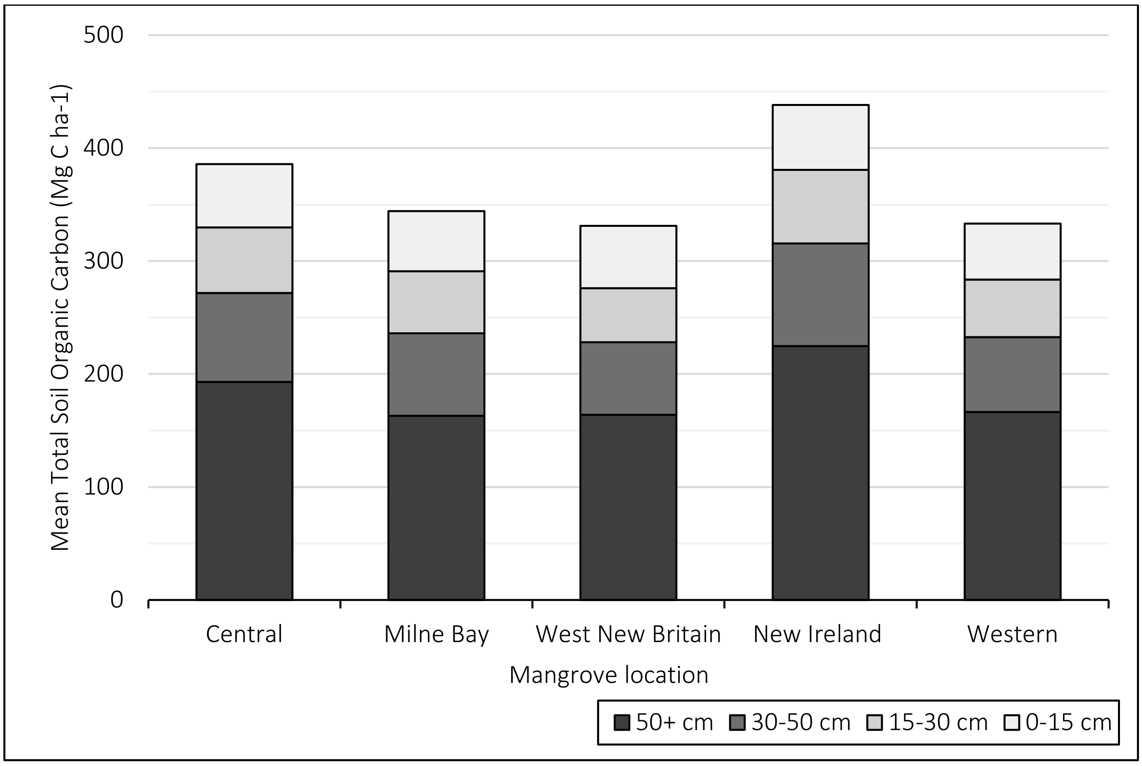

Figure 59. Mean total soil organic carbon (SOC) stocks in mangroves at different soil depths in PNG. SOC stock was highest in New Ireland (434 Mg C ha^{-1}), Central (386 Mg C ha^{-1}), and Milne Bay (344 Mg C ha^{-1}).

Across all 24 mangrove study sites in PNG, SOC ranged from 1.7 to 36.6% carbon content and approximately 105 to 476 Mg C ha^{-1}. Figure 60 to Figure 64 summarise the SOC at each mangrove study site and demonstrate the variability between sites and at different depths. Soil organic carbon varied significantly between sites, reflecting differences in soil properties and organic matter inputs. These differences suggest spatial variability in carbon storage potential, possibly influenced by site-specific factors such as mangrove species, land use history, and soil texture. Where higher SOC stocks were observed at sites, such as Sivasat in New Ireland, may indicate more favourable conditions for carbon accumulation or reduced rates of organic matter decomposition.

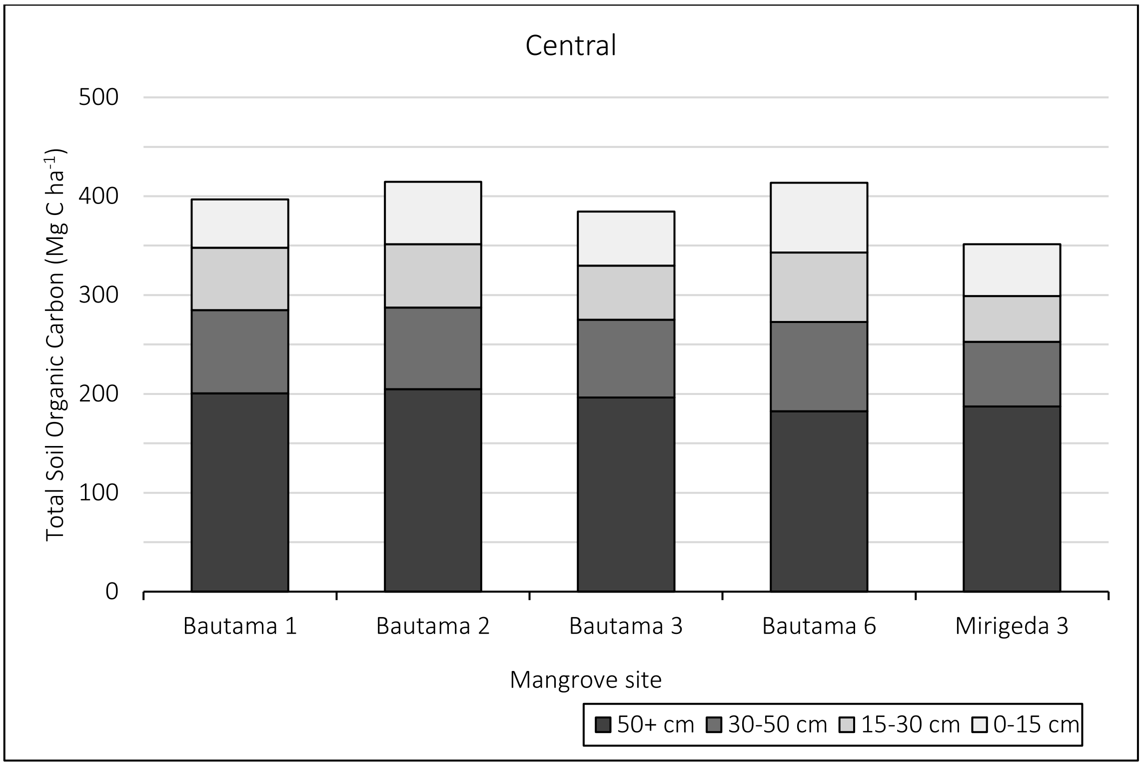

Figure 60. Mangrove soil organic carbon at the six mangrove sites at different soil depths in Central Province, Papua New Guinea. Bautama Sites 1-3 were located in the Seven Day Adventist mangrove restoration site.

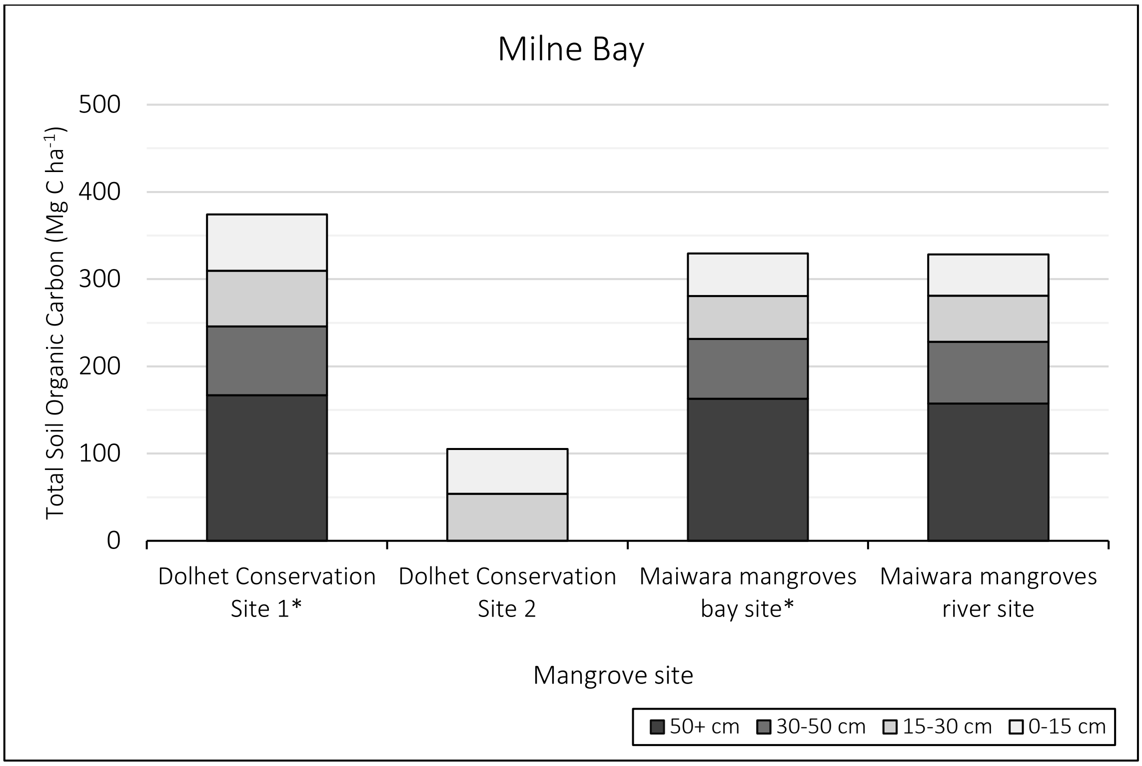

Figure 61. Mangrove soil organic carbon at the four mangrove sites at different soil depths in Milne Bay Province, Papua New Guinea. The asterisk (*) is indicative of a degraded site, these sites had current and historic wood harvesting pressures (notably a majority of Milne Bay assessment sites were exposed to wood harvesting pressures).

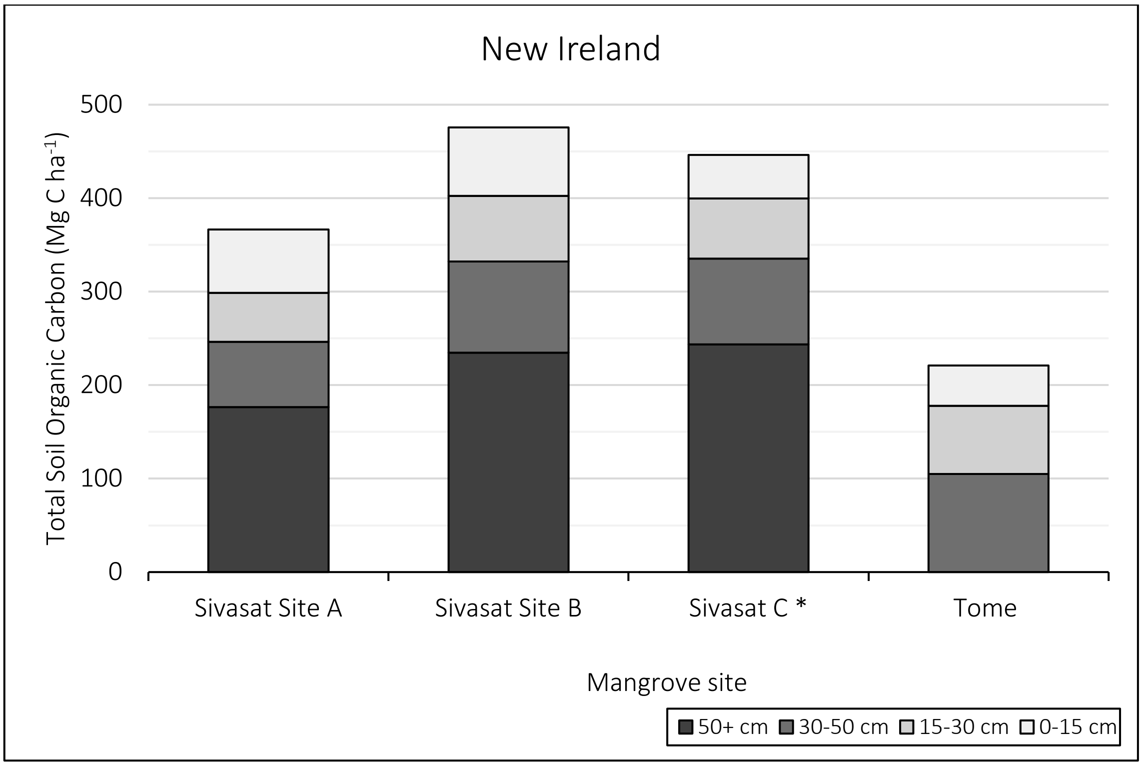

Figure 62. Mangrove soil organic carbon at the four mangrove sites at different soil depths vin New Ireland Province, Papua New Guinea. The asterisk (*) is indicative of a degraded site, it was cleared of most mangrove trees in 2023 for a road development that didn't go ahead, this site was associated with the lowest carbon levels for this location.

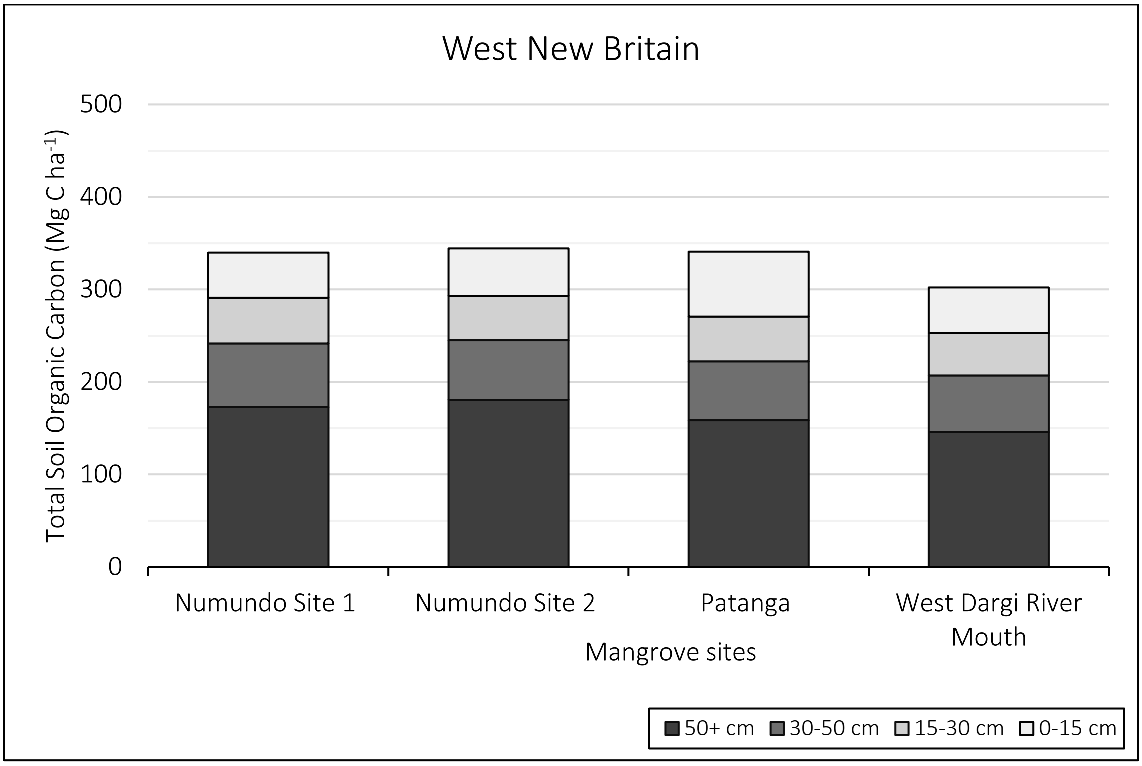

Figure 63. Mangrove soil organic carbon at the four mangrove sites at different soil depths in West New Britain Province, Papua New Guinea.

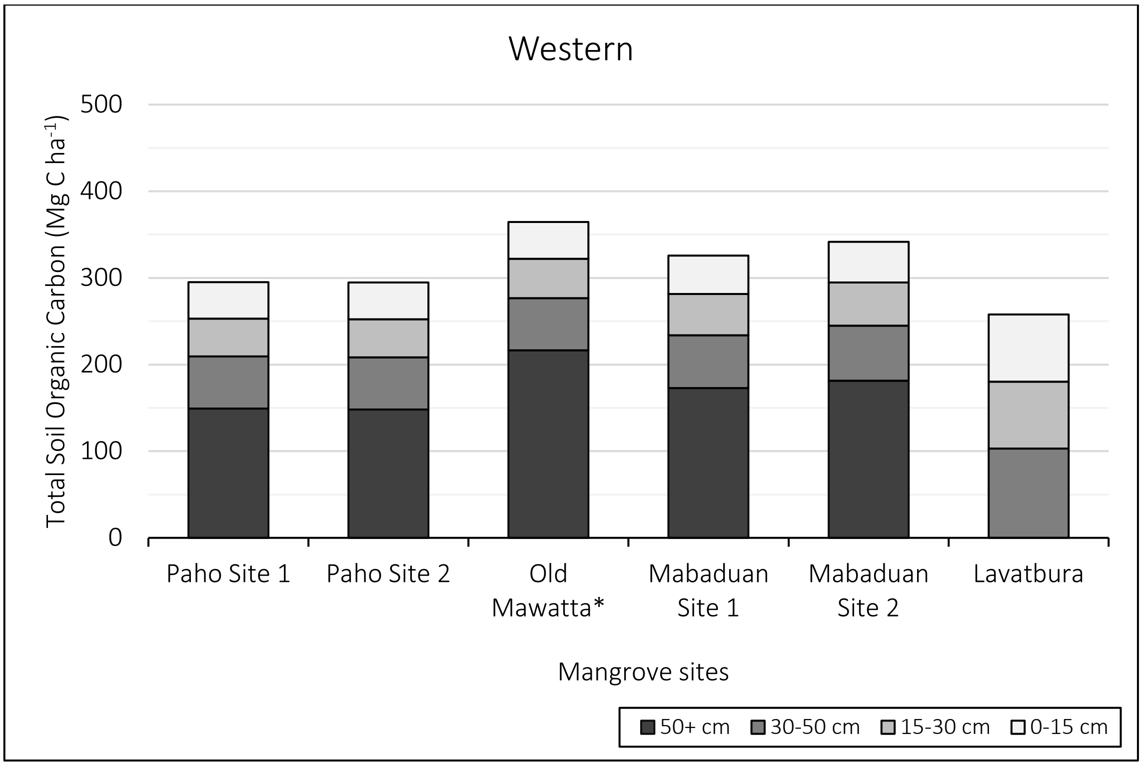

Figure 64. Mangrove soil organic carbon (Mg C ha^{-1}) at the five mangrove sites at different soil depths in Western Province, Papua New Guinea. The asterisk (*) is indicative of a degraded site, it was significantly degraded to due to pressures associated with adjacent palm oil plantation and erosion, this site had the lowest carbon levels for this location.

5.3.4 Total ecosystem carbon

Mean total ecosystem carbon stocks (TECS) varied across the five (5) study locations in PNG (Figure 65). Mean TECS were highest in New Ireland with 786 Mg C ha^{-1}, and in West New Britain with 681 Mg C ha^{-1}, and Western Province with 641 Mg C ha^{-1}. Comparatively, Central and Milne Bay Provinces had relatively lower mean TECS of 566 and 467 Mg C ha^{-1}, respectively. For all study locations, except West New Britain, soil organic carbon (SOC) was the greatest contributor to TECS.

New Ireland had the highest mean TECS (786 Mg C ha^{-1}), with SOC being the largest carbon pool, contributing 434 Mg C ha^{-1} and accounting for approximately 55% of the TECS. Living trees were the next largest contributor making up approximately 45% of TECS, with above-ground tree carbon storage (TCS) contributing 281 Mg C ha^{-1} and below-ground TCS contributing 71 Mg C ha^{-1}. Dead trees contributed negligible amounts to TECs at this location (Figure 65).

Sites in the West New Britain Province also had high mean TECS, approximately 681 Mg C ha^{-1}. Unlike other locations, living trees were the most dominant carbon pool, accounting for approximately 51% of TECS, with 278 Mg C ha^{-1} coming from above-ground TCS and 72 Mg C ha^{-1} from below-ground TCS. Dead trees made insignificant contributions to TECs at this location (Figure 65).

Sites across the Western Province had a mean TECS of approximately 641 Mg C ha^{-1}. Soil organic carbon again dominated (333 Mg C ha^{-1}), followed by TCS from both above-ground (254 Mg C ha^{-1}) and below-ground (50 Mg C ha^{-1}). Dead trees contributed only a small fraction (Figure 65).

Central Province had relatively lower mean TECS of approximately 556 Mg C ha^{-1}, with the majority of carbon contributed by SOC (386 Mg C ha^{-1}). Smaller contributions came from living trees, both above-ground (154 Mg C ha^{-1}) and below-ground (26 Mg C ha^{-1}), with minor inputs from dead trees (Figure 65).

Milne Bay also had relatively lower mean TECS, approximately 467 Mg C ha^{-1}. Soil organic carbon was the greatest contributor, accounting for as much as 74% of TECS at 344 Mg C ha^{-1}, which was a notably higher percent contribution than any other study location. This was followed by above-ground live TCS (94 Mg C ha^{-1}) and below-ground live TCS (27 Mg C ha^{-1}). Dead TCS contributed only a small fraction (Figure 65).

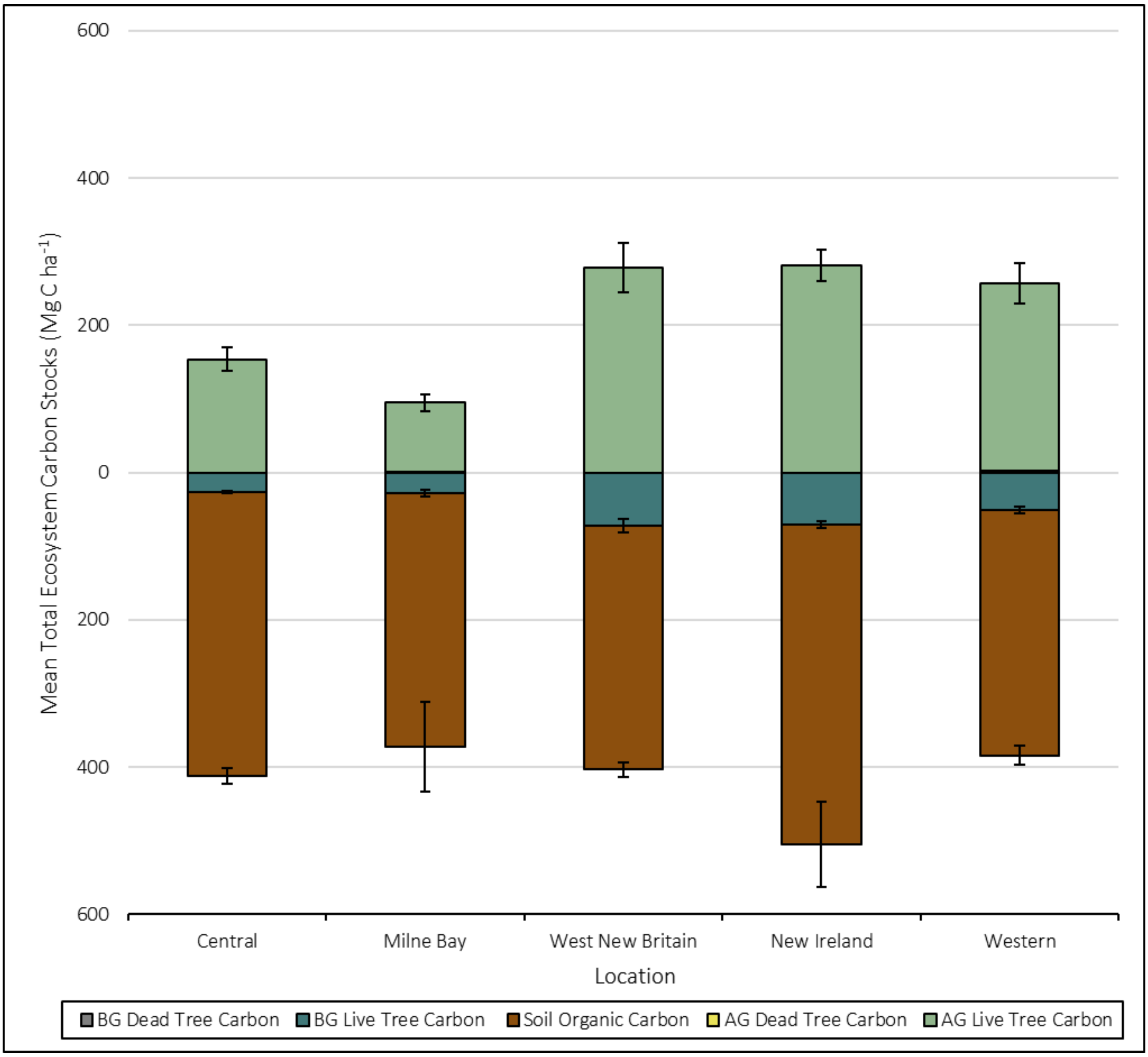

Figure 65. Mean total ecosystem carbon stocks (TECS) across five locations in Papua New Guinea, partitioned by carbon pools: soil organic carbon, above-ground (AG) and below-ground (BG) live tree carbon, and dead tree carbon. Soil organic carbon was individually the largest carbon pool across most study locations, followed by live trees. Mean TECS were relatively higher in New Ireland, West New Britain and Western Provinces, and relatively lower in Central and Milne Bay Provinces. Error bars represent the standard error of the mean.

5.4 Summary

The Seagrass and Mangrove (SaM) ecosystems of PNG provide essential services like biodiversity enhancement, coastal protection, carbon sequestration, food production, as well as sources of firewood and construction materials. This study represents the largest field-based carbon assessment for PNG, covering 24 mangrove sites and 17 seagrass sites, across locations including Central, Milne Bay, Western, New Ireland and West New Britain provinces.

Mangrove forests in PNG have been estimated to contain the largest carbon stocks globally, with above-ground carbon stocks totalling approximately 574.3 Tg (equivalent to about 1,042.4 Mg C ha^{-1}) and below-ground stocks of 114.0 Tg (around 206.9 Mg C ha^{-1})[41]. Consequently, they are considered a significant component of global carbon regulation.

Although no prior field-based carbon stock assessments exist for Papua New Guinea's SaM ecosystems to allow for direct comparison, the results of this study support the broader body of literature suggesting that SaM ecosystems in PNG represent significant carbon sinks. Consistent with the blue carbon literature, highest carbon stocks were typically found associated with riverine and deltaic mangroves systems (i.e. Paho River, Dargi River, Maiwara River).

Key findings:

Seagrass ecosystems

- Across study locations, SOC in surface layers (0-15 cm) ranged from 41 to 50 Mg C ha^{-1}. Sampling to depths greater than 15 cm was challenging, except at sites in West New Britain Province, which limited our ability to capture the full vertical profile of SOC. This limitation likely results in an underestimation of total carbon stocks, as deeper sediment layers in seagrass meadows may store additional carbon. However, the limited deeper samples collected showed similar variability to surface layers. Past studies of seagrass ecosystems from Fiji[42], Indonesia[43] and Palau[44] found levels ranging from 0.32 to 65.8 Mg C ha^{-1}, as such these results are within an expected range for island nations in Melanesia.
- Across all PNG study sites and depths (up to 1 m), SOC stocks ranged from 42 to 338 Mg C ha^{-1}. These values are substantially higher than those reported for seagrass sediments to 1 m in Indonesia[45] 0.32 to 65.8 Mg C ha^{-1} and are more comparable to values reported to 1 m in Singapore[46] (138 Mg C ha^{-1}) and to 2.4 m in sub-tropical Australia[47] (365 Mg C ha^{-1}).
- The elevated SOC levels in our findings may reflect methodological differences, but also the high species diversity and structural complexity of PNG's seagrass meadows. Four species—E*nhalus acoroides, Cymodocea rotundata, Halodule pinifolia/uninervis, and Halophila ovalis/Halophila minor*—were consistently observed, along with *E. acoroides* present at 80% of sites.

[41] Simard, M., Fatoyinbo, L., Smetanka, C., Rivera-Monroy, V.H., Casta˜neda-Moya, E., Thomas, N., Van der Stocken, T., 2019. Mangrove canopy height globally related to precipitation, temperature and cyclone frequency. Nat. Geosci. 12 (1), 40–45.
[42] Singh, S., Lal, M. M., Southgate, P. C., Wairiu, M., & Singh, A. (2022). Blue carbon storage in Fijian seagrass meadows: First insights into carbon, nitrogen and phosphorus content from a tropical southwest Pacific Island. *Marine Pollution Bulletin, 183*, Article 113432. https://doi.org/10.1016/j.marpolbul.2022.113432
[43] Stankovic, M., Mishra, A. K., Rahayu, Y. P., Lefcheck, J., Murdiyarso, D., Friess, D. A., ... & Prathep, A. (2023). Blue carbon assessments of seagrass and mangrove ecosystems in South and Southeast Asia: Current progress and knowledge gaps. *Science of the Total Environment*, *904*, 166618.
[44] Kauffman, J. B., Heider, C., Cole, T. G., Dwire, K. A., & Donato, D. C. (2011). Ecosystem carbon stocks of Micronesian mangrove forests. *Wetlands, 31*(2), 343–352. https://doi.org/10.1007/s13157-011-0148-9
[45] Stankovic, M., Mishra, A. K., Rahayu, Y. P., Lefcheck, J., Murdiyarso, D., Friess, D. A., ... & Prathep, A. (2023). Blue carbon assessments of seagrass and mangrove ecosystems in South and Southeast Asia: Current progress and knowledge gaps. *Science of the Total Environment*, *904*, 166618.
[46] Phang, V. X. H., Chou, L. M., & Friess, D. A. (2015). Ecosystem carbon stocks across a tropical intertidal habitat mosaic of mangrove forest, seagrass meadow, mudflat and sandbar. *Earth Surface Processes and Landforms, 40*(11), 1387–1400. https://doi.org/10.1002/esp.3745
[47] Brown, D. R., Conrad, S., Akkerman, K., Fairfax, S., Fredericks, J., Hanrio, E., Sanders, L. M., Scott, E., Skillington, A., Tucker, J., van Santen, M. L., & Sanders, C. J. (2016). Seagrass, mangrove and saltmarsh sedimentary carbon stocks in an urban estuary; Coffs Harbour, Australia. *Regional Studies in Marine Science, 8*, 1–6. https://doi.org/10.1016/j.rsma.2016.08.005

- Mixed-species meadows were found at 14 of 17 sites, a common feature in PNG, and are known to enhance organic matter trapping due to their dense canopy and root structures.
- Additional contributing factors include sediment characteristics, proximity to mangroves and coral reefs, and lower disturbance levels in some provinces—particularly New Ireland, which recorded the lowest threat scores.

Mangrove ecosystems

- Our field-based study found that PNG mangroves are among the most carbon-rich globally, with mean total ecosystem stocks (TECS) across locations ranging from 467 to 786 Mg C ha^{-1} (for depths <100 cm), aligning with regional estimates of 130 to 1,700 Mg C ha^{-1} depending on soil depth, forest type and location.[48]
- Highest mean TECS were found at the New Ireland (786 Mg C ha^{-1}), and West New Britain (681 Mg C ha^{-1}) study locations.
- High TECS were typically found at study sites associated with major rivers (e.g., Paho, Dargi, and Maiwara Rivers), and those dominated by high densities of *Rhizophora stylosa*.
- Across all locations, SOC was typically the dominant carbon pool, accounting for –approximately 52 to 74% of mean TECS. West New Britain was an exception where SOC and live trees carbon storage contributed nearly equal amounts to TECS at approximately 49% and 51%, respectively.
- Sites in Central and Milne Bay exhibited lower above-ground tree carbon storage but relatively high SOC. This may be attributed to the high densities of species such as *Avicennia marina*, which allocate more biomass below-ground, thereby, increasing SOC. Additionally, the disturbance history of these sites (e.g., logging) could play a role, as SOC is generally more resilient than above-ground tree carbon storage.

[48] Refer to Table 2 in the Introduction chapter for this report for a matrix comparing reported carbon levels from regional studies, including references.

SOLOMON ISLANDS

6 Solomon Island carbon assessments

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6.1 Solomon Islands study sites

Seagrass meadows and mangrove forests were surveyed across three provinces in the Solomon Islands, which included Isabel, Western, Malaita and Guadalcanal Provinces. The survey locations for both mangroves and seagrass are shown below in Figure 66, including Marovo (Western Province), Lau Lagoon (Malaita Province), and Santa Isabel and Papatura Islands (Isabel Province). A total of 19 mangrove sites and 11 seagrass sites were surveyed across a diversity of geomorphological settings in order to capture representative data for these dynamic ecosystems (Figure 66 to Figure 69).

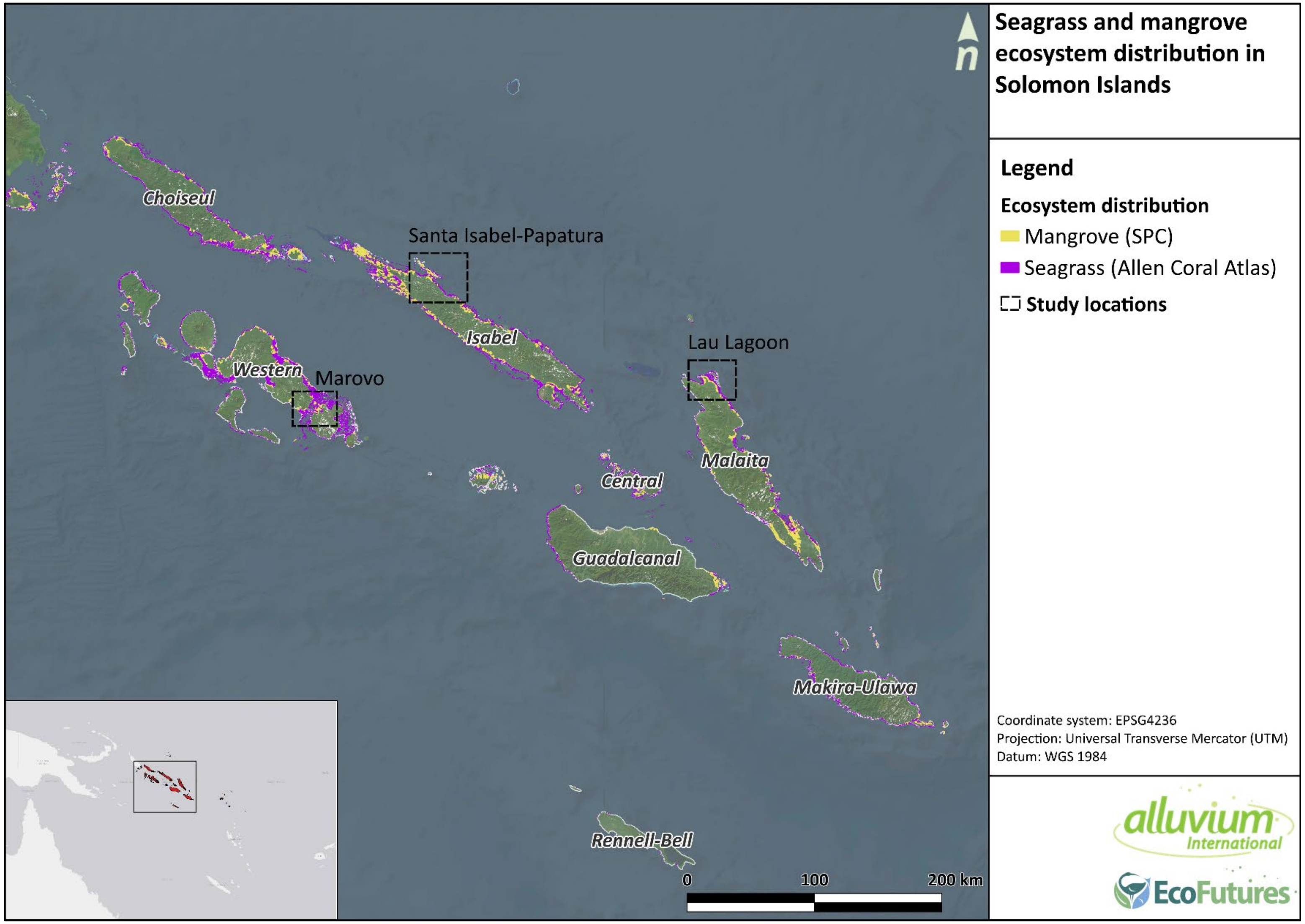

Figure 66. Seagrass and mangrove ecosystem distribution and survey locations in the Solomon Islands.

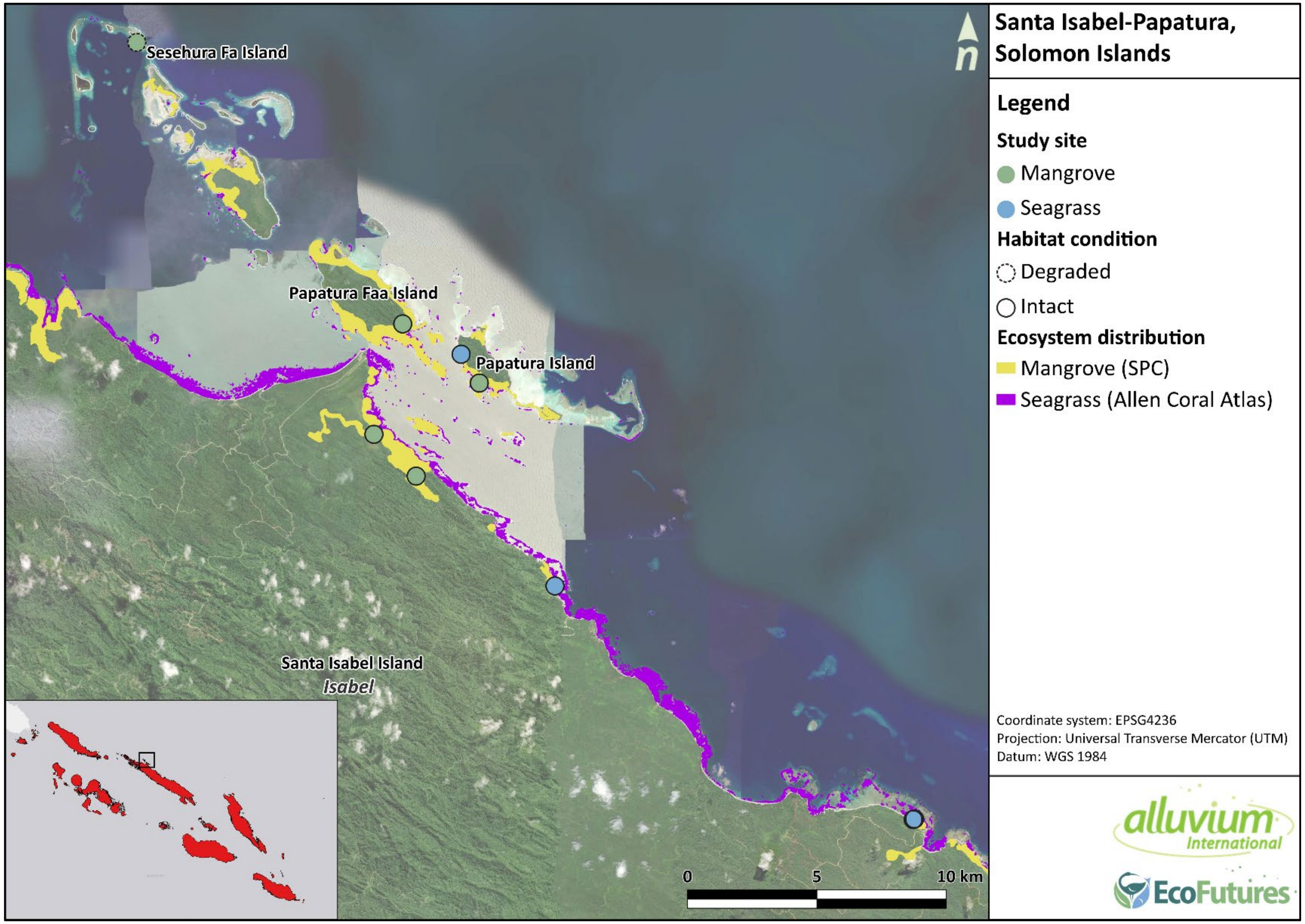

Figure 67. Seagrass and mangrove ecosystem distribution and survey sites in Santa Isabel-Papatura. At this location were one (1) degraded and four (4) intact mangrove sites and one (1) intact seagrass site.

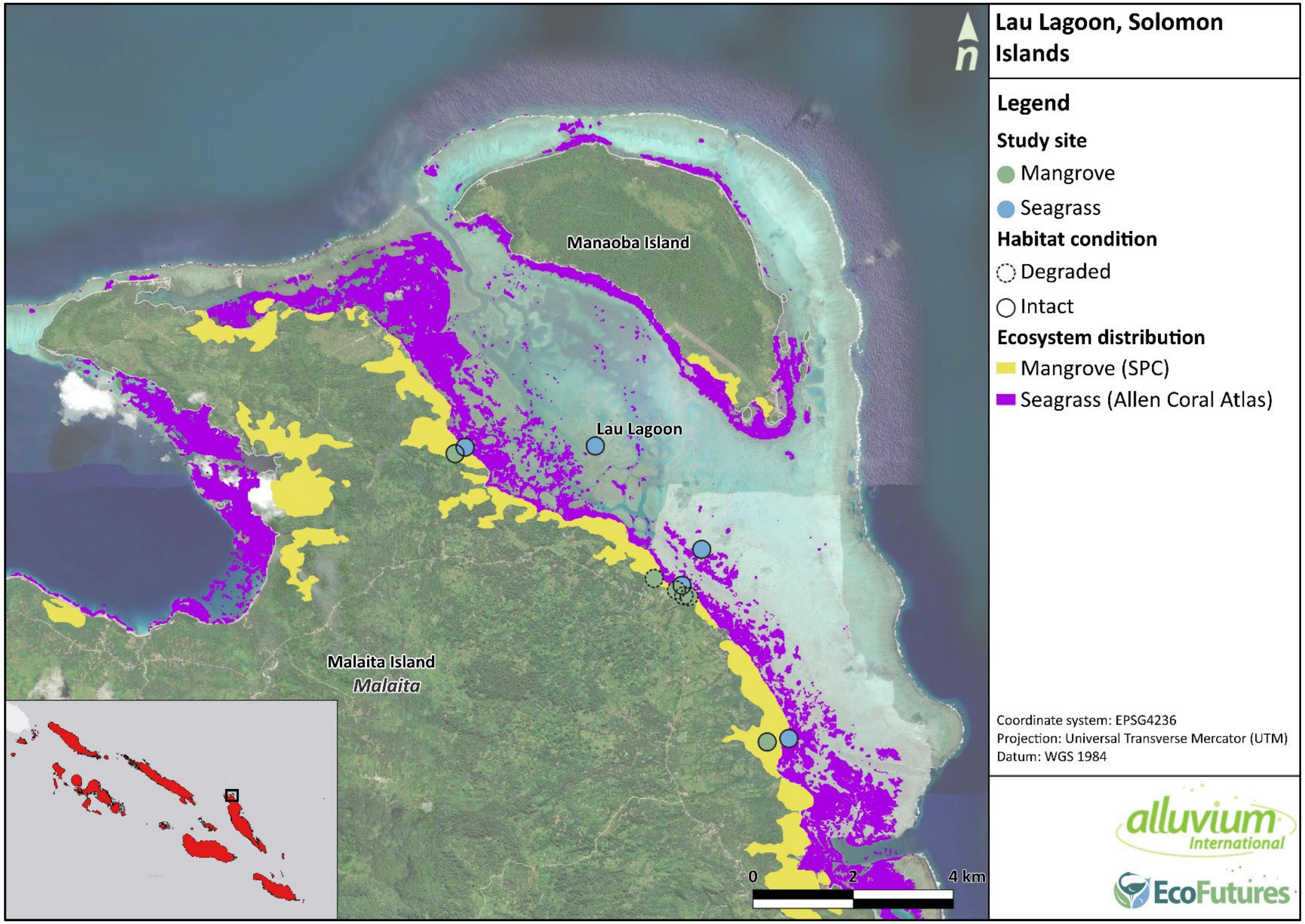

Figure 68. Seagrass and mangrove ecosystem distribution and survey sites in Lau Lagoon. At this site were five (5) intact seagrass sites and two (2) intact and four (4) degraded mangrove sites

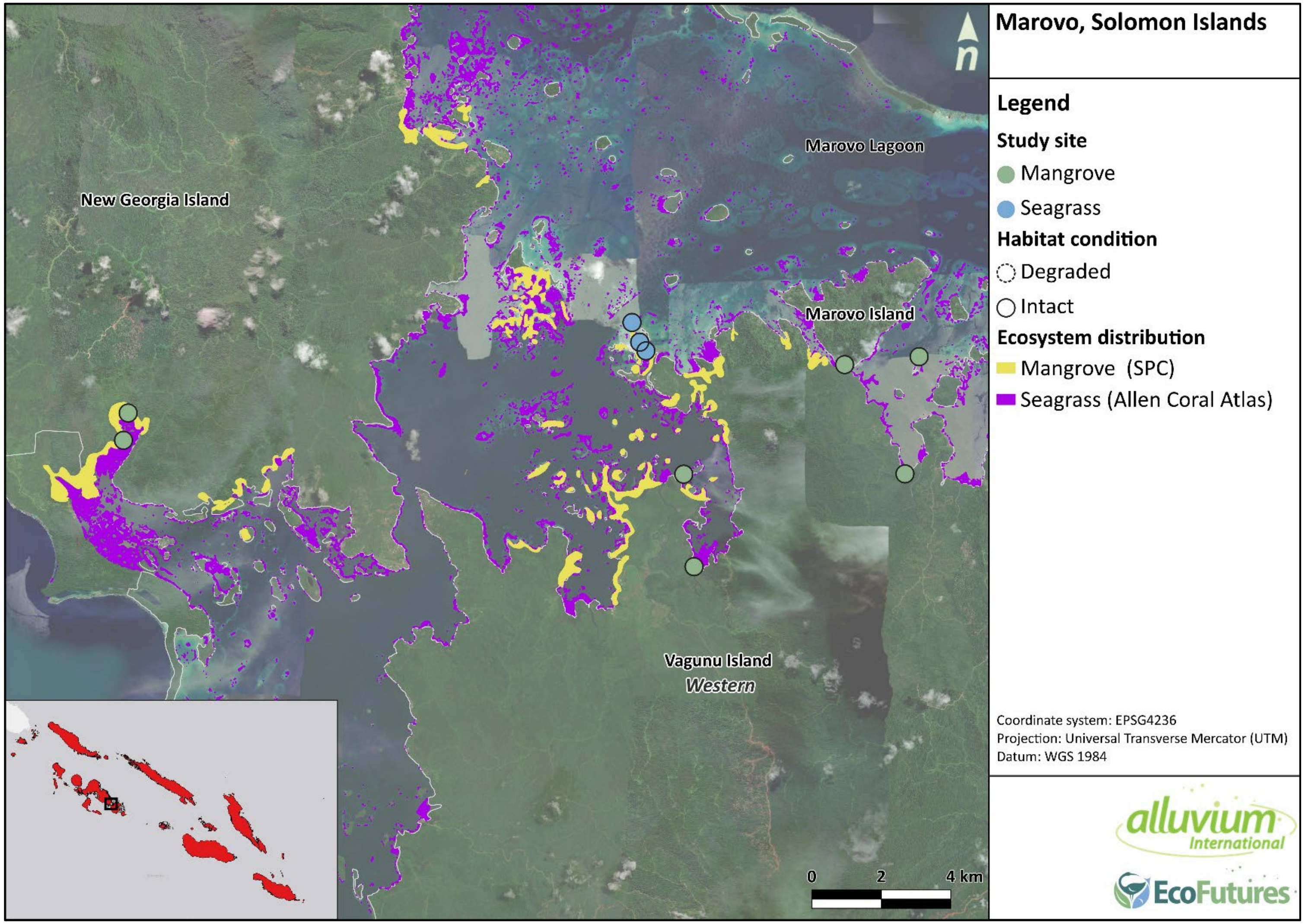

Figure 69. Seagrass and mangrove ecosystem distribution and survey sites in Marovo. At this location were three (3) intact seagrass sites and seven (7) intact mangrove sites.

6.2 Solomon Island carbon assessment results – Seagrass

This results section for seagrass ecosystems reports only soil organic carbon measurements, as this study has focused on assessing the dominant carbon pools in blue carbon systems, and above-ground (AG) and below-ground (BG) carbon is not considered a significant component of the total ecosystem carbon pool in seagrass meadows.

6.2.1 Soil organic carbon

Sampling was limited to the upper 50 cm of the sediment profile due to field constraints, with some sites only being sampled at the surface in the upper 15 cm. This is a common limitation in seagrass carbon assessments as they are typically logistically challenging environments, with inundation typically affecting the integrity of soil cores.

Across all eleven (11 sites) sampled in the Solomon Islands, Soil Organic Carbon (SOC) at seagrass sites ranged from 1.4% to 11.3%, and 42 to 182 Mg C ha^{-1}. The mean SOC content was relatively similar in seagrass sites at Marovo and Santa Isabel-Papatura with a mean of 42 Mg C ha^{-1} and 44 Mg C ha^{-1}, respectively (Figure 70). By comparison, Lau Lagoon had a significantly higher mean SOC storage, however, this was mostly related to multiple soil depths being sampled at this location as sites in Lau Lagoon had a mean SOC of approximately 51 Mg C ha^{-1} at 0-15 cm depths (Figure 70 and Figure 71). There was low variation in soil organic carbon between depth categories 0-15 cm, 15-30 cm, and 30-50 cm with relatively similar mean values at all depths, noting not all depths were sampled at all sites.

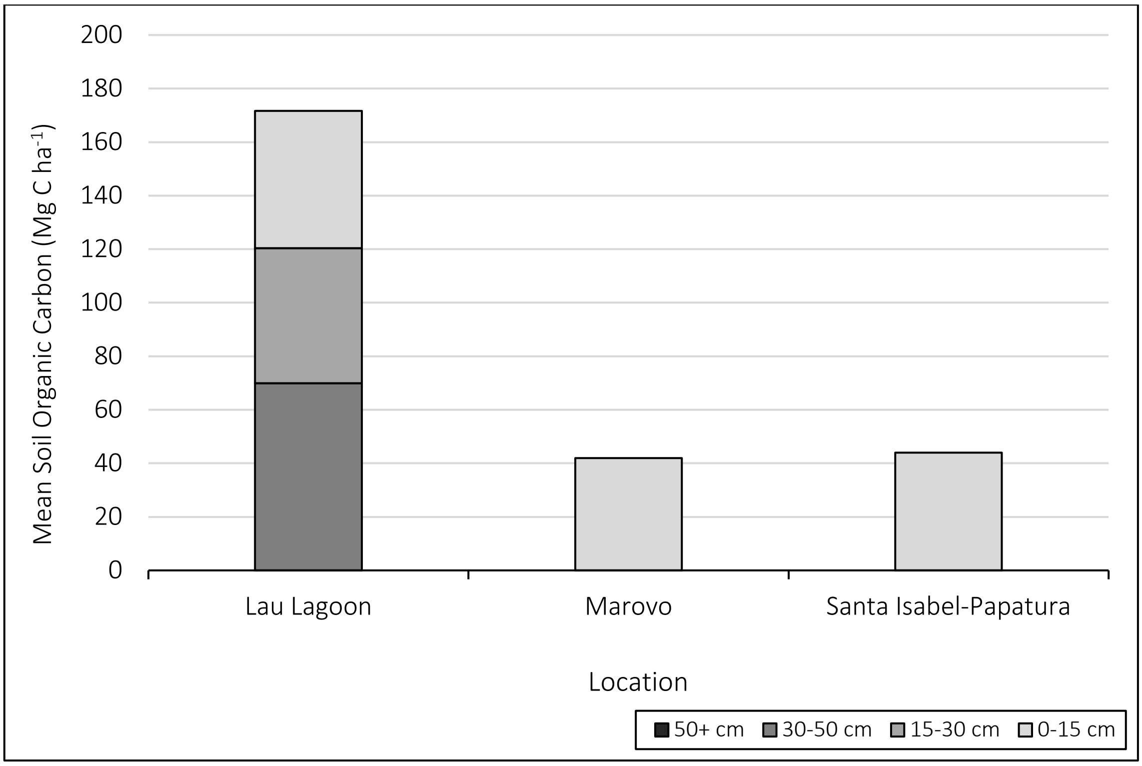

Figure 70. Mean total soil organic carbon (Mg C ha^{-1}) at different soil depths in seagrass sites in survey locations in the Solomon Islands.

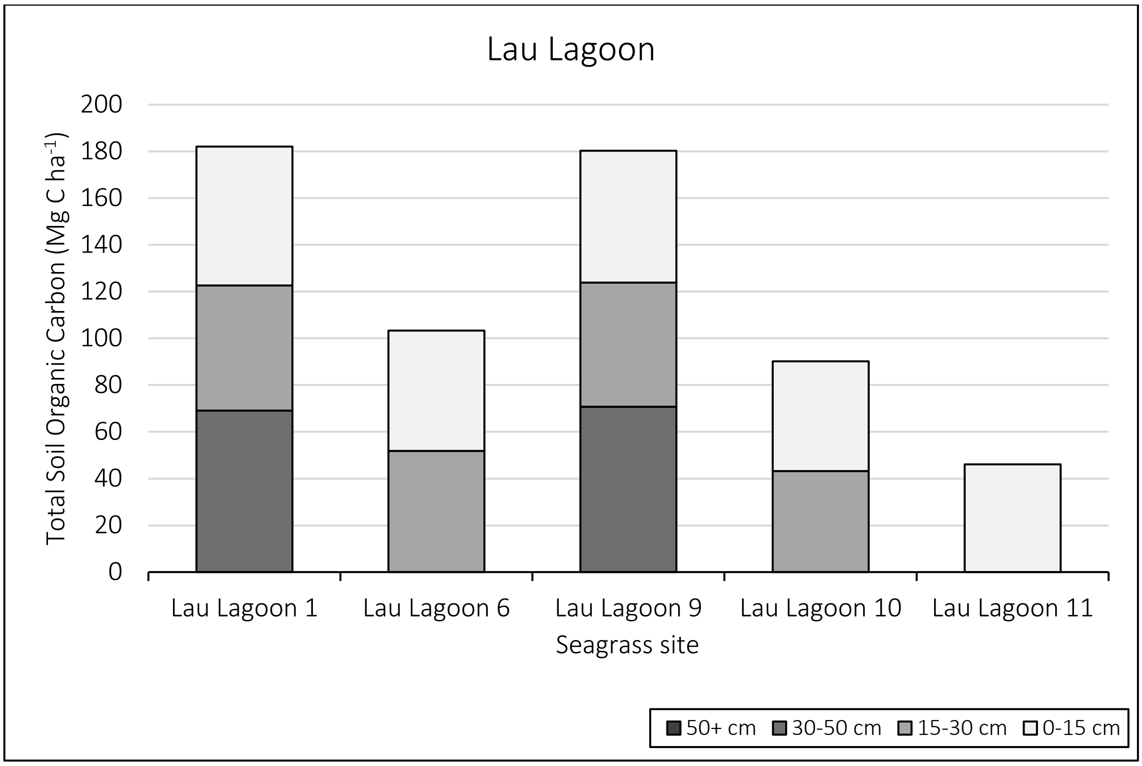

Figure 71. Seagrass soil organic carbon (Mg C ha^{-1}) at different soil depths at the five seagrass sites surveyed in Lau Lagoon in the Solomon Islands.

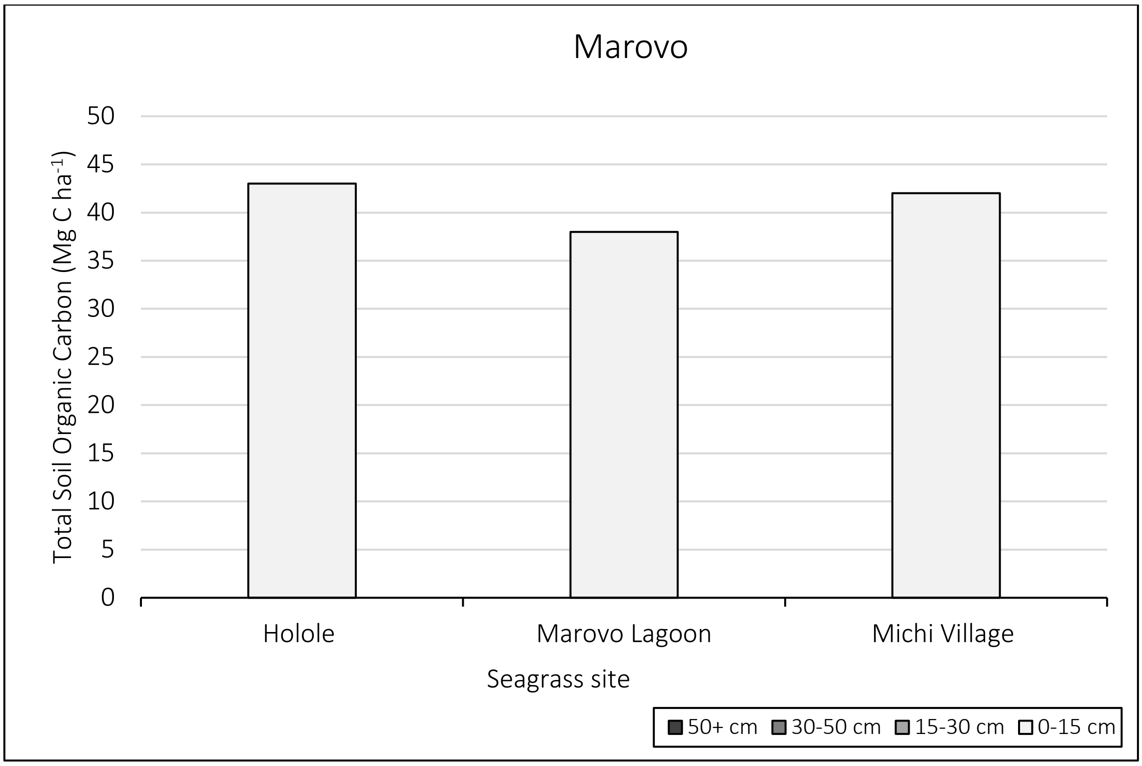

Figure 402. Seagrass soil organic carbon (Mg C ha^{-1}) at different soil depths at the three seagrass sites surveyed in Marovo in the Solomon Islands.

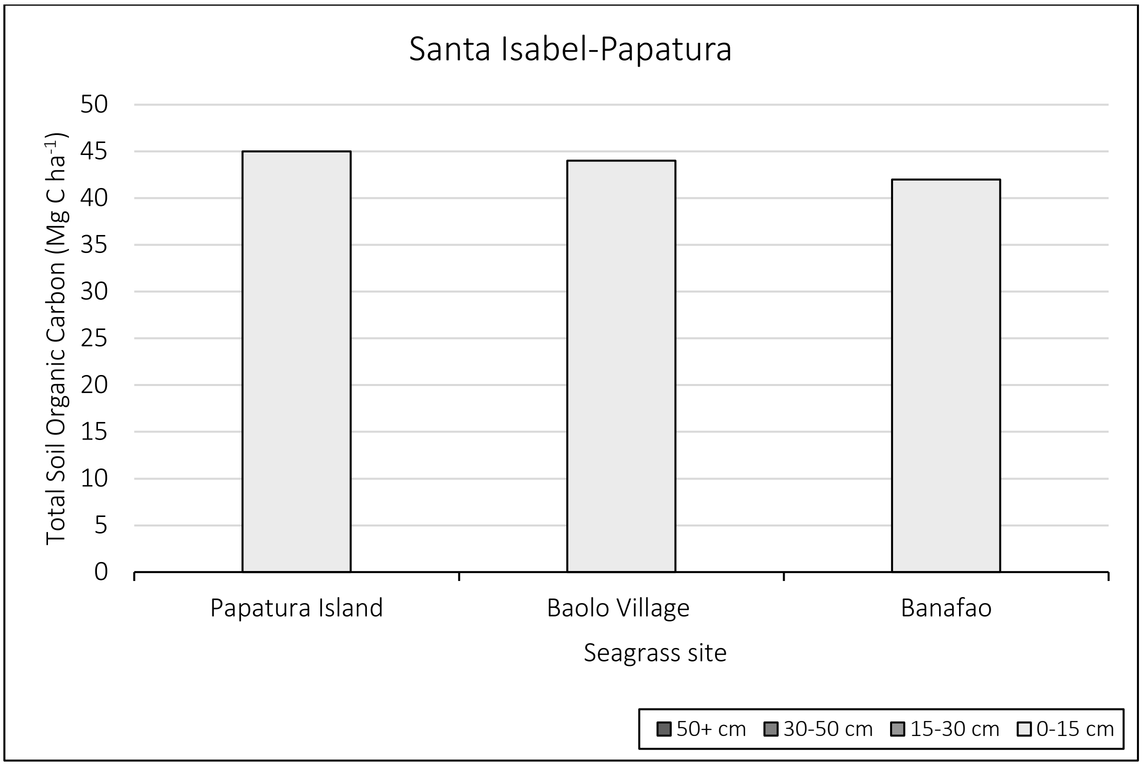

Figure 73. Seagrass soil organic carbon (Mg C ha^{-1}) at different soil depths at one seagrass site surveyed in Lau Lagoon in the Solomon Islands.

6.3 Solomon Island carbon assessment results – Mangrove

This results section for mangrove ecosystems is systematically divided into several subsections to provide a comprehensive analysis of the data. Initially, species density is examined across various locations, offering insights into the geographical distribution of species. Subsequent subsections focus on the comparative analysis of above-ground (AG) and below-ground (BG) tree carbon storage (TCS), evaluated across different locations and land use conversion categories. These comparisons help understand the spatial variations in carbon stock distribution and their implications for carbon storage and ecosystem dynamics.

6.3.1 Species Density

Across the six sites in Lau Lagoon, *Rhizophora apiculata* had the highest tree density, with 3,018 ± 508 trees ha^{-1}, followed by *Bruguiera gymnorhiza* (818 ± 125 trees ha^{-1}), *Ceriops tagal* (578 ± 362 trees ha^{-1}), *Aegiceras corniculatum* (588 trees ha^{-1}), and *Sonneratia alba* (445 ± 302 trees ha^{-1}) (Figure 74). The least dominant species at this location was *Avicennia marina*, with a density of 65 trees ha^{-1} (Figure 74). *Rhizophora apiculata* is known for its extensive root systems and high biomass, which suggests a substantial capacity for carbon sequestration at this location. Furthermore, the presence of other species like *Bruguiera gymnorhiza*, *Ceriops tagal*, *Aegiceras corniculatum*, and *Sonneratia alba* contributes to a diverse carbon pool. Different species have varying rates of carbon uptake and storage, enhancing the overall carbon sequestration potential of the ecosystem.

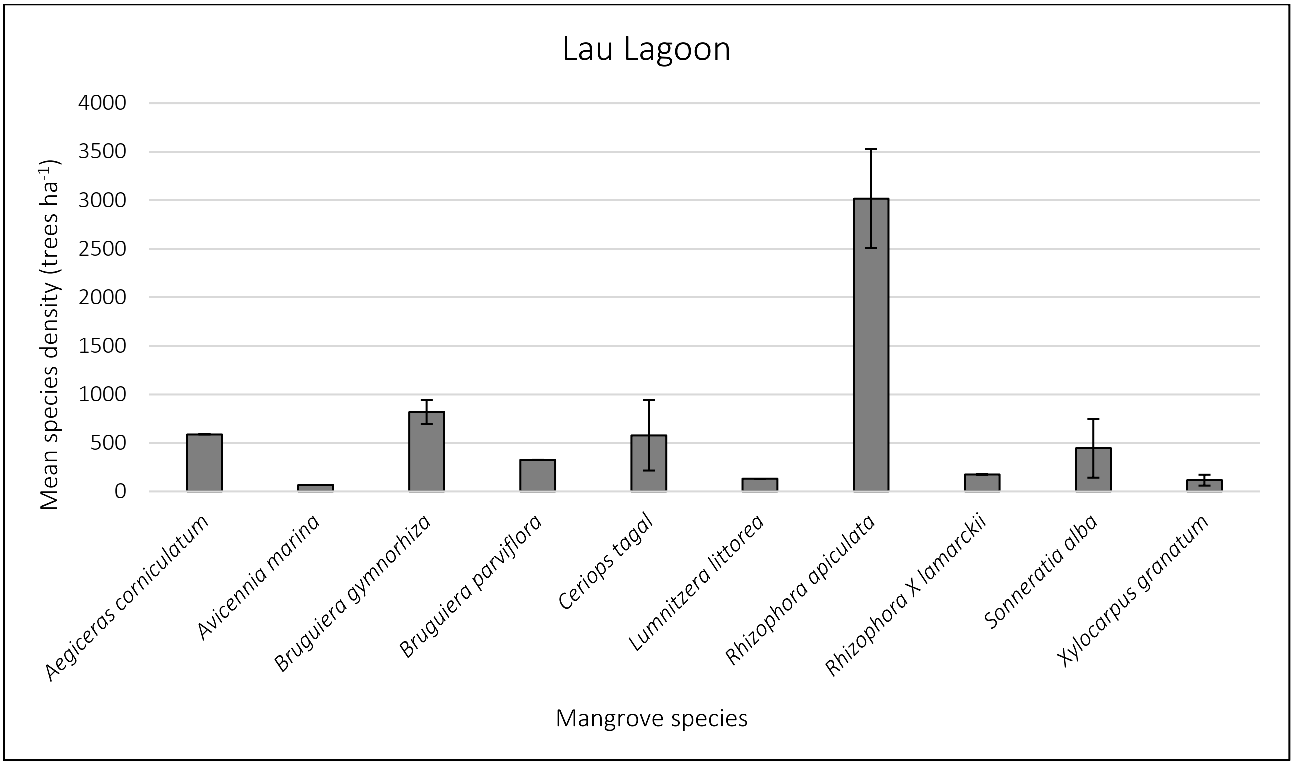

Figure 74. Bar graph showing the average density of mangrove species (± SE) in Lau Lagoon. *Rhizophora apiculata* exhibited the highest density at 3,018 trees ha^{-1}, followed by *Bruguiera gymnorhiza* (818 trees ha^{-1}), *Ceriops tagal* (578 trees ha^{-1}), *Aegiceras corniculatum* (588 trees ha^{-1}), and *Sonneratia alba* (445 trees ha^{-1}). *Avicennia marina* was the least dominant species, with a density of 65 trees ha^{-1}. Error bars represent the standard error of the mean.

Across the seven sites in Marovo, *Rhizophora stylosa* and *Scyphiphora hydrophylacae* had the highest density, with 1,518 and 970 trees ha^{-1}, respectively (Figure 75)—noting however they were only present at one site. *Rhizophora stylosa* is highly effective in carbon storage due to its extensive stilt roots and substantial above-ground biomass. These stilt roots not only stabilize the soil and prevent erosion but also trap carbon-rich sediments, while the dense above-ground biomass stores significant amounts of carbon, contributing greatly to blue carbon sequestration. This reflected in the carbon storage analysis in Section 6.3.3 of the report. *Bruguiera gymnorhiz*a had a tree density of 638 ± 57 trees ha^{-1} and *Rhizophora apiculata* had a density of 430 ± 63 trees ha^{-1}. All other species had a density < 350 trees ha^{-1}.

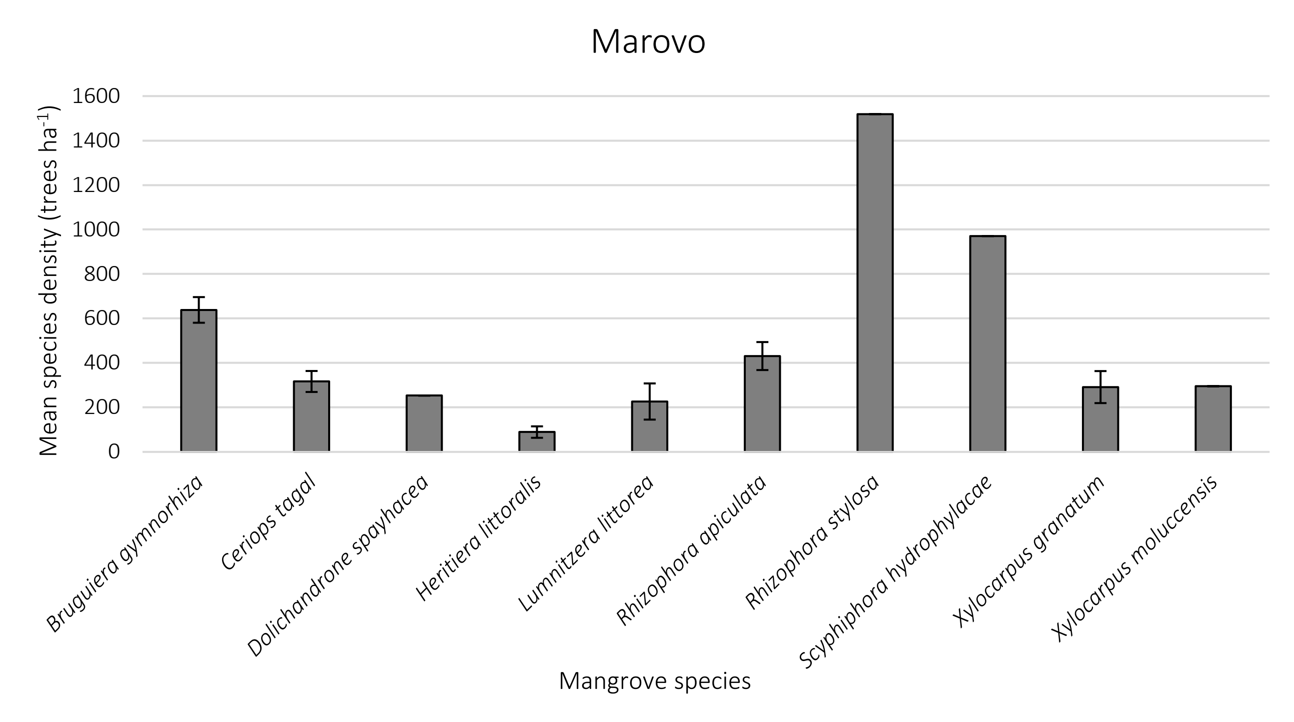

Figure 75. Bar graph showing the average density of mangrove species (± SE) in Marovo. *Rhizophora stylosa* (1518 trees ha^{-1}) and *Scyphiphora hydrophylacea* (970 trees ha^{-1}) had the highest densities. *Bruguiera gymnorhiza* had 638 trees ha^{-1}, and *Rhizophora apiculata* had 430 trees ha^{-1}. Other species had densities below 350 trees ha^{-1}. Error bars represent the standard error of the mean.

At the four sites assessed in the location Santa Isabel-Papatura, *Ceriops tagal* and *Rhizophora apiculata* were the most dominant species, with a density of 1,708 ± 241 trees ha^{-1} and 1,530 ± 246 trees ha^{-1}, respectively (Figure 76). Both species are significant contributors to blue carbon storage; however, *Rhizophora apiculata* is known to store more carbon due to its greater biomass and extensive root systems. *Rhizophora apiculata* is commonly found in Southeast Asia and the Pacific Islands, where it plays a crucial role in stabilising shorelines and sequestering carbon in both its biomass and the soil. *Ceriops tagal* is similarly effective in carbon storage, particularly in soil carbon sequestration, due to its robust root systems. This species is prevalent in tropical and subtropical regions and contributes greatly to the overall carbon storage capacity of mangrove ecosystems. Both *Lumnitzera littorea* and *Bruguiera hainesii* also had high species densities of 852 ± 358 trees ha^{-1} and 845 ± 102 trees ha^{-1}, respectively (Figure 76). Notably, *Bruguiera hainesii* is of conservation significance and is listed as Critically Endangered by the IUCN; it is only found in isolated locations, including the Solomon Islands.

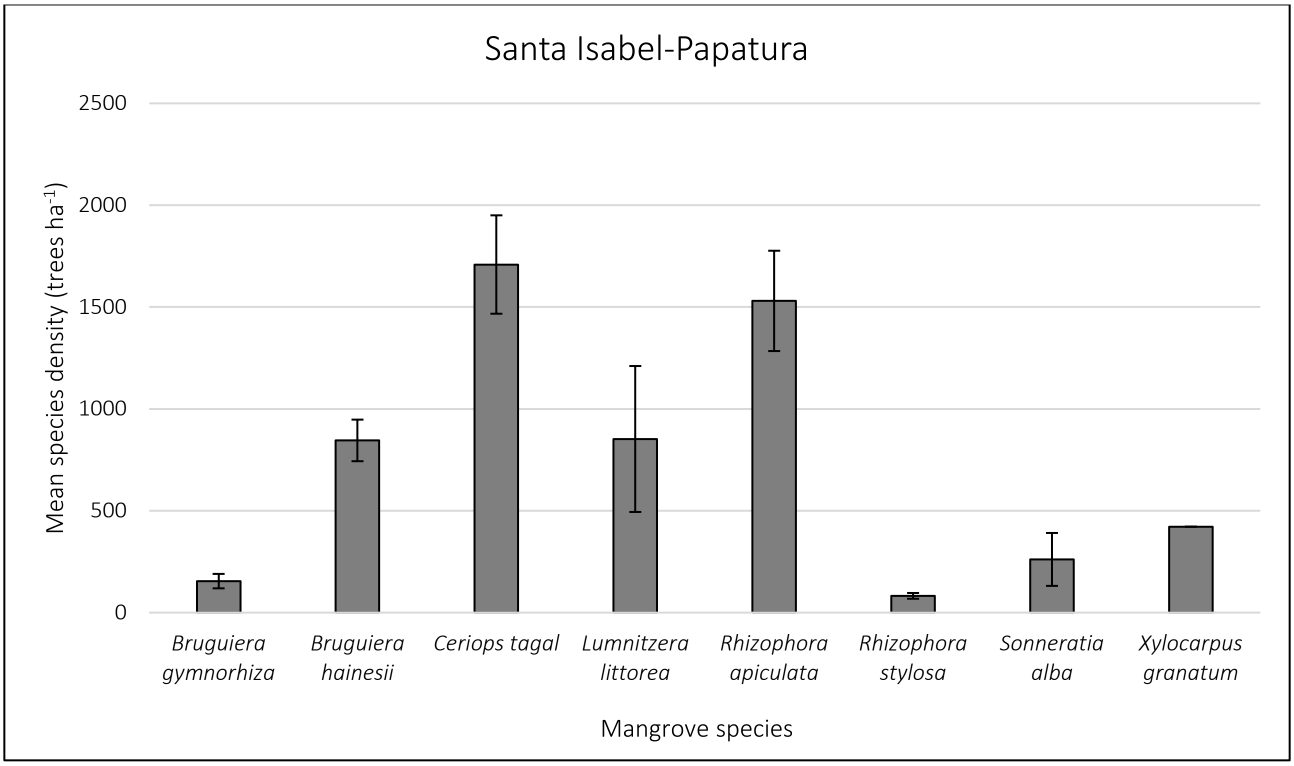

Figure 76. Bar graph showing the average density of mangrove species (± SE) in Santa Isabel-Papatura. *Ceriops tagal* had the highest density at 1708 trees ha^{-1}, as well as *Rhizophora apiculata* at 1530 trees ha^{-1}. *Bruguiera hainesii* had a density of 845 trees ha^{-1}, and *Lumnitzera littorea* had 852 trees ha^{-1}. All other species had densities below 450 trees ha^{-1}. Error bars represent the standard error of the mean.

6.3.2 Above-ground and below-ground tree carbon storage

Tree carbon storage (TCS) refers to the amount of carbon stored within trees, which can be stored above-ground (in their trunks, stems, foliage, aerial roots and prop roots) and below-ground (in their roots). Total TCS refers to the sum of the carbon stored in trees both above-ground (AG) and below-ground (BG).

Figure 77. Illustration of total tree carbon storage stored in trees both above and below-ground.

Upper and lower estimates for total TCS were calculated for each site across Solomon Islands and compared between locations (Figure 78). In this section, we report the lower estimates unless otherwise stated. Total live TCS for sites assessed across Solomon Islands ranged from 9 Mg C ha^{-1} to 1,065 Mg C ha^{-1}.

When comparing across different locations, mangroves in Marovo resulted with the highest TCS, with a mean total TCS (mean ± standard error) of 564 ± 43 Mg C ha^{-1}. The highest TCS at this location is likely related to both species composition (with a high density of *Rhizophora stylosa* present) and ecosystem health. This was followed by Santa Isabel-Papatura, which had a mean total TCS of 418 ± 28 Mg C ha^{-1} (Figure 78), and Lau Lagoon which had a mean total TCS of 310 ± 53 Mg C ha^{-1}(Figure 78).

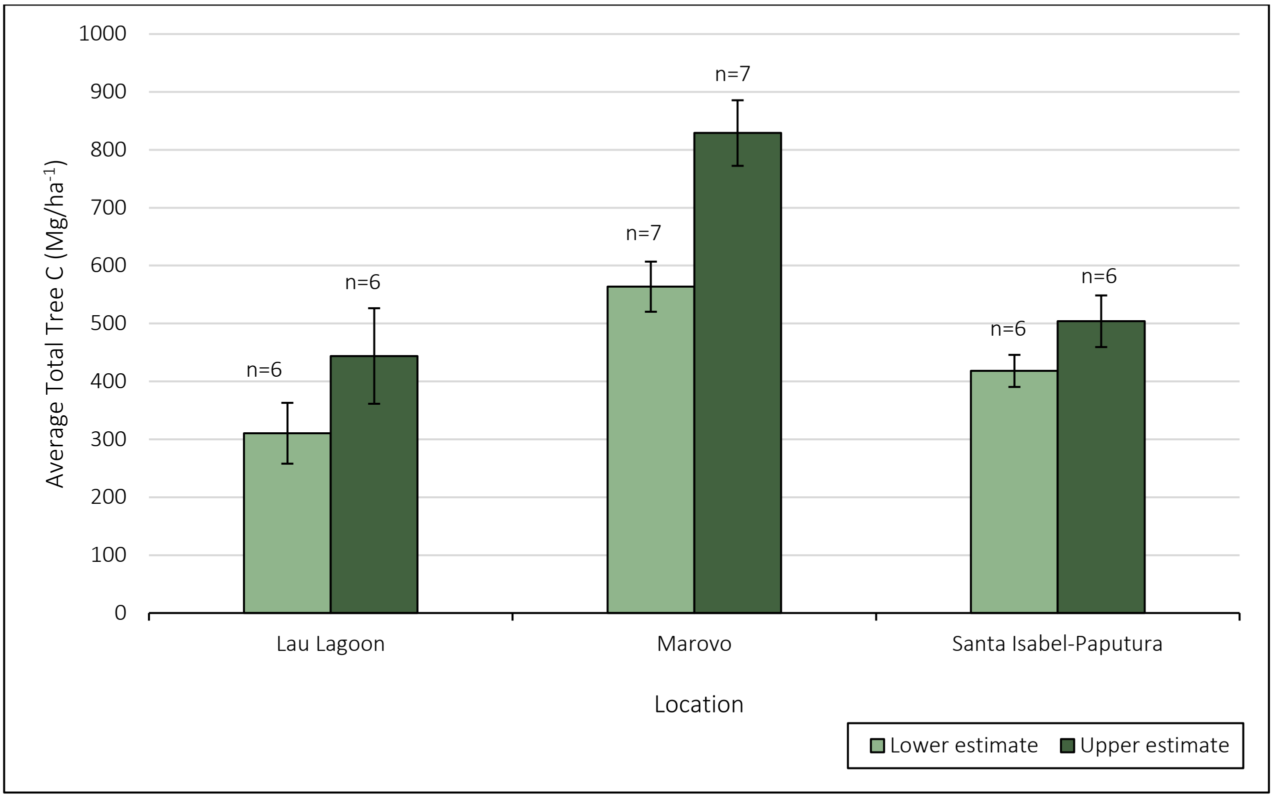

Figure 78. Mean tree carbon storage (± SE) in the Solomon Islands. Marovo had the highest carbon storage at 564 Mg C ha^{-1}, followed by Santa Isabel-Papatura (418 Mg C ha^{-1}) and Lau Lagoon (310 Mg C ha^{-1}). Error bars represent the standard error of the mean.

Across the three locations in the Solomon Islands, Marovo had the highest above-ground (AG) tree carbon storage at 462 ± 37 Mg C ha^{-1}, followed by Santa Isabel-Papatura with 281 ± 28 Mg C ha^{-1}, and Lau Lagoon with 272 ± 48 Mg C ha^{-1} (Figure 79).

Similarly, the highest below-ground (BG) tree carbon storage was in Marovo (101 ± 7 Mg C ha^{-1}) and Santa Isabel-Papatura (97 ± 11 Mg C ha^{-1})(Figure 81). Reflecting the AG tree carbon storage results, Lau Lagoon had the lowest BG tree carbon storage, reporting 39 ± 5 Mg C ha^{-1} , respectively (Figure 81).

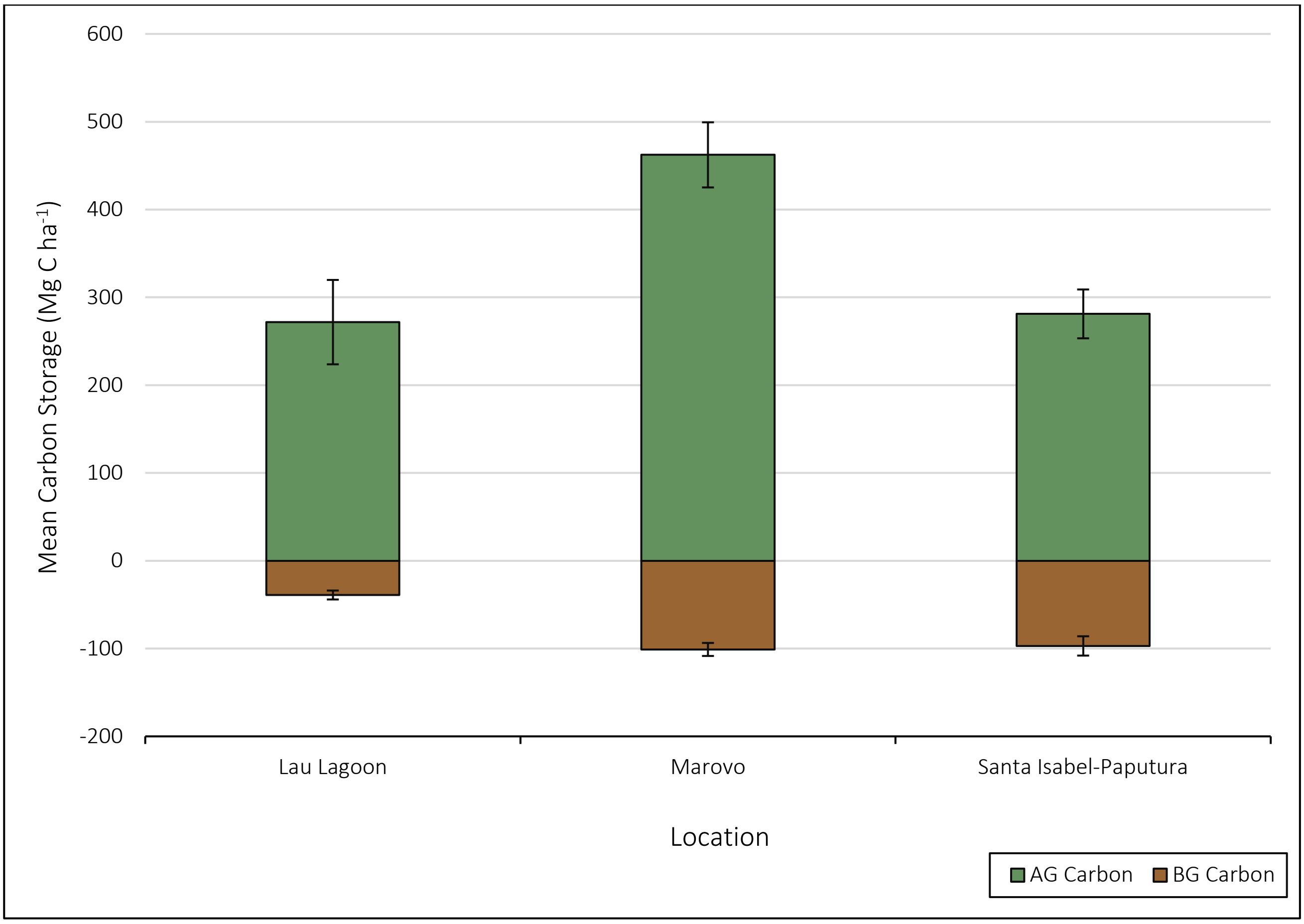

Figure 79. Above-ground (AG) and below-ground (BG) total tree carbon storage in Solomon Islands: Marovo had the highest AG tree carbon storage (462 Mg C ha^{-1}), followed by Santa Isabel-Papatura (281 Mg C ha^{-1}) and Lau Lagoon (272 Mg C ha^{-1}). Marovo had the highest BG tree carbon storage (101 Mg C ha^{-1}), followed by Santa Isabel-Papatura (97 Mg C ha^{-1}) and Lau Lagoon (39 Mg C ha^{-1}). Error bars represent standard error.

There was significant variation in AG and BG tree carbon storage between sites at each location. Higher levels were typically found in river deltas such as Jalire River Mouth and Lau Lagoon Site 5, which were 1,065 and 824 Mg C ha^{-1}, respectively (Figure 80 and Figure 82). The few degraded sites that were assessed were found to have relatively lower TCS, ranging from 9 to 200 Mg C ha^{-1}.

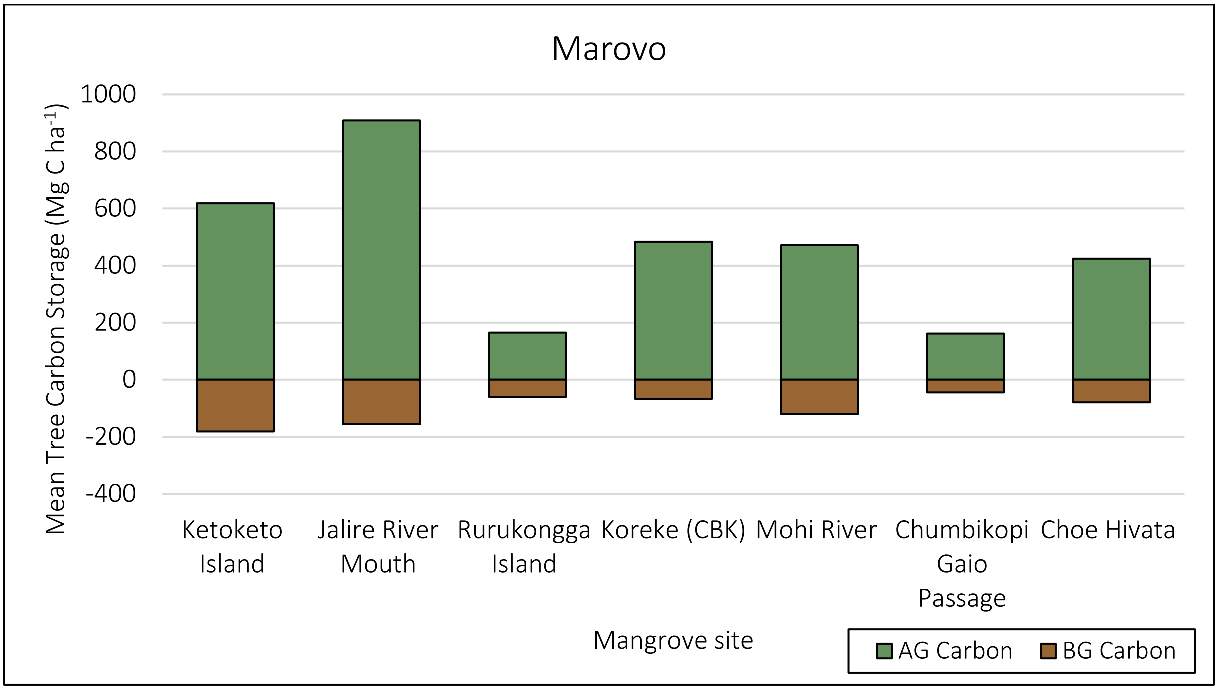

Figure 80. Above-ground (AG) and below-ground (BG) mangrove mean total tree carbon storage at each mangrove assessment site for assessment sites in Marovo, Solomon Islands. Riverine sites included Jalire River, Mohi River, Choe Hivata, Koreke. Mohi River and Choe Hivata (western Choe region); Rurukongga Islands, Koreke (CBK) and Chumbikopi Gaio Passage (eastern Marovo region); Ketoketo Island and Jalire River (central Marovo/Michi region).

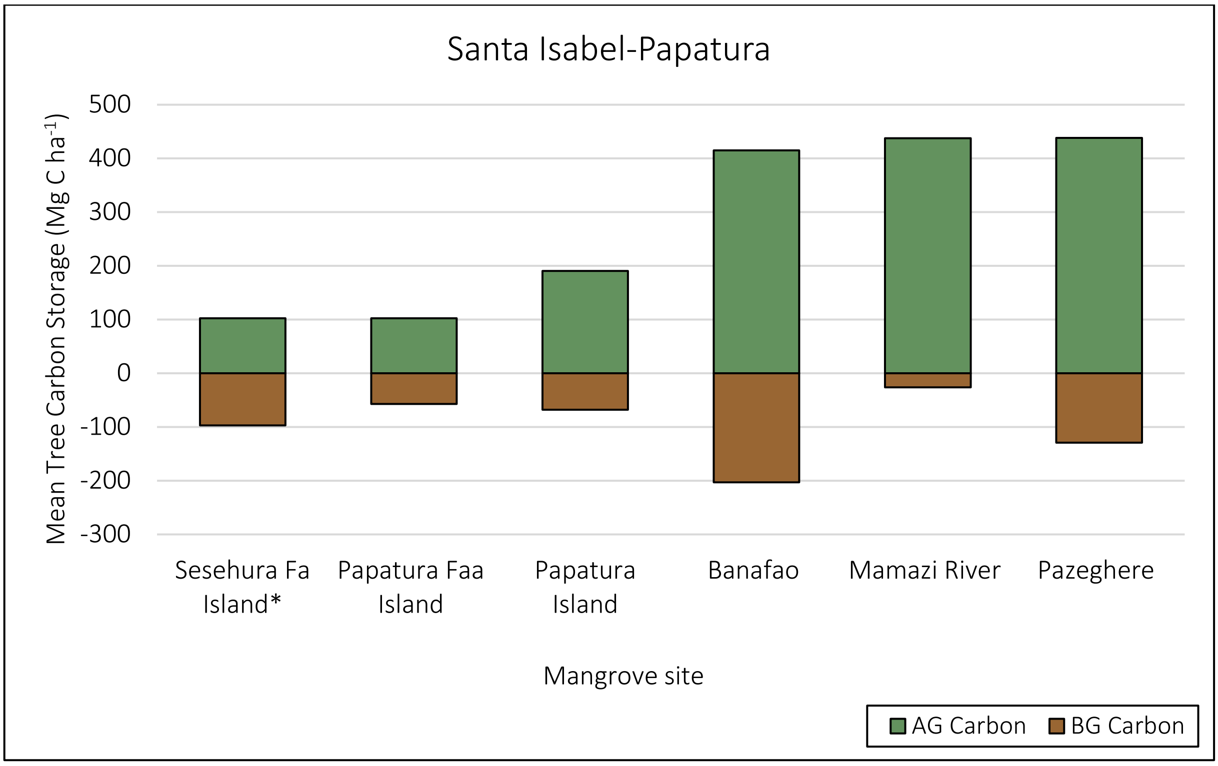

Figure 81. Above-ground (AG) and below-ground (BG) mangrove Mean total tree carbon storage at each mangrove assessment site for assessment sites in Santa Isabel-Papatura, Solomon Islands. The asterisk (*) is indicative of a degraded site, this site had cyclone induced erosion and impounding. Riverine sites were Pazehere and Mamazi River.

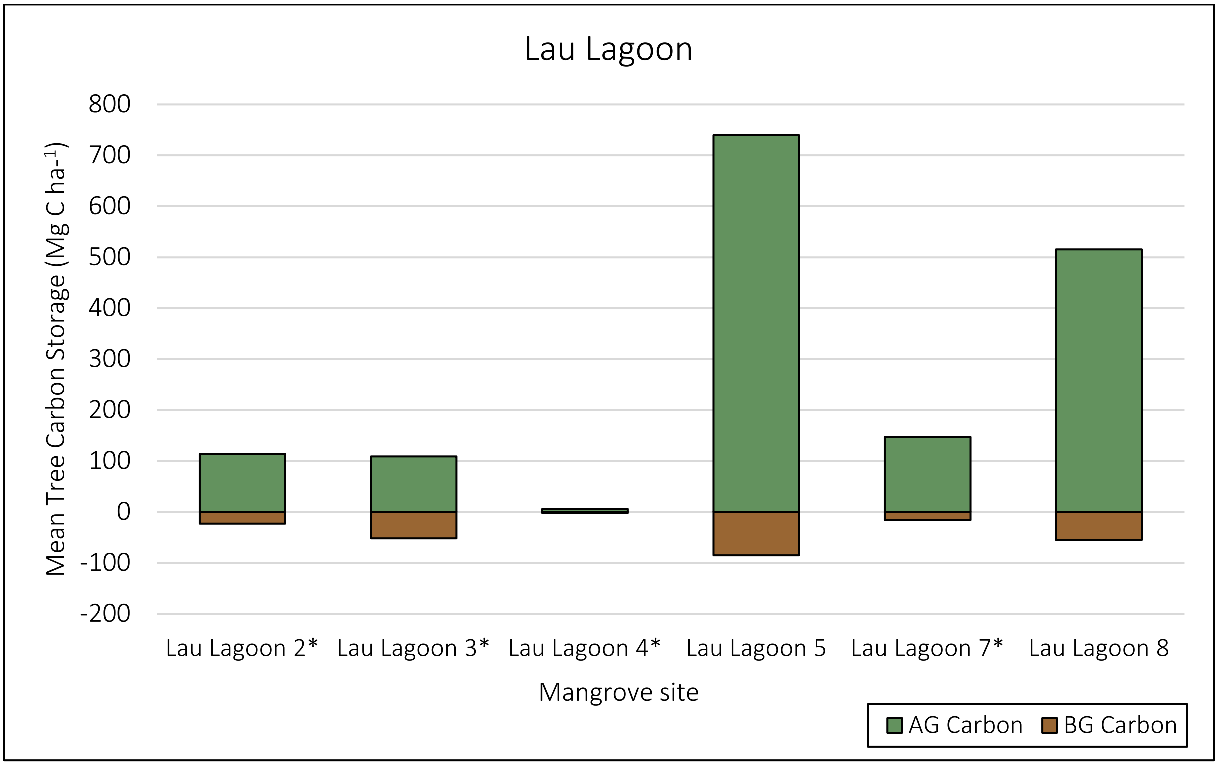

Figure 82. Above-ground (AG) and below-ground (BG) mangrove Mean total tree carbon storage at each mangrove assessment site for assessment sites in Lau Lagoon, Solomon Islands. The asterisk (*) is indicative of a degraded site, these sites are managed for wood harvesting and were historically cleared for the cultivation of mangrove species used in local food provision. Lau Lagoon sites 5 and 8 were associated with small tidal creeks.

6.3.3 Soil organic carbon

Mangrove soil organic carbon (SOC) sampling in the Solomon Islands represents the first meter of the sediment profile at most sites. However, due to field constraints and challenging conditions at some locations, obtaining deeper samples was not always possible. Sampling depths at each site are represented in the figures in this section.

Soil organic carbon varied across the three locations in the Solomon Islands, reflecting the differences in soil properties and organic matter inputs. The total SOC stock was highest in Lau Lagoon with a mean total SOC of 465 Mg C ha^{-1}, followed by Marovo (412 Mg C ha^{-1}) and Santa Isabel-Papatura (364 Mg C ha^{-1}) (Figure 83).

At all sites across the Solomon Islands, SOC at mangrove sites ranged from 1.8 % to 36.6 %, and 135 Mg C ha^{-1} to 482 Mg C ha^{-1}. Soil organic carbon stocks at each mangrove site are summarised from Figure 84 to Figure 86, demonstrating the variability in SOC between sites and at different depths.

Soil organic carbon stocks varied significantly across locations and between sites, reflecting differences in soil properties and organic matter inputs. These differences suggest spatial variability in carbon storage potential, possibly influenced by site-specific factors such as mangrove species, land use history, and soil texture. Where higher SOC stocks were observed at sites, such as those in Lau Lagoon, this may indicate more favourable conditions for carbon accumulation or reduced rates of organic matter decomposition.

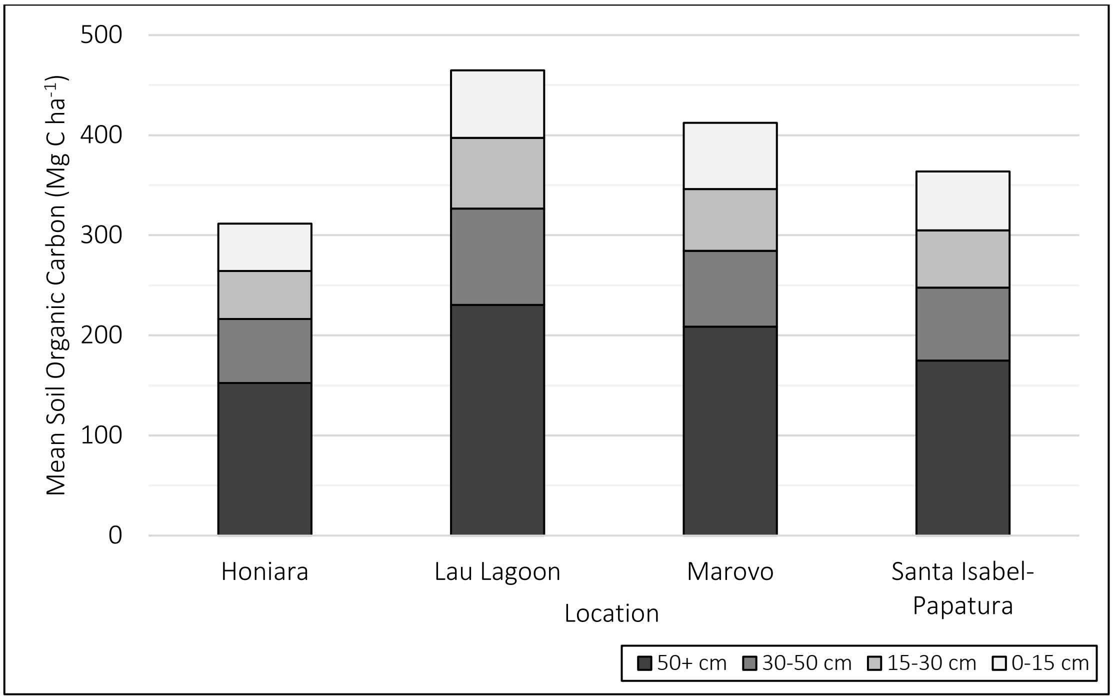

Figure 83. Mean total soil organic carbon (SOC) stocks in mangroves at different soil depths in Solomon Islands. SOC stock was highest in Lau Lagoon (465 Mg C ha^{-1}), followed by Marovo (412 Mg C ha^{-1}) and Santa Isabel-Papatura (364 Mg C ha^{-1}).

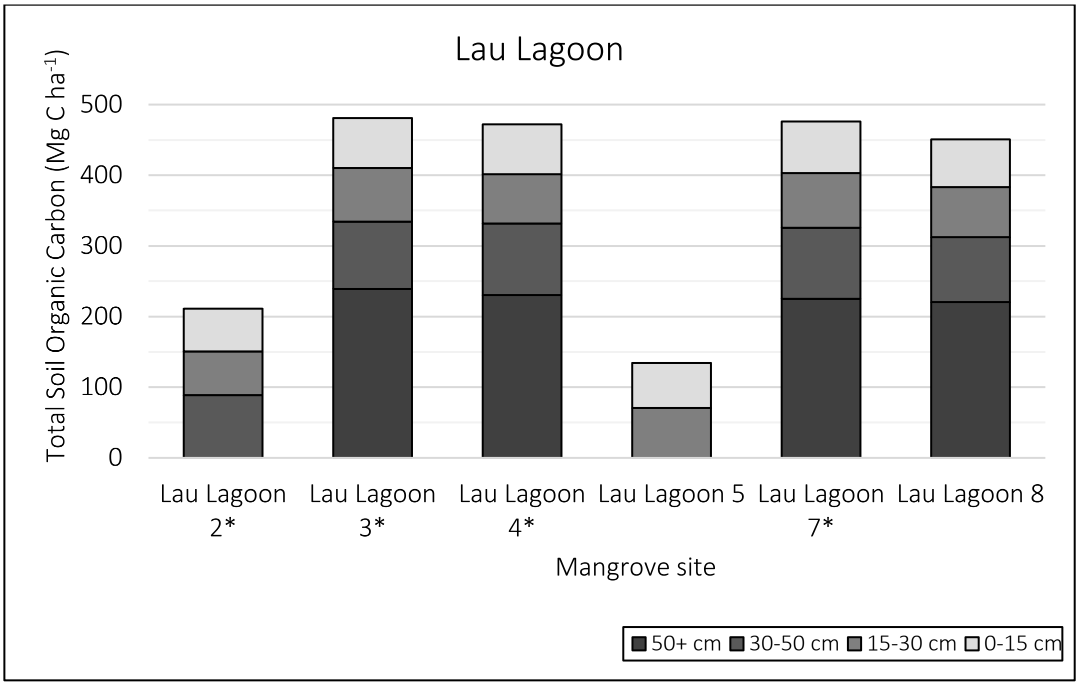

Figure 41. Mangrove soil organic carbon the six mangrove sites at different soil depths in Lau Lagoon, Solomon Islands. The asterisk (*) is indicative of a degraded site, these sites are managed for wood harvesting and were historically cleared for the cultivation of mangrove species used in local food provision. Site 5 and 8 were associated with small tidal creeks.

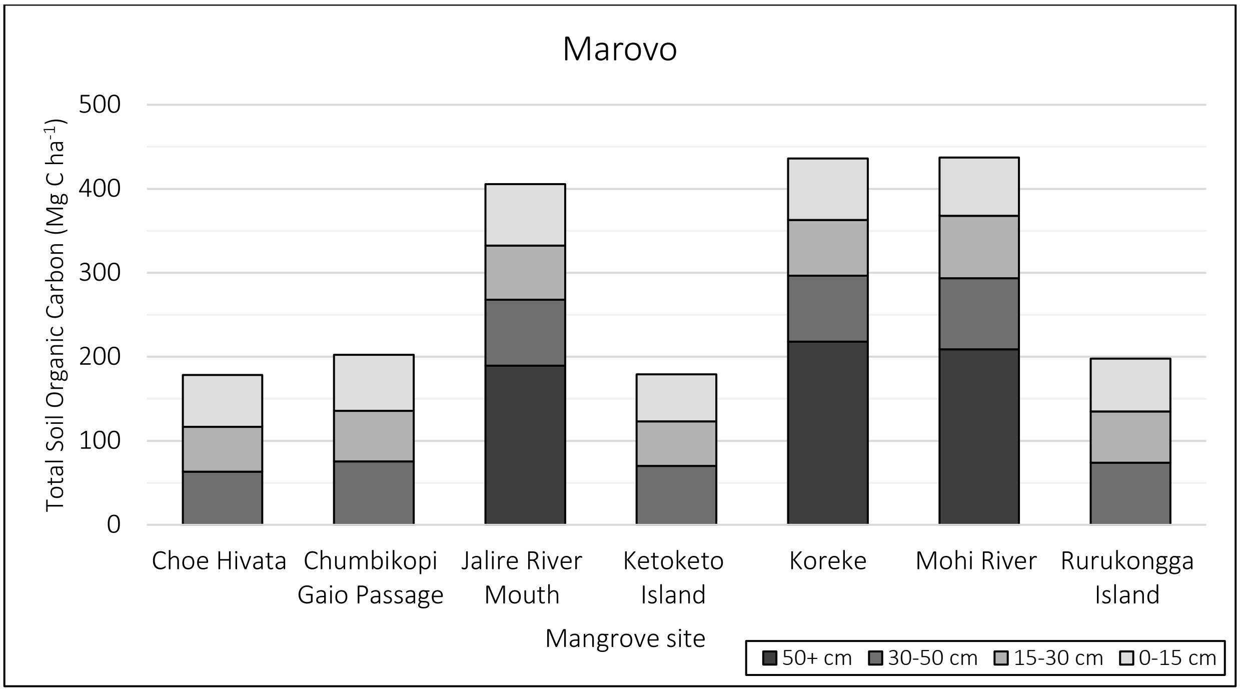

Figure 42. Mangrove soil organic carbon at the seven mangrove sites at different soil depths in Marovo, Solomon Islands. Sites included: Mohi River and Choe Hivata (western Choe region); Rurukongga Islands, Koreke (CBK) and Chumbikopi Gaio Passage (eastern Marovo region); and Ketoketo Island and Jalire River (central Marovo/Michi region). Riverine sites were Jalire River, Mohi River, Choe Hivata, Koreke.

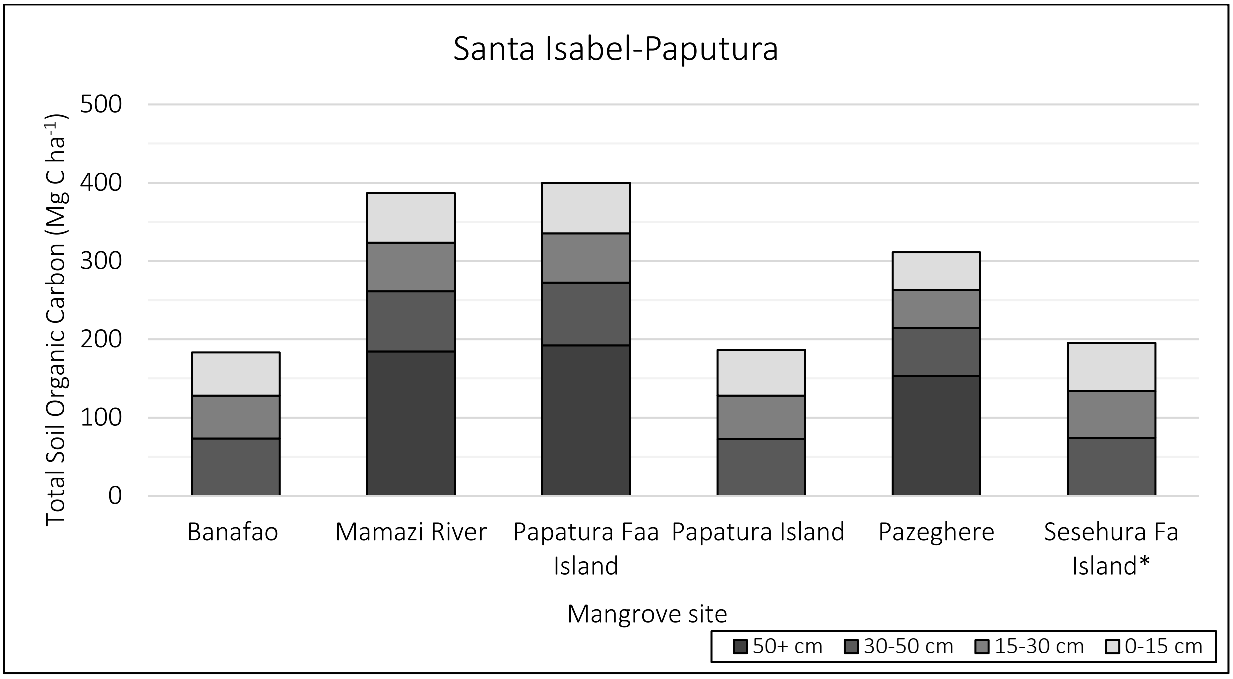

Figure 86. Mangrove soil organic carbon at the two mangrove sites at different soil depths in Santa Isabel-Papatura, Solomon Islands. The asterisk (*) is indicative of a degraded site, this site had cyclone induced erosion and impounding. Riverine sites were Pazehere and Mamazi River.

6.3.4 Total ecosystem carbon

Mean total ecosystem carbon stocks (TECS) varied across the three study locations, with the highest stock estimates observed in Marovo (Figure 87). With the exception of Marovo, soil organic carbon (SOC) was typically the largest carbon pool, accounting for approximately 42 to 60% of mean TECS. Above-ground live Tree Carbon Storage (TCS) was the next largest contributor, while below-ground live TCS and dead TCS represented relatively minor components.

In Morovo, despite having the greatest mean TECS of approximately 976 Mg C ha^{-1}, SOC was not the largest contributor of carbon at this location. Unlike the other study locations, living trees contributed the most to TECS, accounting for approximately 53% of TECS. Above-ground TCS contributed 428 Mg C ha^{-1} and below-ground TCS contributed 91 Mg C ha^{-1}. Soil organic carbon contributed approximately 42% of TECS at 412 Mg C ha^{-1}. Dead trees also contributed a considerable amount to TECS, both above-ground (34 Mg C ha^{-1}) and below-ground (11 Mg C ha^{-1}) (Figure 87).

In Lau Lagoon, the mean TECS was approximately 774 Mg C ha^{-1}. Soil organic carbon was the largest contributor (465 Mg C ha^{-1}), followed by above-ground live TCS (264 Mg C ha^{-1}) and below-ground live TCS (36 Mg C ha^{-1}). In comparison, dead TCS contributed only a small fraction (Figure 87).

In Santa Isabel-Papatura, the mean TECS was approximately 726 Mg C ha^{-1}. Soil organic carbon was the greatest contributor to TECS (364 Mg C ha^{-1}), followed by above-ground live TCS (243 Mg C ha^{-1}), and below-ground live TCS (75 Mg C ha^{-1}). Dead TCS also contributed a considerable amount (at 44 Mg C ha^{-1}, respectively) (Figure 87).

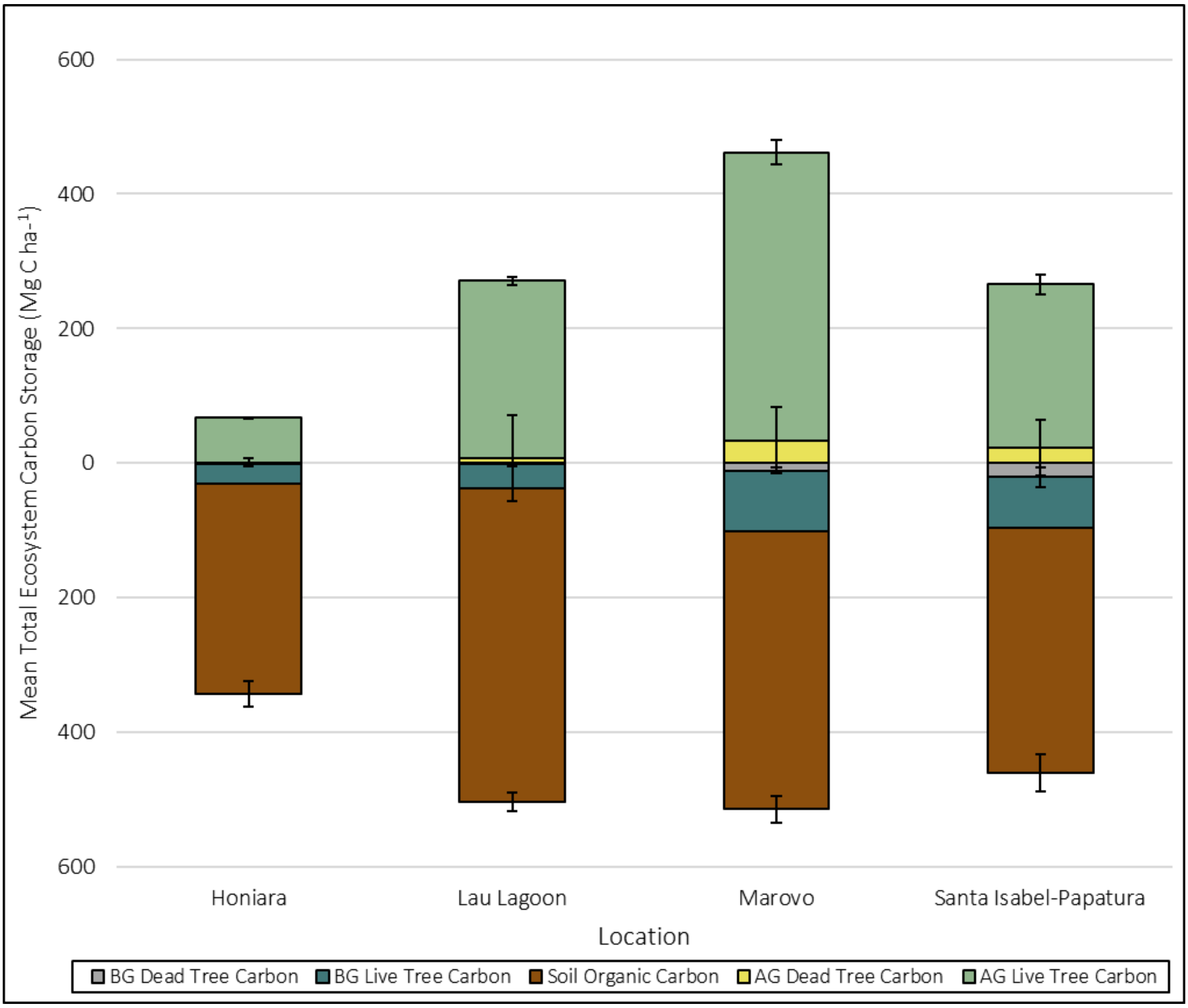

Figure 87. Mean total ecosystem carbon stocks (TECS) across three survey locations in Solomon Islands, partitioned by carbon pools: Soil organic carbon; Above-ground (AG) and Below-ground (BG) Live Tree Carbon Storage; and AG and BG Dead Tree Carbon Storage. Soil organic carbon was the dominant pool at all sites, with mean TECS were highest in Marovo (976 Mg C ha^{-1}), followed by Lau Lagoon (774 Mg C ha^{-1}) and Santa Isabel-Papatura (726 Mg C ha^{-1}). Soil organic carbon contributed the most to TECS. Error bars represent the standard error of the mean.

6.4 Summary

The seagrass and mangrove ecosystems of the Solomon Islands provide vital ecosystem services, including shoreline protection, biodiversity support, carbon sequestration, and resources for local livelihoods. This study represents one of the most comprehensive field-based blue carbon assessments in the Solomon Islands to date, covering 21 mangrove and 11 seagrass sites across Isabel, Western, Malaita, and Guadalcanal Provinces.

While previous carbon studies in the Pacific are limited, this assessment reveals that the Solomon Islands host some of the highest recorded total ecosystem carbon stocks (TECS) in the region. Total ecosystem carbon stocks in mangrove systems reached up to 976 Mg C ha^{-1} in Marovo, with above-ground Tree Carbon Storage as high as 428 Mg C ha^{-1} and soil organic carbon (SOC) up to 412 Mg C ha^{-1}. These values are comparable to or exceed those reported in Fiji[49], Palau[50], and Indonesia[51], and approach levels recorded in high-biomass systems like Vanuatu[52] and northern Australia[53].

Key Findings:

Seagrass Ecosystems

- Soil organic carbon in seagrass sites ranged from 42 to 182 Mg C ha^{-1}. These SOC values were significantly higher than those reported in Indonesia (0.32-65.8 Mg C ha^{-1}), Fiji (31-47 Mg C ha^{-1}), and Palau (48 Mg C ha^{-1}).
- The high SOC levels and seagrass cover likely reflect favourable site conditions, low disturbance, and the structural complexity of the meadows.
- Mixed-species meadows were common (found at six of eleven sites), and *Enhalus acoroides* was dominant in many high-coverage meadows, particularly in Lau Lagoon, which had the highest average seagrass cover (68%). Most sites experienced low levels of threat.
- Mean SOC values were relatively consistent across depths (0-50 cm), suggesting stable carbon accumulation across the sediment profile.

Mangrove Ecosystems

- Live Tree Carbon Storage (TCS) varied widely from 9 to 1,065 Mg C ha^{-1}, with the highest values recorded in riverine sites such as Jalire River Mouth and Lau Lagoon Site 5.
- Mangrove forests were dominated by *Rhizophora apiculata, R. stylosa, Ceriops tagal*, and *Bruguiera gymnorhiza*, with species composition varying by location.
- Above-ground TCS reached up to 428 Mg C ha^{-1}, comparable to high-end values reported in Vanuatu (537-1,318 Mg C ha^{-1}) and Palau (588 Mg C ha^{-1}).
- Soil organic carbon stocks across sites ranged from 178 to 481 Mg C ha^{-1}, comparable to values reported in Fiji (84-490 Mg C ha^{-1}), Singapore (307 Mg C ha^{-1}), and Indonesia (2-575 Mg C ha^{-1}).
- Total Ecosystem Carbon was highest in Marovo (976 Mg C ha^{-1}), followed by Lau Lagoon (774 Mg C ha^{-1}) and Santa Isabel-Papatura (726 Mg C ha^{-1}).

[49] Cameron, C., Kennedy, B., Tuiwawa, S., Goldwater, N., Soapi, K., & Lovelock, C. E. (2021). High variance in community structure and ecosystem carbon stocks of Fijian mangroves driven by differences in geomorphology and climate. *Environmental Research*, *192*, 110213

[50] Kauffman, J. B., Heider, C., Cole, T. G., Dwire, K. A., & Donato, D. C. (2011). Ecosystem carbon stocks of Micronesian mangrove forests. *Wetlands, 31*(2), 343–352. https://doi.org/10.1007/s13157-011-0148-9

[51] Daniel M Alongi (2012) Carbon sequestration in mangrove forests, Carbon Management, 3:3, 313-322, DOI: 10.4155/cmt.12.20

[52] Baereleo, R., Kalfatak, D., Kanas, T., Bulu, M., Ham, J., Kaltavara, J., Sammy, E., Dovo, P., Duke, N., MacKenzie, J., Sheaves, M., Johnston, R., & Yuen, L. (2025). *Mangrove EcoSystems for Climate Change Adaptation and Livelihoods (MESCAL) Biodiversity Assessments Technical Report*. Viliame Pita Waqalevu (Ed.). Vanuatu: MESCAL Project.

[53] Daniel M Alongi (2012) Carbon sequestration in mangrove forests, Carbon Management, 3:3, 313-322, DOI: 10.4155/cmt.12.20

- With the exception of Marovo, SOC was the dominant carbon pool across locations, contributing 42 to 60% of mean TECS. In Marovo, live trees were the most dominant carbon pool, contributing to 53% of mean TECS.
- Degraded sites (e.g., parts of Lau Lagoon), impacted by logging or managed for food provision, had lower live tree carbon storage but retained moderate to high SOC, highlighting the resilience of below-ground carbon pools.

VANUATU

7 Vanuatu carbon assessments

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7.1 Vanuatu study sites

Seagrass meadows and mangrove forests were surveyed across three Islands in Vanuatu, including Efate, Malekula and Espiritu Santo. The survey locations for both mangroves and seagrass are shown in Figure 88, including: Moso-Undine Bay and Port Vila-Eratap (Efate Island, Shefa Province), Santo and Malo-Aore (Espiritu Santo Island, Sanma Province) and Malekula and Maskelyne (Malekula Island, Malampa Province). A total of 19 mangrove sites and 14 seagrass sites were surveyed across a diversity of geomorphological settings in order to capture representative data for these dynamic ecosystems. Locations and sites are shown in detail in Figure 88 to Figure 95.

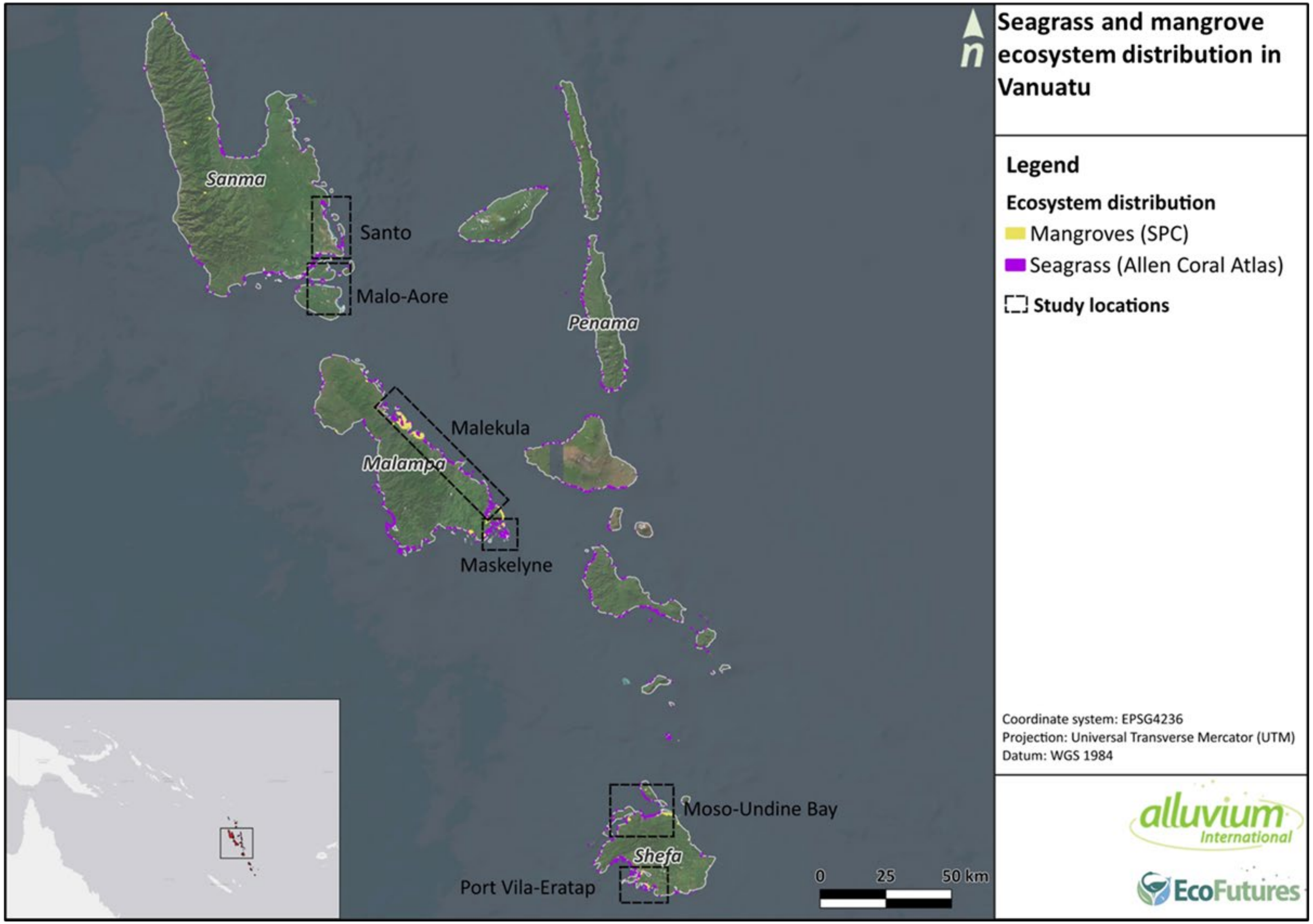


Figure 88. Seagrass and mangrove ecosystem distribution and survey locations in Vanuatu.

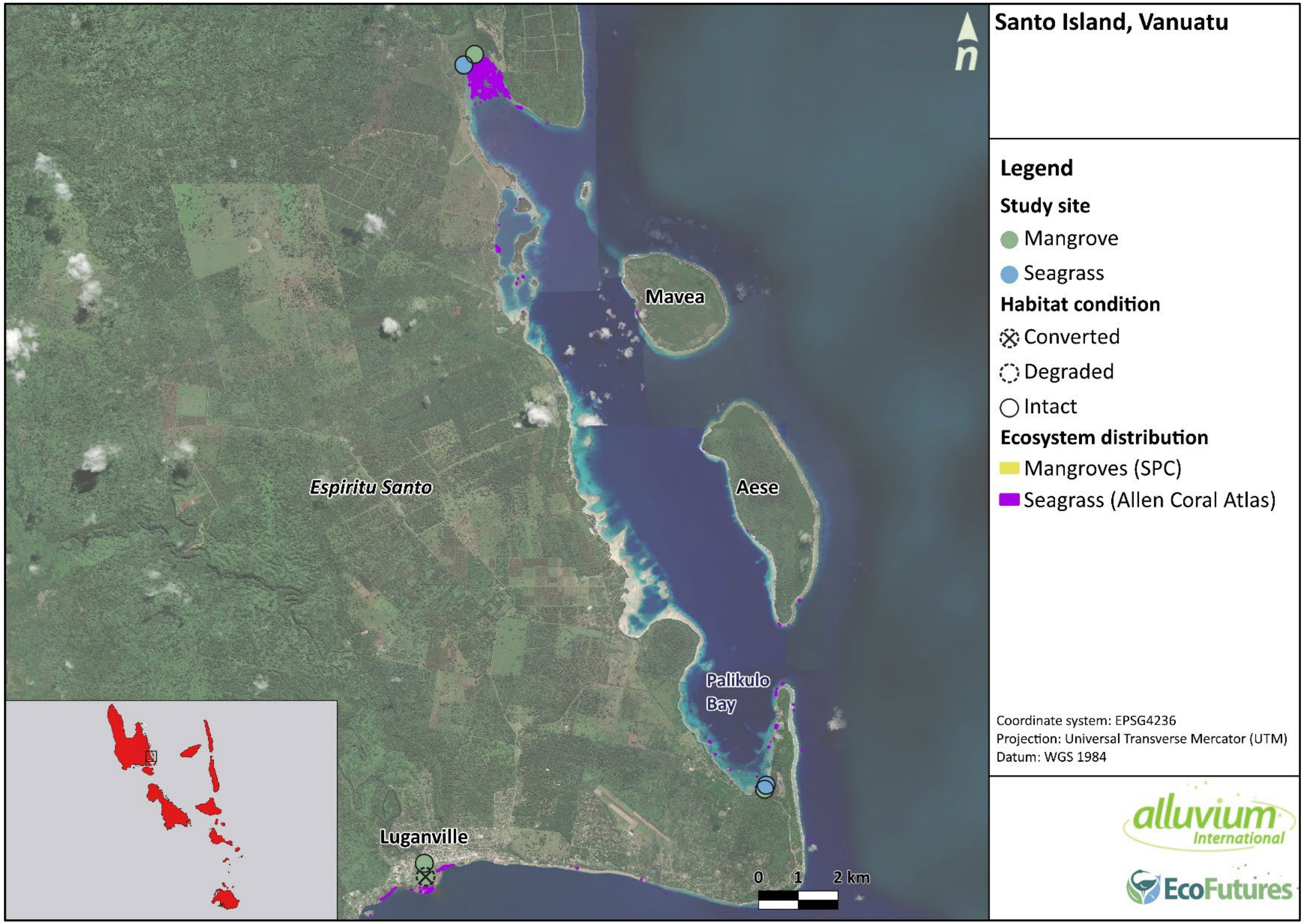


Figure 89. Seagrass and mangrove ecosystem distribution and survey sites at Santo. At this location, three (3) intact and one (1) converted mangrove sites and two (2) intact seagrass sites were assessed.

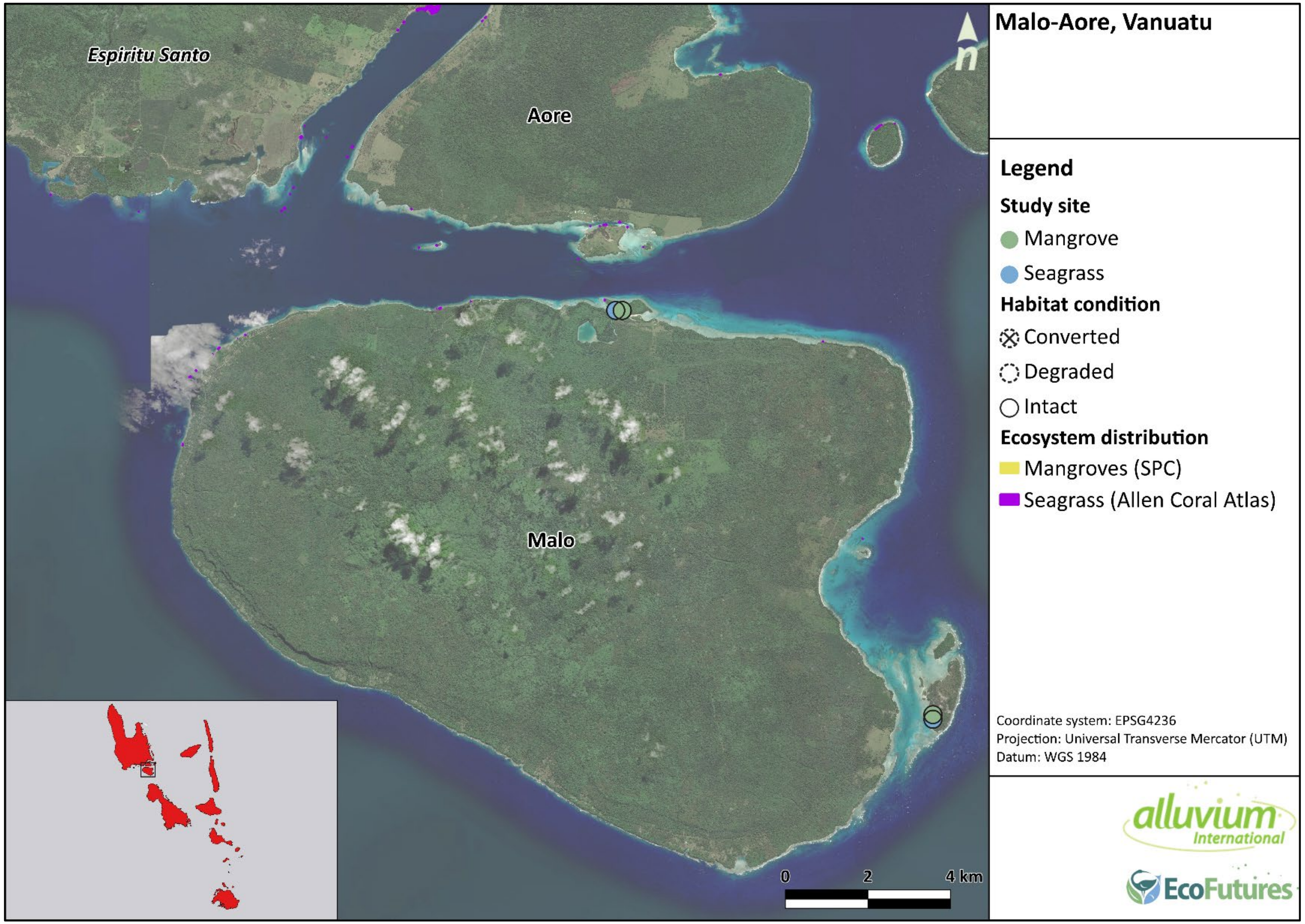


Figure 90. Seagrass and mangrove ecosystem distribution and survey sites at Malo-Aore. At this location, two (2) intact mangrove sites and two (2) intact seagrass sites were assessed.

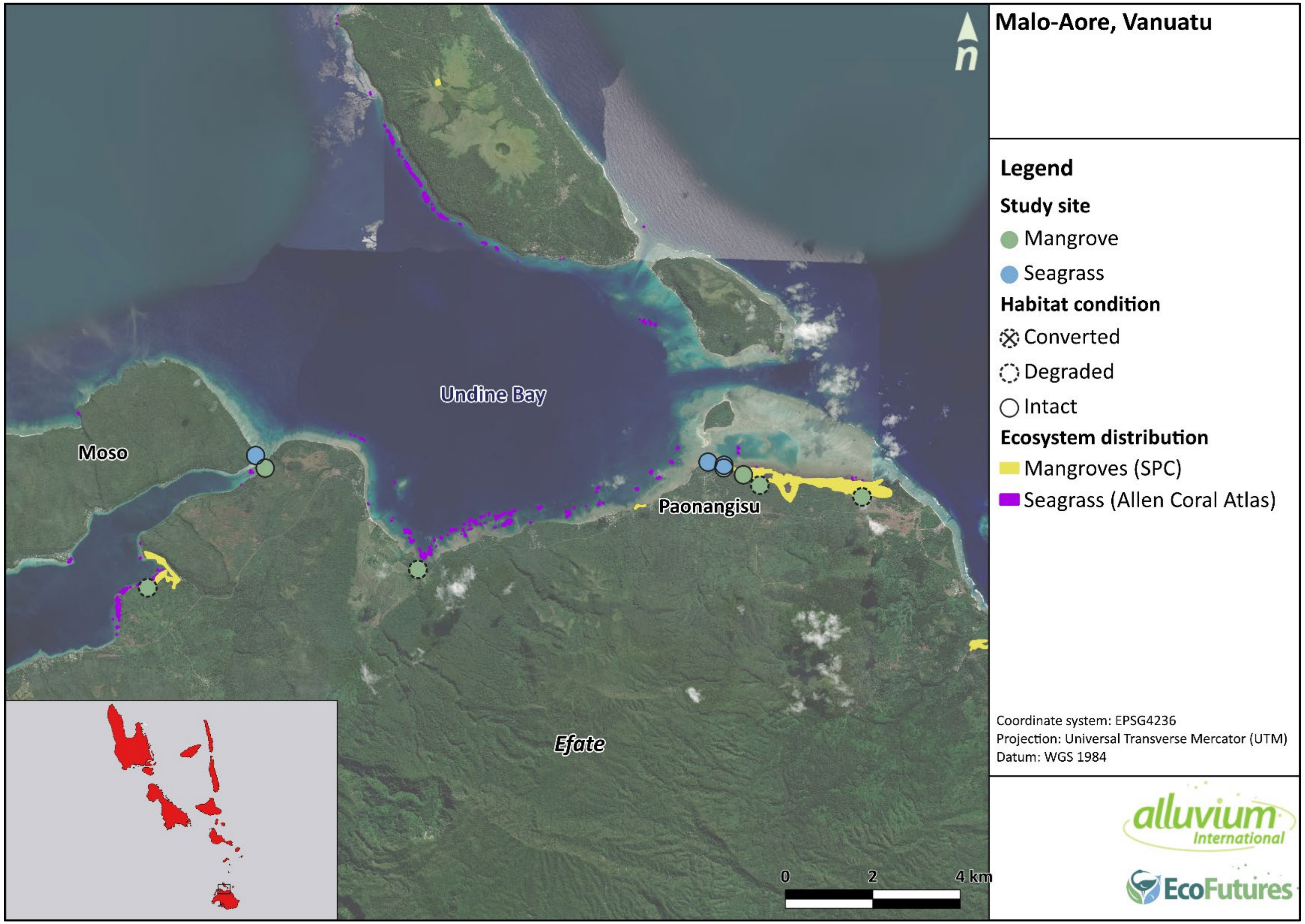


Figure 91. Seagrass and mangrove ecosystem distribution and survey sites at Moso-Undine Bay. At this location, three (3) intact and four (4) degraded mangrove sites and two (2) intact seagrass sites were assessed.

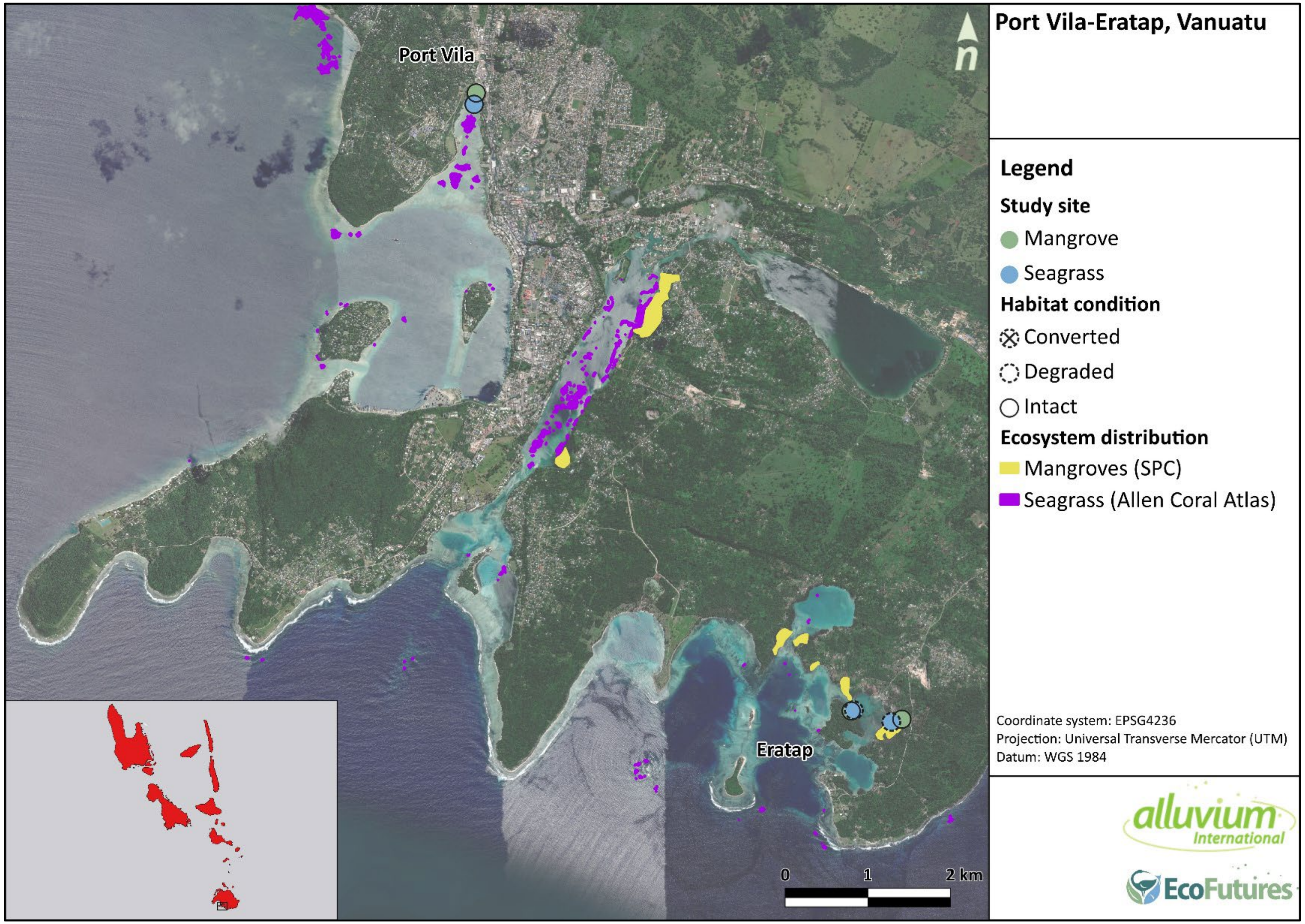


Figure 92. Seagrass and mangrove ecosystem distribution and survey sites at Port Vila-Eratap. At this location, one (1) intact and two (2) degraded mangrove sites and three (3) intact seagrass sites were assessed.

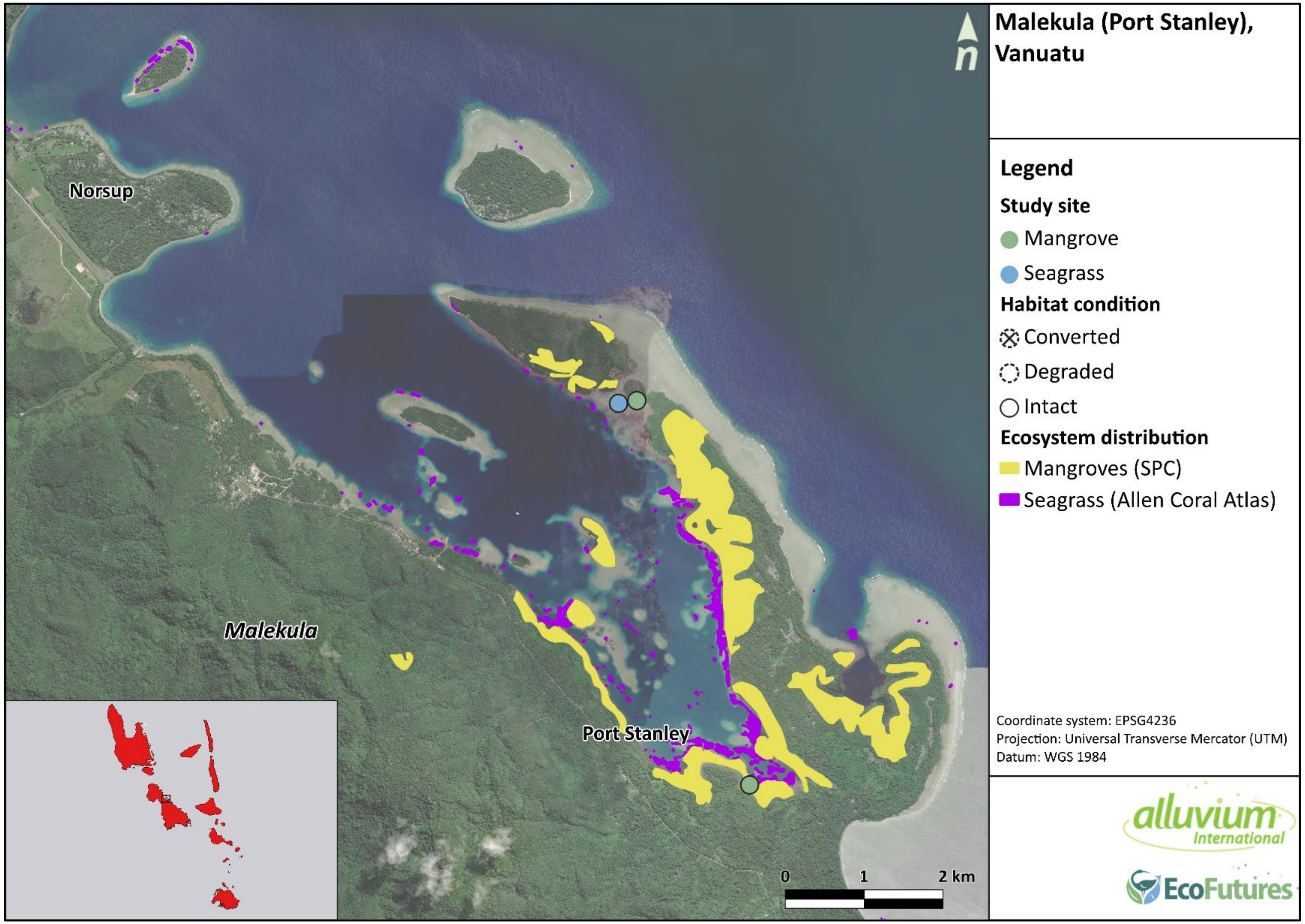


Figure 93. Seagrass and mangrove ecosystem distribution and survey sites at Malekula (Port Stanley section). At this location two (2) intact mangrove sites and one (1) intact seagrass site were assessed.

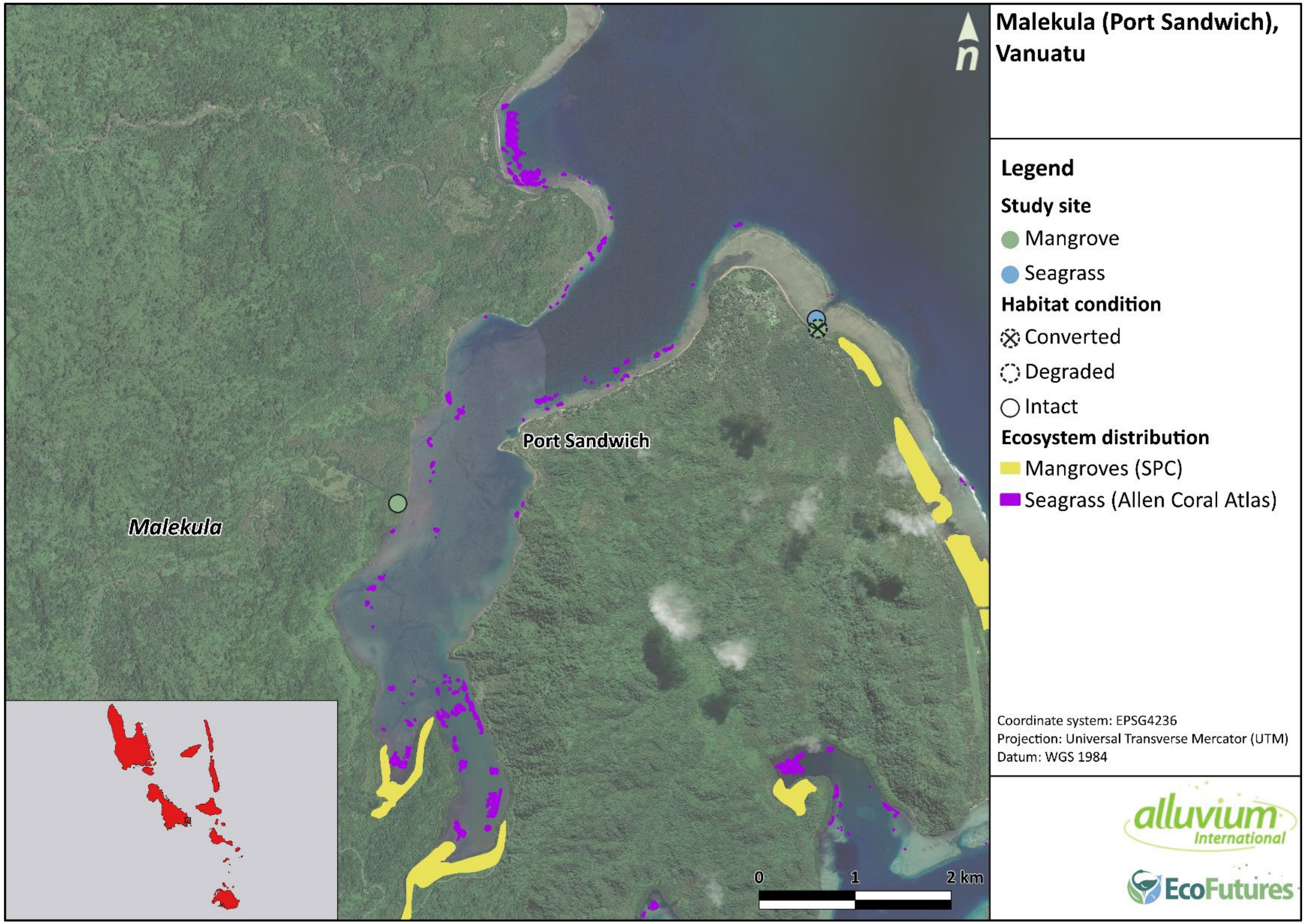


Figure 94. Seagrass and mangrove ecosystem distribution and survey sites at Malekula (Port Sandwich section). At this location, one (1) intact mangrove site, one (1) converted mangrove site, and one (1) intact seagrass site were assessed.

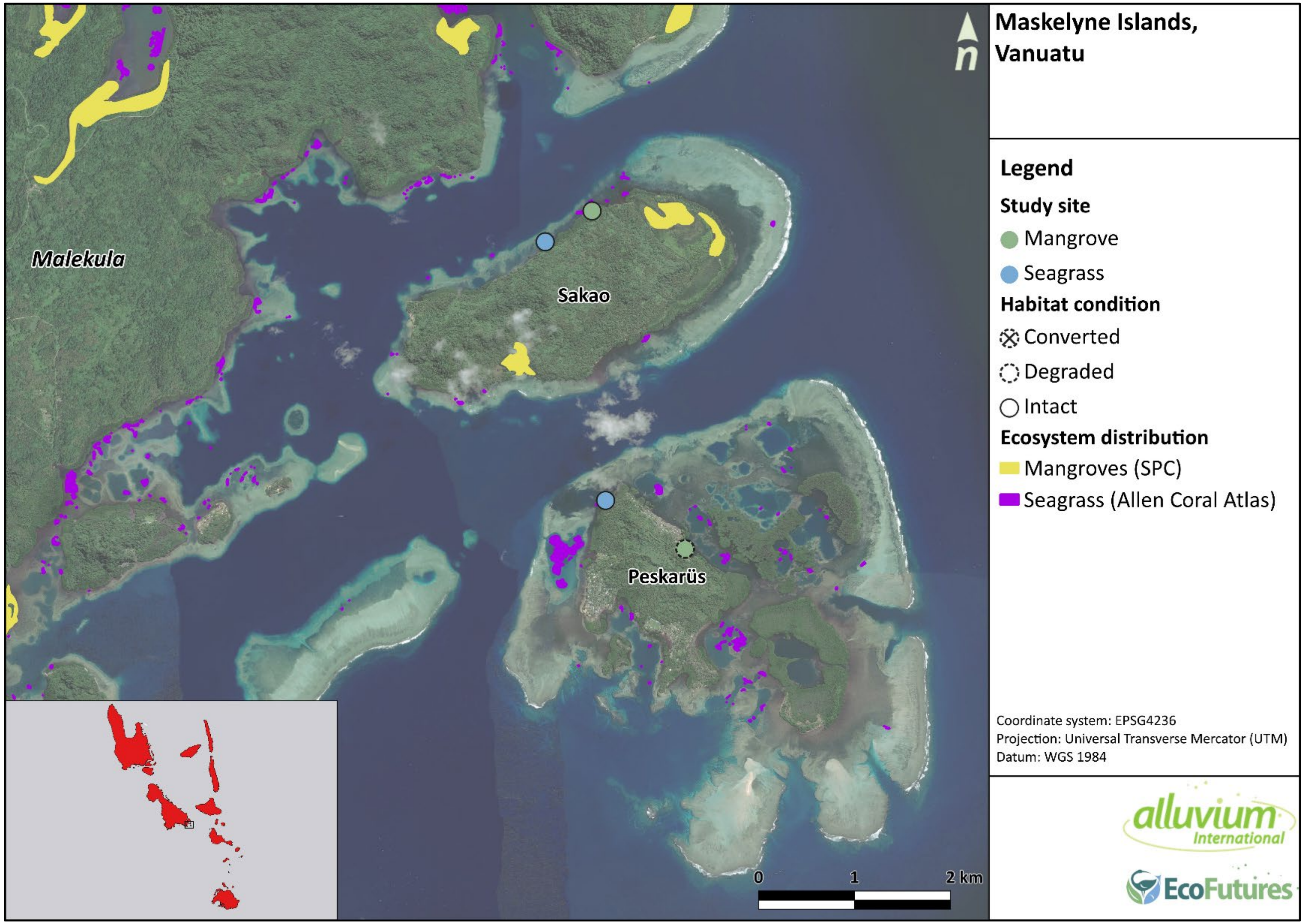


Figure 95. Seagrass and mangrove ecosystem distribution and survey sites in the Maskelyne Islands. At this location, one (1) intact and one (1) degraded mangrove site and two (2) intact seagrass sites were assessed.

7.2 Vanuatu carbon assessment results – Seagrass

This results section for seagrass ecosystems presents only soil organic carbon (SOC) measurements, reflecting the study's focus on the dominant carbon pools in blue carbon ecosystems. Above-ground (AG) and below-ground (BG) biomass carbon is not considered a significant component of the total ecosystem carbon pool in seagrass meadows.

7.2.1 Soil organic carbon

Sampling was restricted to limited depths, with samples typically representing the upper 30 cm of the sediment profile. Samples between the upper 30 to 100 cm of the sediment profile were difficult to obtain due to field constraints. This is a common limitation in seagrass carbon assessments as they are typically logistically challenging environments. Sampling depths at each study site and location are represented in the figures in this section.

Across study locations in Vanuatu, seagrass ecosystems were found to range from a mean total of 77 to 161 Mg C ha^{-1} (Figure 96). The highest mean SOC levels were found in Moso-Undine Bay (161 Mg C ha^{-1}), despite not being able to obtain samples at depths greater than 30 cm. Excluding Moso-Undine Bay, SOC was relatively consistent within depth intervals across different locations, ranging from approximately 43 to 47 Mg C ha^{-1} at 0-15 cm depths and 32 to 48 Mg C ha^{-1} at 15-30 cm depths (Figure 96).

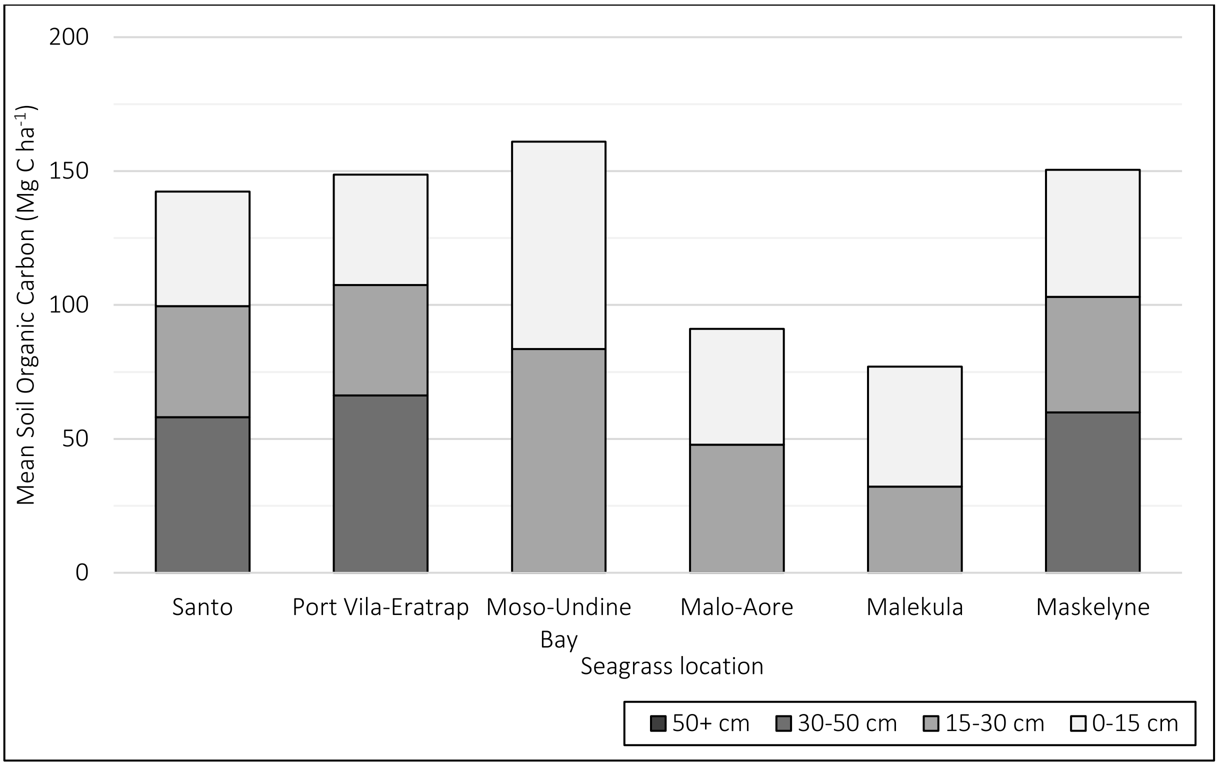


Figure 96. Mean total soil organic carbon in seagrass meadows at different soil depths across the six survey locations in Vanuatu.

Across all 14 seagrass study sites in Vanuatu, the mean total SOC showed some variation, with carbon content ranging from 1% to 12% and stocks ranging from 44 to 161 Mg C ha^{-1}. This variation is potentially due to differences in sampling depths, as some sites had soil cores collected from depths greater than 15 cm. Figure 97 to Figure 102 summarise SOC stocks at each mangrove assessment site and demonstrate the variability between sites at different depths. Soil organic carbon stocks may also have varied between sites due to differences in soil properties, organic matter inputs, and rates of organic matter decomposition.

The highest mean total SOC (161 Mg C ha^{-1}) was obtained at a study site in Tuaaimatic at the Port Vila-Eratap study location, where sampling included depth intervals from 0-15 cm, 15-30 cm, and 30-50 cm. This site was associated with a riverine system, which may contribute to more organic matter inputs.

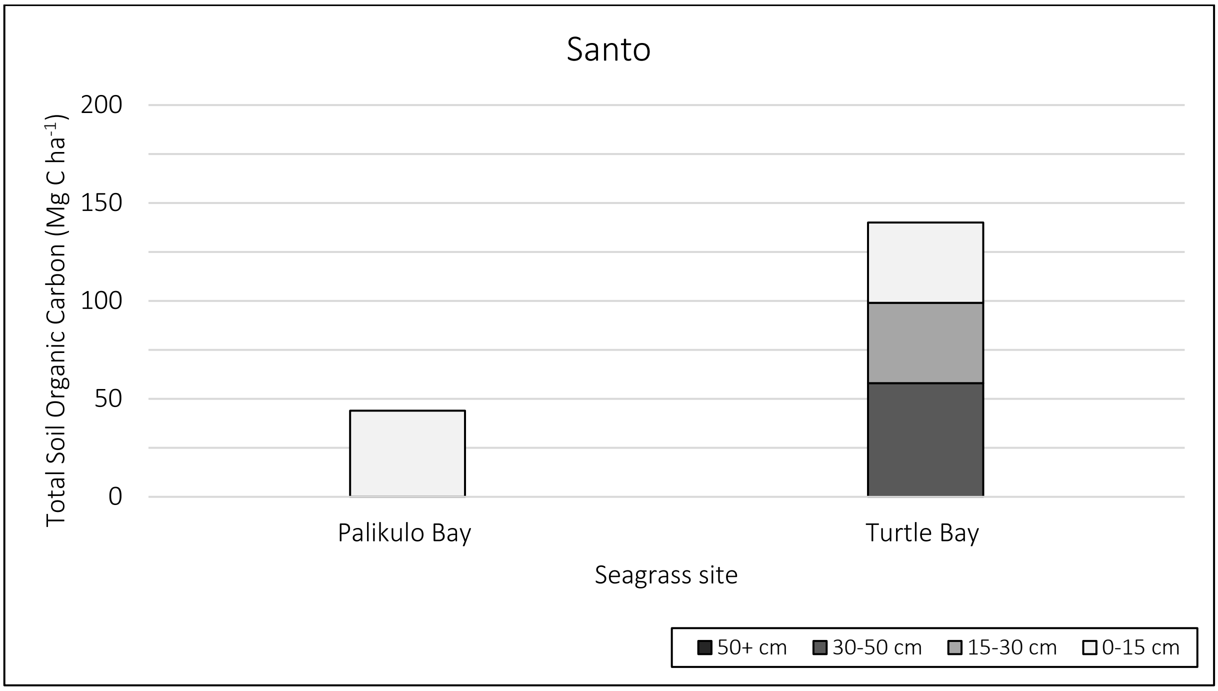


Figure 97. Seagrass soil organic carbon at different soil depths at two seagrass sites on Santo, Vanuatu.

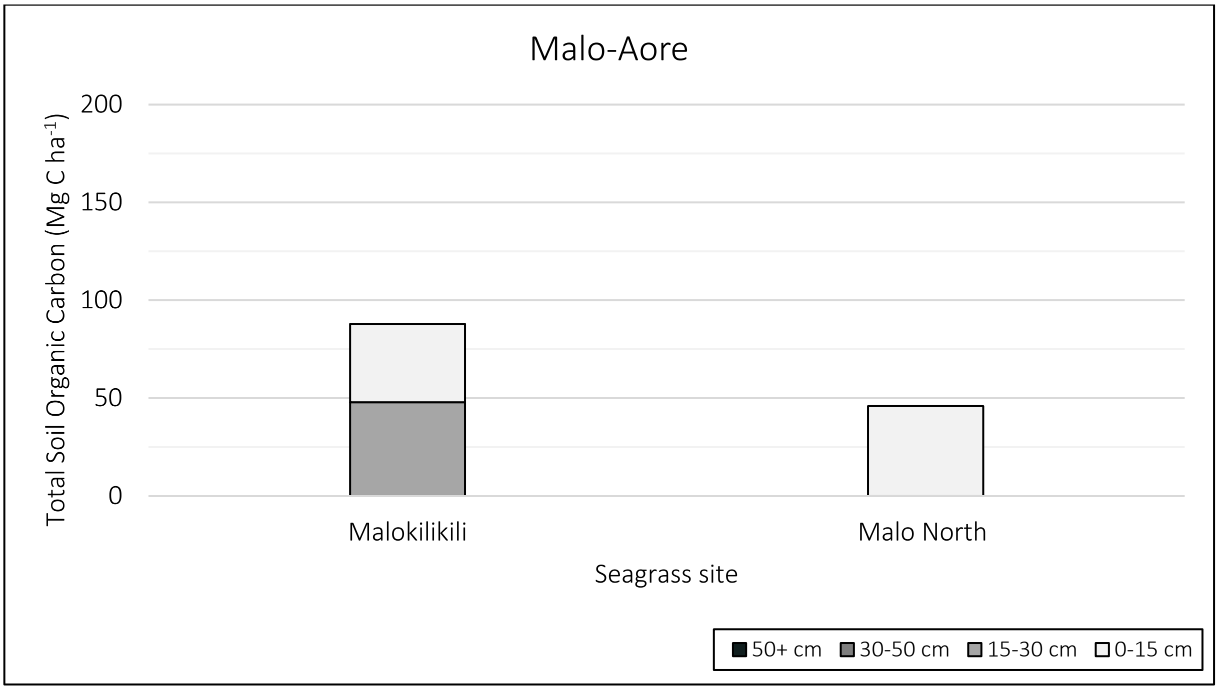


Figure 98. Seagrass soil organic carbon at different soil depths at two seagrass sites in Malo-Aore, Vanuatu.

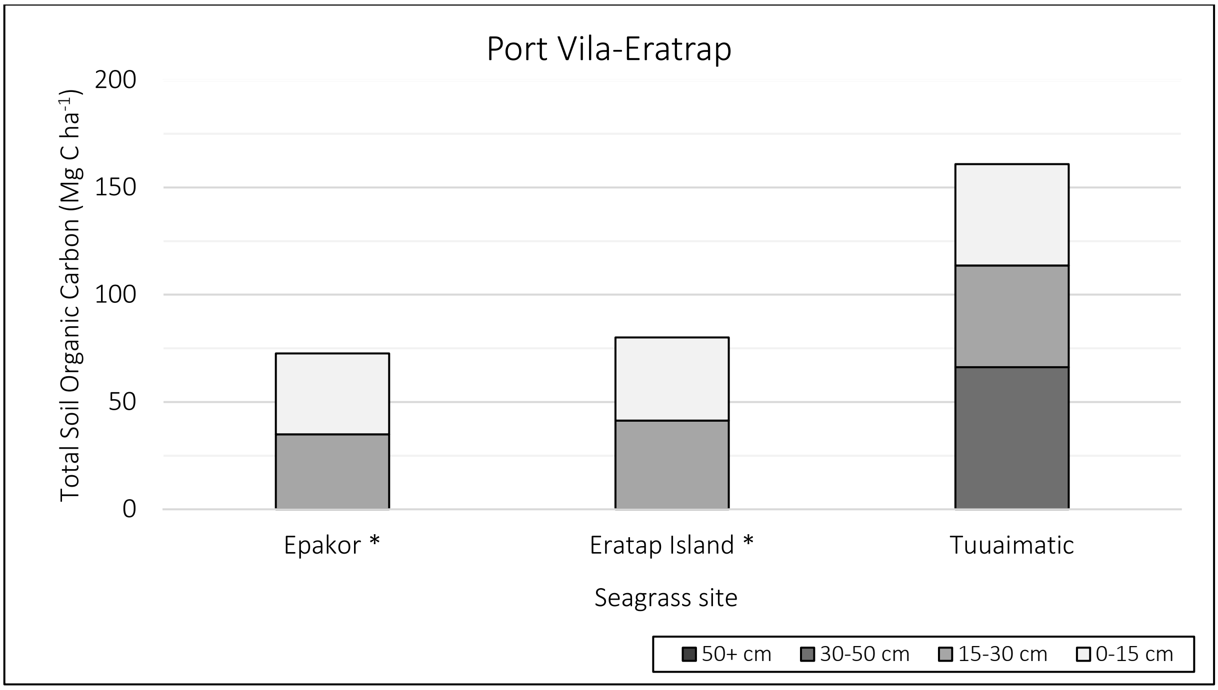


Figure 99. Seagrass soil organic carbon at different soil depths at three seagrass sites in Port Vila-Eratap, Vanuatu. An asterisk (*) indicates a degraded site. Two assessment sites were classified as degraded, due to clearing for tourism and cyclone impact (Eratap only).

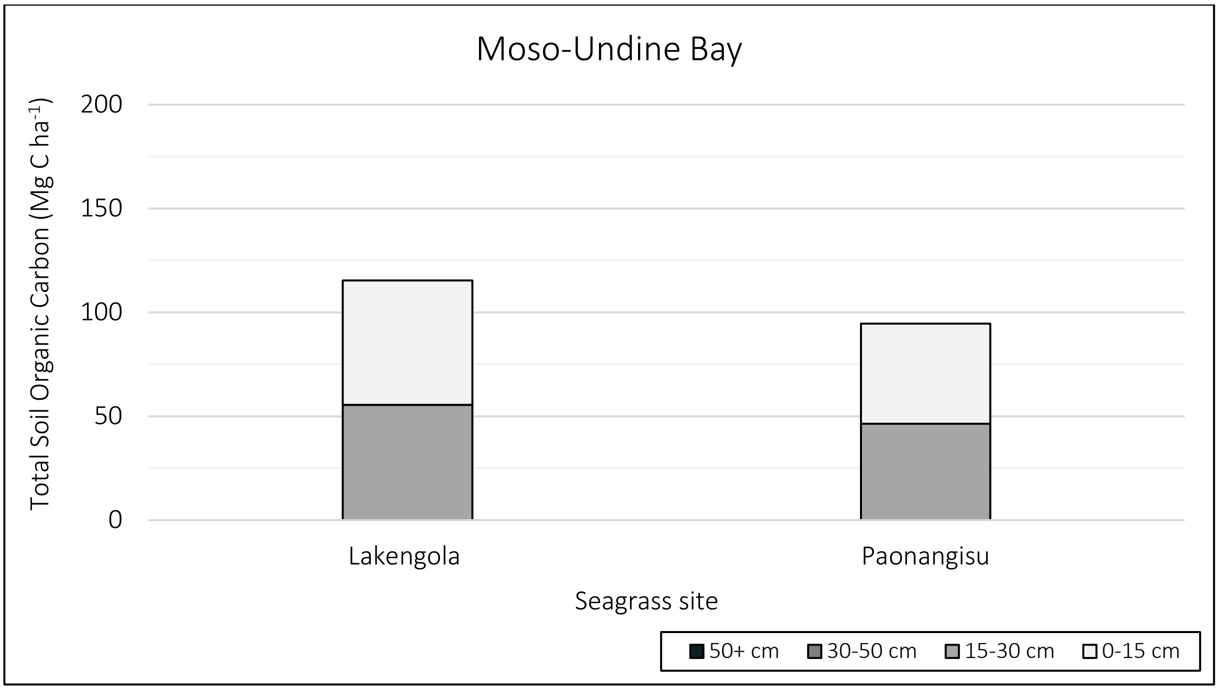


Figure 100. Seagrass soil organic carbon at different soil depths at two seagrass sites in Moso-Undine Bay, Vanuatu.

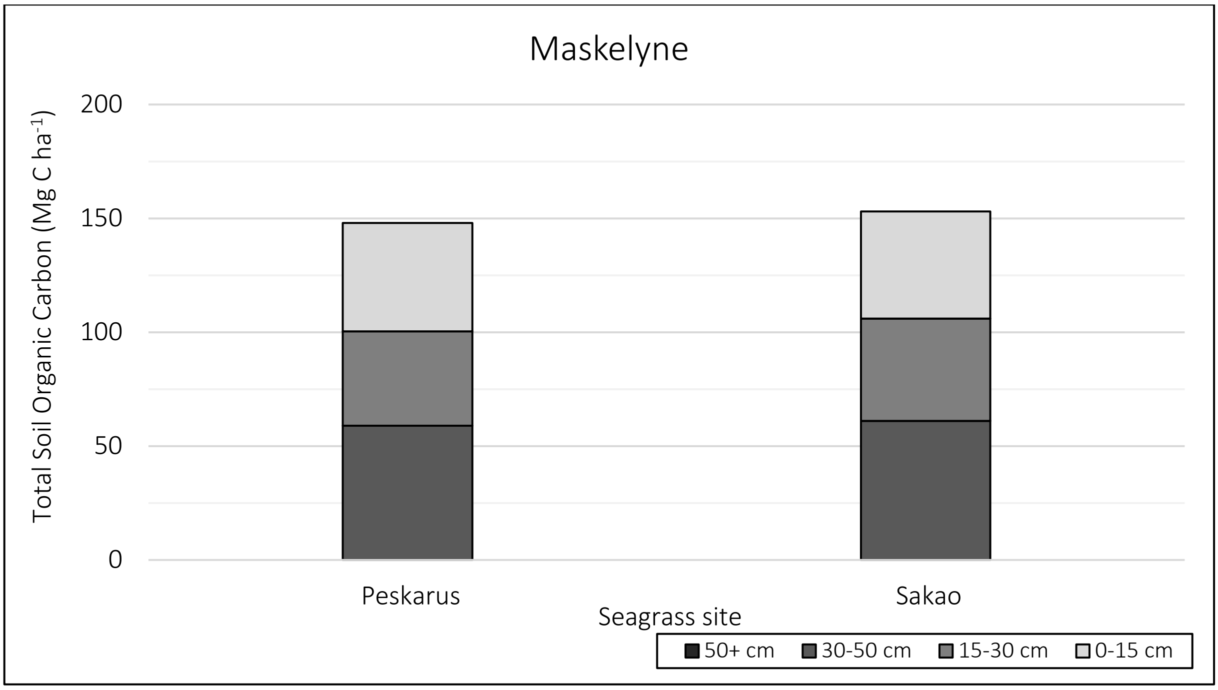


Figure 101. Seagrass soil organic carbon at different soil depths at two seagrass sites in the Maskelyne Islands, Vanuatu.

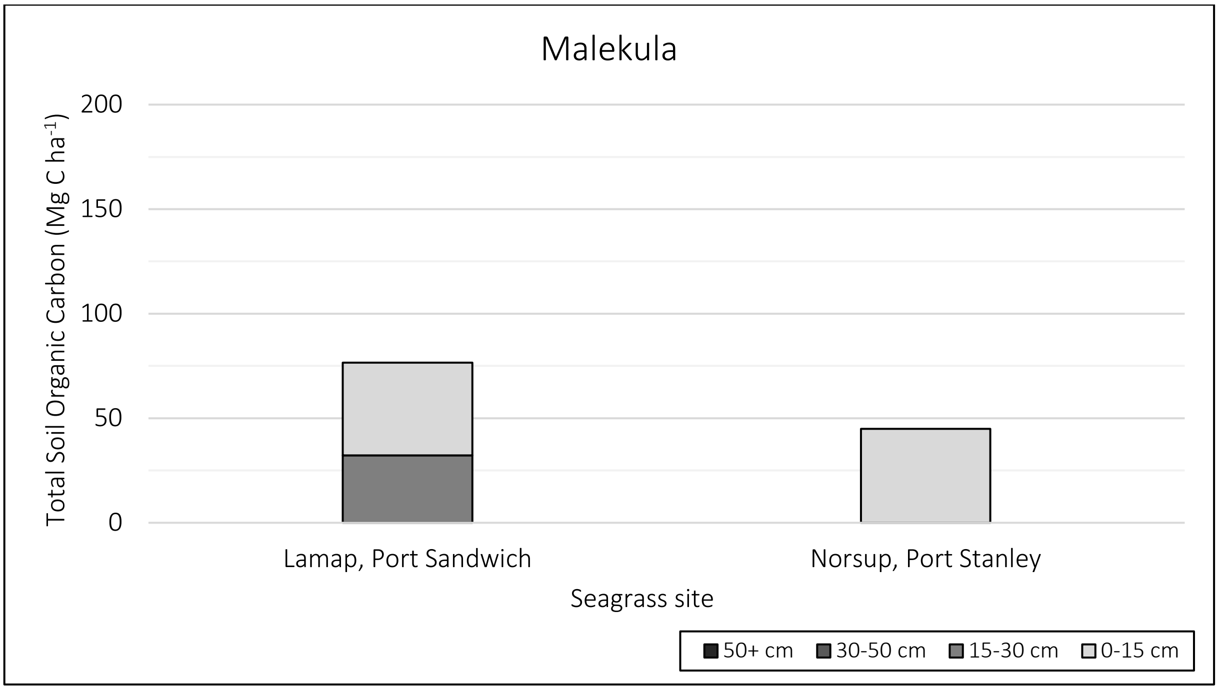


Figure 102. Seagrass soil organic carbon at different soil depths at two seagrass sites in Malekula, Vanuatu.

7.3 Vanuatu carbon assessment results – Mangrove

This results section for mangrove ecosystems is systematically divided into several subsections to provide a comprehensive analysis of the data. Initially, species density is examined across various locations, offering insights into the geographical distribution of species. Subsequent subsections focus on the comparative analysis of above-ground (AG) and below-ground (BG) biomass, evaluated across different locations and land use conversion categories. These comparisons help understand the spatial variations in carbon stock distribution and their implications for carbon storage and ecosystem dynamics.

7.3.1 Species density

The mean species density (mean ± standard error) was measured in trees per hectare (trees ha^{-1}) across six (6) mangrove sites in Moso-Undine Bay. Sites in this location were predominantly covered by a dense stand of *Rhizophora stylosa*, with a mean density of 1,150 ± 88 trees ha^{-1} (Figure 103). This was followed by *Xylocarpus granatum* (647 trees ha^{-1}) and *Ceriops tagal* (486 ± 104 trees ha^{-1}). The least dominant species were *Lumnitzera littorea* (225 trees ha^{-1}), *Sonneratia alba* (170 ± 30 trees ha^{-1}) and *Bruguiera gymnorhiza* (171 ± 101 trees ha^{-1}).

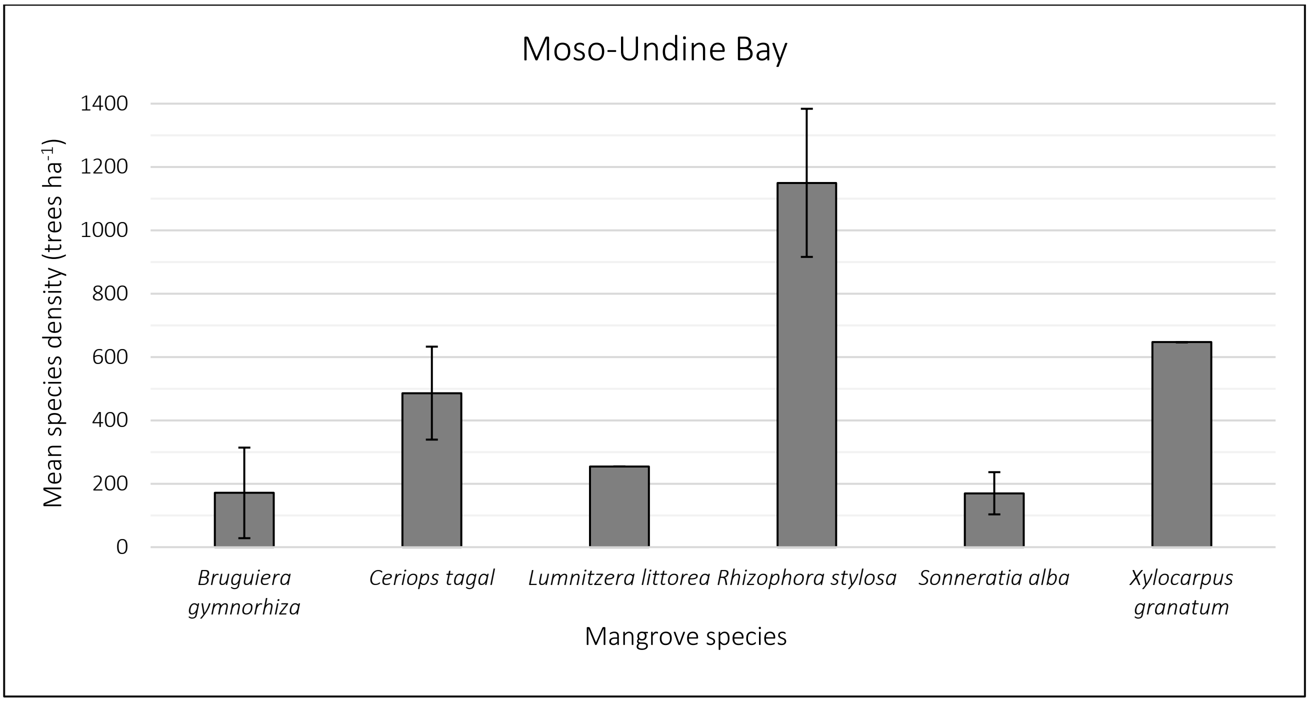


Figure 103. Bar graph showing the mean density of mangrove species in Moso-Undine Bay. *Rhizophora stylosa* exhibited the highest density at 1,150 trees ha^{-1}, followed by *Xylocarpus granatum* and *Ceriops tagal* with densities of 647 and 486 trees ha^{-1}, respectively. *Lumnitzera littorea* (255 trees ha^{-1}), *Sonneratia alba* (170 trees ha^{-1}) and *Bruguiera gymnorhiza* (171 trees ha^{-1}) had the lowest densities. Error bars represent the standard error of the mean.

In Port Vila-Eratap, *Rhizophora stylosa* had the highest mean density, with 1,109 ± 191 trees ha^{-1}, followed by *Sonneratia alba* (465 trees ha^{-1}) and *Bruguiera gymnorhiza* (273 ± 44 trees ha^{-1}) (Figure 104). The least dominant species at this location was *Xylocarpus granatum*, with a density of 26 trees ha^{-1} (Figure 104). *Rhizophora stylosa* is known for its extensive root systems and high biomass. This suggests a substantial capacity for carbon sequestration at this location. Furthermore, the presence of other species like *Bruguiera gymnorhiza*, *Sonneratia alba* and *Xylocarpus granatum* contributes to a diverse carbon pool. Different species have varying rates of carbon uptake and storage, enhancing the overall carbon sequestration potential of the ecosystem.

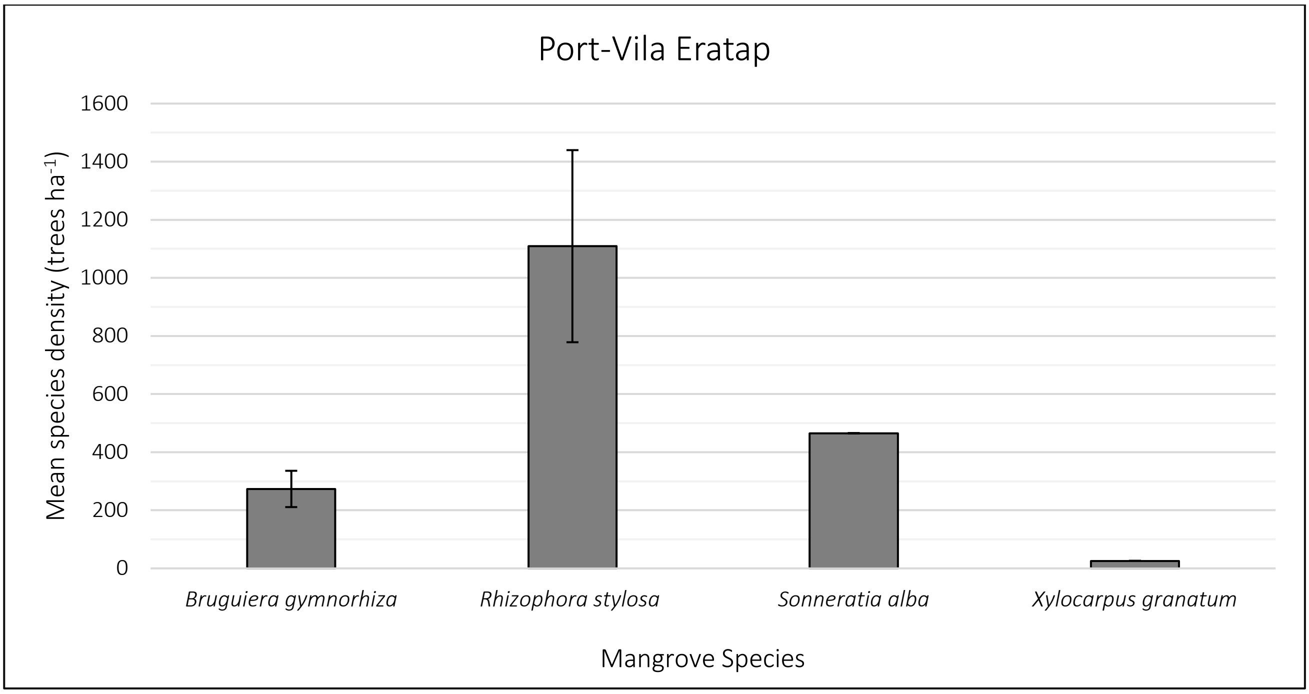


Figure 104. Bar graph showing the mean density of mangrove species in Port Vila-Eratap.

In Santo, *Rhizophora stylosa*, *Avicennia marina*, and *Sonneratia alba* had the highest mean densities, with 883 ± 371 trees ha^{-1}, 436 ± 103 trees ha^{-1}, and 401 ± 11 trees ha^{-1}, respectively (Figure 105). *Rhizophora stylosa* is highly effective in carbon storage due to its extensive stilt roots and substantial above-ground biomass. These stilt roots not only stabilize the soil and prevent erosion but also trap carbon-rich sediments, while the dense above-ground biomass stores significant amounts of carbon, contributing greatly to blue carbon sequestration. This effectiveness is reflected in the carbon storage analysis in Section 7.3.3 of the report. *Ceriops tagal* had a tree density of 64 ± 21 trees ha^{-1}, while *Bruguiera gymnorhiza* had the lowest density at this location, with a total of 17 trees ha^{-1} (Figure 105).

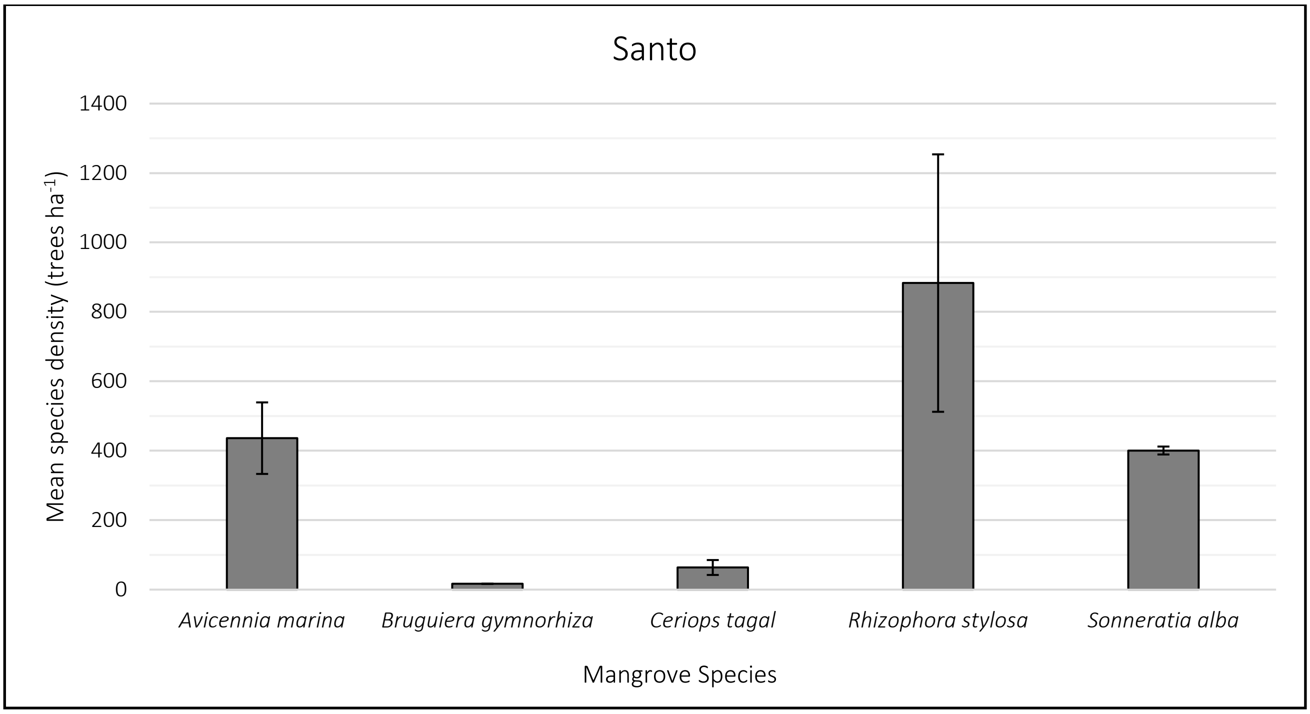


Figure 105. Bar graph showing the mean density of mangrove species in Santo. *Rhizophora stylosa* (883 trees ha^{-1}), *Avicennia marina* (436 trees ha^{-1}) and *Sonneratia alba* had 401 trees ha$^{-1.}$ had the highest densities. *Ceriops tagal* had 64 trees ha^{-1}. *Bruguiera gymnorhiza* had the lowest density when compared to all other species (17 trees ha^{-1}). Error bars represent the standard error of the mean.

In Malo-Aore, *Ceriops tagal* and *Rhizophora stylosa* were the dominant species, with densities of 456 ± 314 trees ha^{-1} and 425 ± 247 trees ha^{-1}, respectively (Figure 106). *Rhizophora stylosa* is commonly found in Southeast Asia and the Pacific Islands, where it plays a crucial role in stabilizing shorelines and sequestering carbon in both its biomass and the soil. *Ceriops tagal* is also effective in carbon storage, particularly in soil carbon sequestration, due to its robust root systems. This species is prevalent in similar tropical and subtropical regions, contributing to the overall carbon storage capacity of mangrove ecosystems. *Avicennia marina* had a density of 119 ± 75 trees ha^{-1}, while all other remaining species had a density of 31 trees ha^{-1} or less.

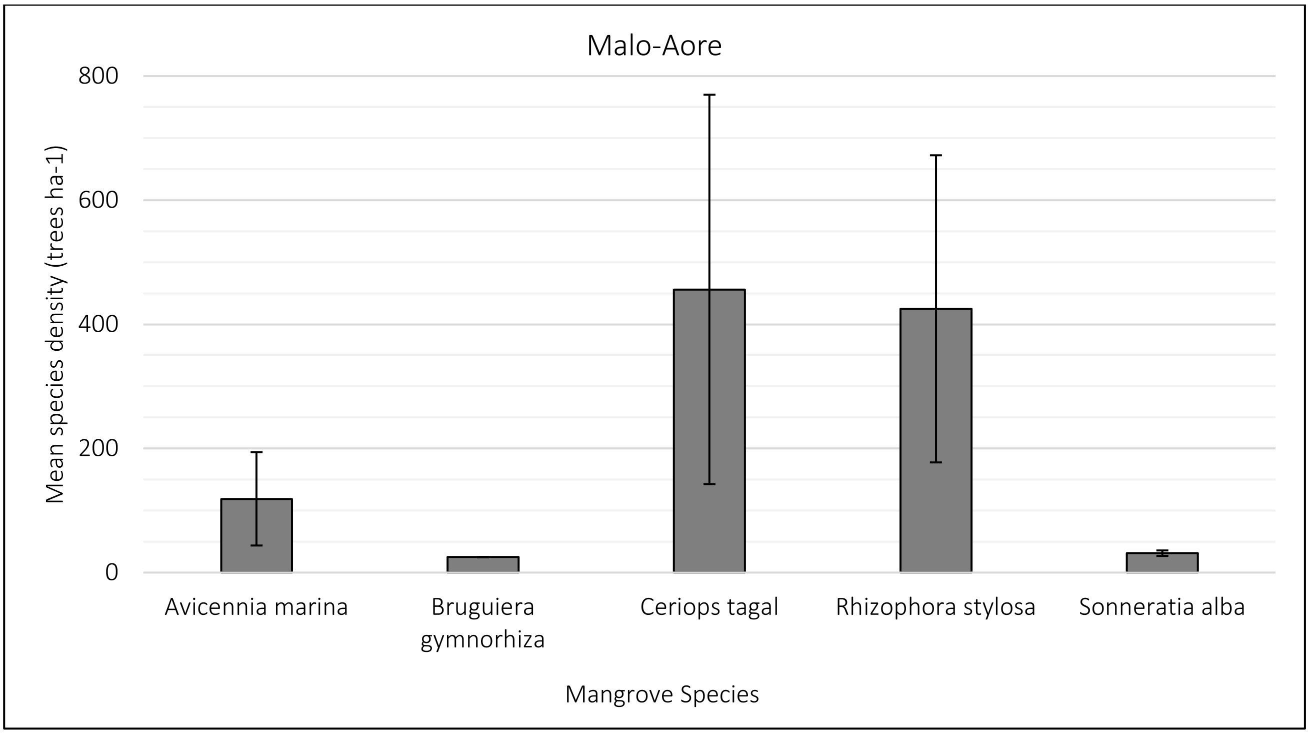


Figure 106. Bar graph showing the mean density of mangrove species in Malo-Aore. *Ceriops tagal* (456 trees ha^{-1}) and *Rhizophora stylosa* (425 trees ha^{-1}) had the highest densities, followed by *Avicennia marina* (119 trees ha^{-1}), while the remaining two species had a density <31 trees ha-1. Error bars represent the standard error of the mean.

In Malekula, *Sonneratia alba* had a tree density of 1,204 ± 845 trees ha^{-1}, while *Ceriops tagal* had a tree density of 513 trees ha^{-1}. *Sonneratia alba* is known for its substantial above-ground biomass, which plays a significant role in carbon storage (Figure 107). When compared to other mangrove species such as *Avicennia marina*, *Sonneratia alba* generally exhibits higher biomass and carbon storage capacity, with larger girth and height resulting in greater biomass and carbon sequestration potential. *Rhizophora stylosa* and *Bruguiera gymnorhiza* had densities of 214 ± 43 trees ha^{-1} and 169 ± 69 trees ha^{-1}, respectively. *Avicennia marina* had the lowest species density at this location, with 65 trees ha^{-1}.

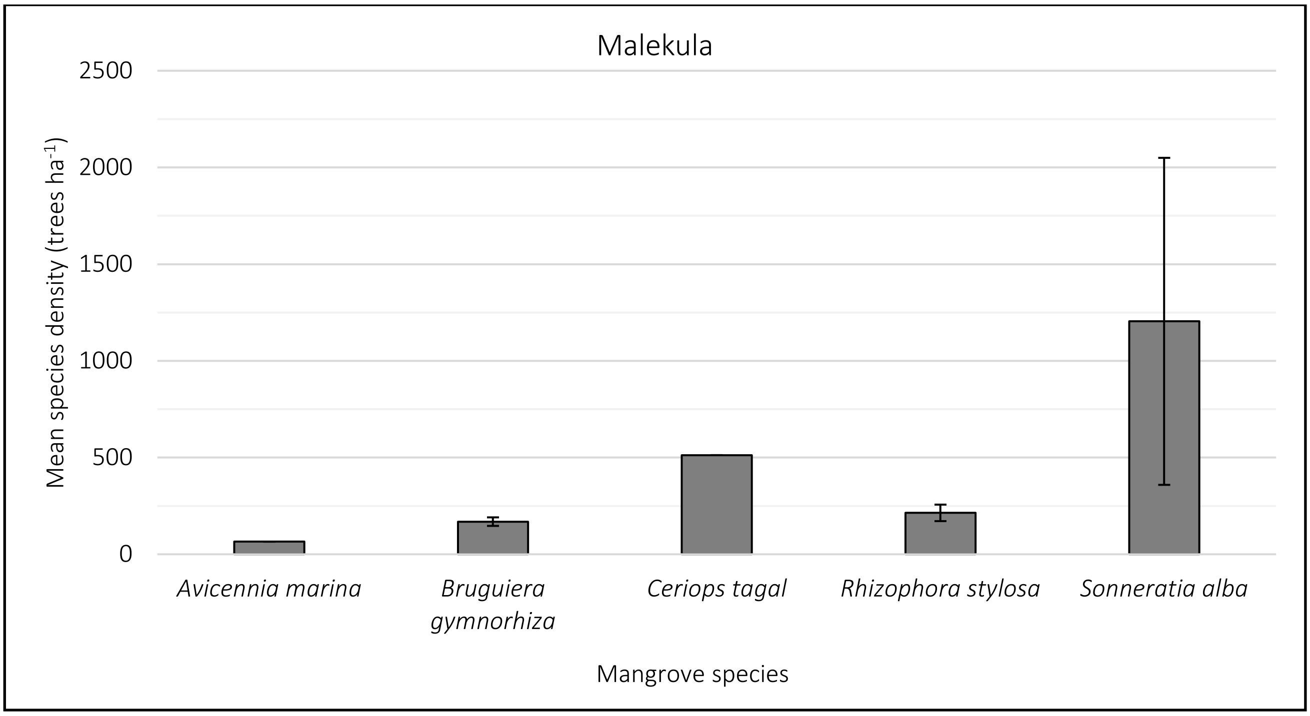


Figure 107. Bar graph showing the mean density of mangrove species in Malekula. *Sonneratia alba* had the highest density at 1,204 trees ha^{-1}, followed by *Ceriops tagal* (513 trees ha^{-1}), *Rhizophora stylosa* (214 trees ha^{-1}) and *Bruguiera gymnorhiza* (169 trees ha^{-1}). *Avicennia marina* had the lowest species density of 65 trees ha^{-1}. Error bars represent the standard error of the mean.

In Maskelyne, *Avicennia marina* had the highest density across the sites, with 661 ± 38 trees ha^{-1} (Figure 109). *Rhizophora stylosa* had a tree density of 624 trees ha^{-1}, while *Ceriops tagal* had a tree density of 128 trees ha^{-1}. *Xylocarpus granatum* had the lowest species density at this location, with 57 trees ha^{-1} (Figure 108).

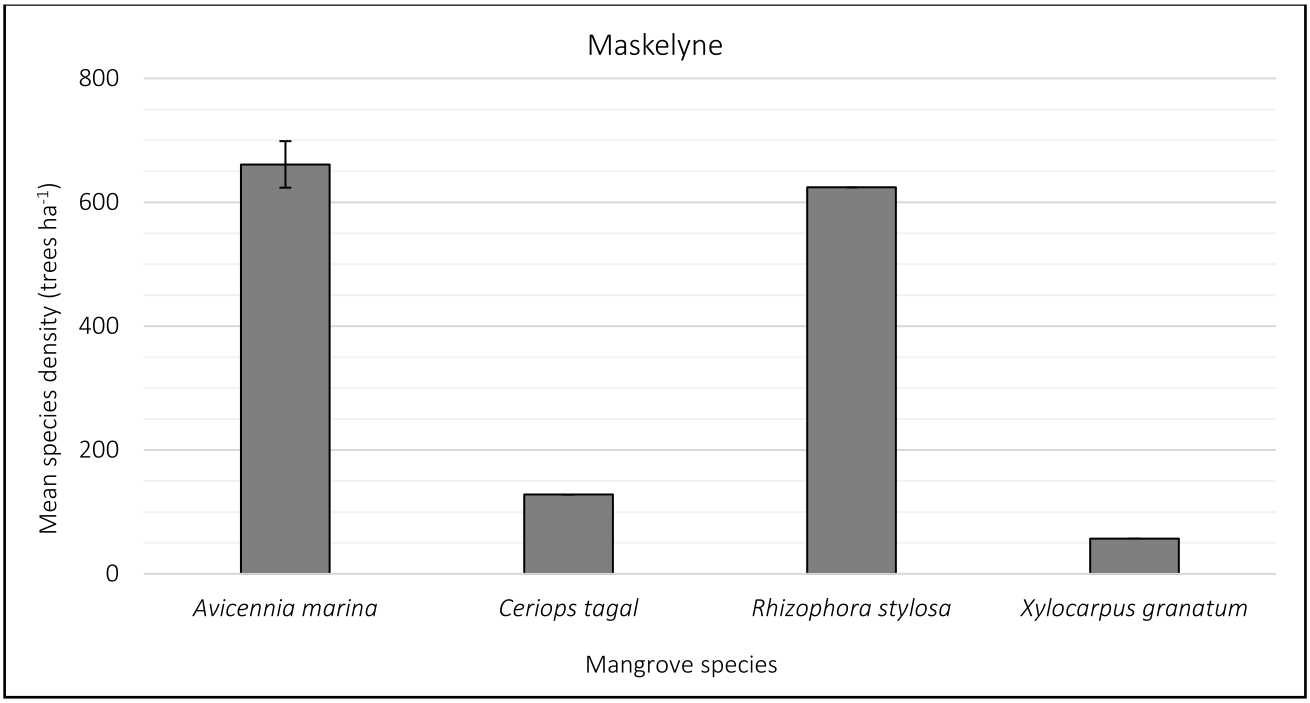


Figure 108. Bar graph showing the mean density of mangrove species in the Maskelyne Islands (Peskarus and Sakao). *Avicennia marina* had the highest density at 661 trees ha^{-1}, followed by *Rhizophora stylosa* at 624 trees ha^{-1}. *Ceriops tagal* and *Xylocarpus granatum* had a density of 128 and 57 trees ha^{-1}, respectively. Error bars represent the standard error of the mean.

7.3.2 Above-ground and below-ground tree carbon storage

As shown in Figure 110, tree carbon storage (TCS) refers to the amount of carbon stored within trees, which can be stored above-ground (in their trunks, stems, foliage, aerial roots and prop roots) and below-ground (in their roots). Total TCS refers to the sum of the carbon stored in trees both above-ground (AG) and below-ground (BG).

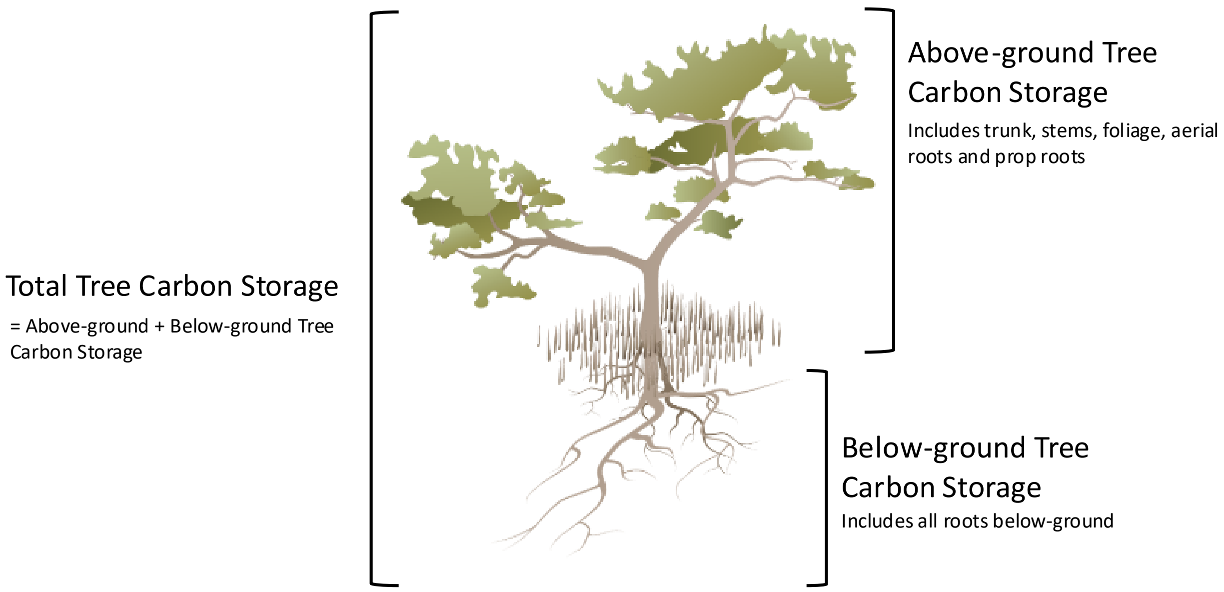
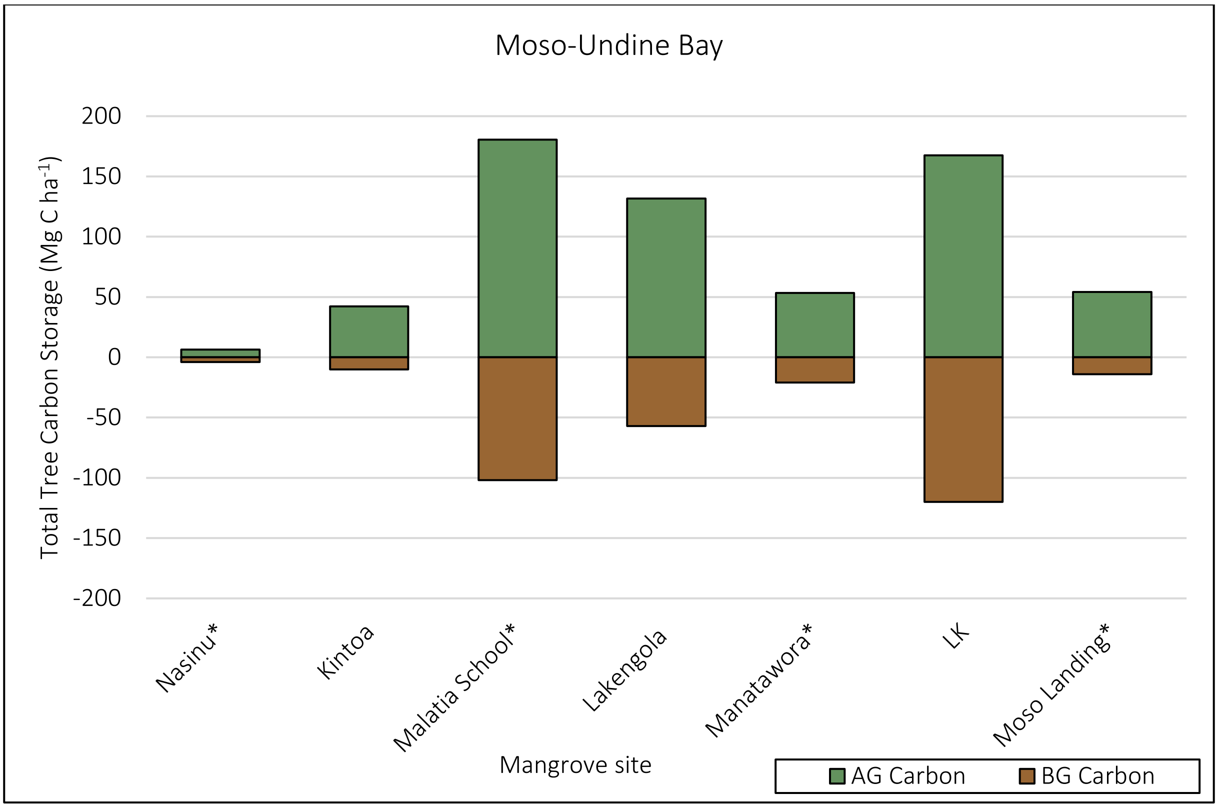


Figure 109. Illustration of total tree carbon storage stored in trees both above and below-ground.

Upper and lower estimates for the mean total TCS were calculated in megagrams of carbon per hectare (Mg C ha^{-1}) for each study location (Figure 110) and study site (Figure 113 to Figure 118) across Vanuatu. In this section, we report the lower estimates unless otherwise stated.



The mean total TCS was also calculated for each study location and is presented as mean ± standard error. Across all locations sampled, Port Vila-Eratap and Santo had the highest mean total TCS, with a total of 367 ± 116 Mg C ha^{-1} and 365 ± 32 Mg C ha^{-1}, respectively (Figure 110). The higher TCS at these locations is likely related to species composition (high density of *Rhizophora stylosa*). By comparison, TCS levels were much lower at Maskelyne (127 ± 14 Mg C ha^{-1}), Moso Undine Bay (138 ± 16 Mg C ha^{-1}), Malo-Aore (142 ± 53 Mg C ha^{-1}) and Malekula (98 ± 38 Mg C ha^{-1}).

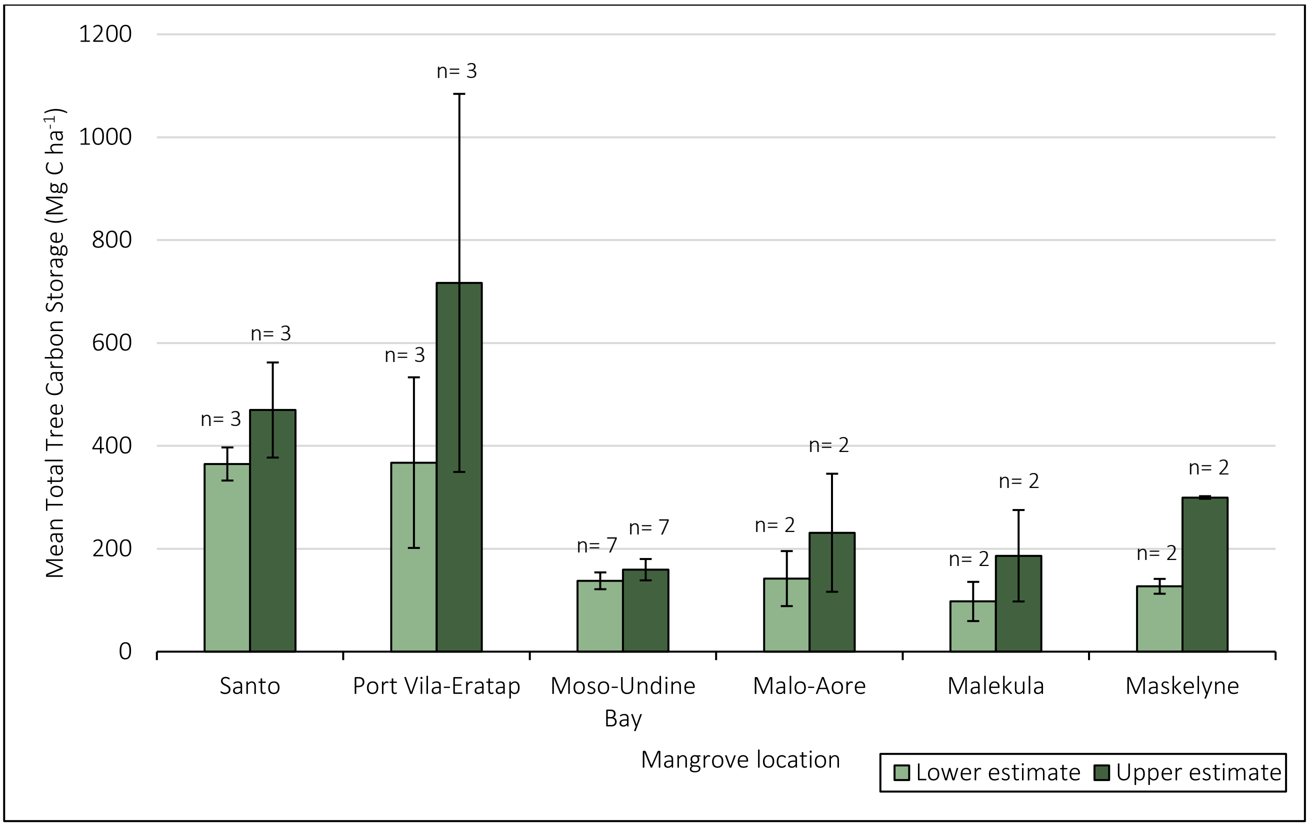


Figure 110. Mean tree carbon storage (± SE) in Vanuatu. Santo had the highest carbon storage at 365 Mg C ha^{-1}, followed by Port Vila-Eratap (367 Mg C ha^{-1}). Relatively lower levels were found at Maskelyne (127 Mg C ha^{-1}), Moso Undine Bay (138 Mg C ha^{-1}), Malo-Aore (142 Mg C ha^{-1}) and Malekula (98 Mg C ha^{-1}). Error bars represent the standard error of the mean.

Across the six locations in Vanuatu, assessment sites in Port Vila-Eratap and Santo had the highest above-ground (AG) tree carbon storage, with 294 ± 138 Mg C ha^{-1} and 246 ± 40 Mg C ha^{-1}, respectively (Figure 110). Relatively lower AG carbon levels were found at Malo-Aore (106 ± 40 Mg C ha^{-1}), Maskelyne (99 ± 8 Mg C ha^{-1}), Moso-Undine Bay (91 ± 10 Mg C ha^{-1}), and Malekula (64 ± 21 Mg C ha^{-1}). Santo exhibited the highest below-ground (BG) tree carbon storage at 119 ± 7 Mg C ha^{-1}, followed by Port Vila-Eratap with 73 ± 28 Mg C ha^{-1}. All other locations had BG tree carbon storage below 50 Mg C ha^{-1}.

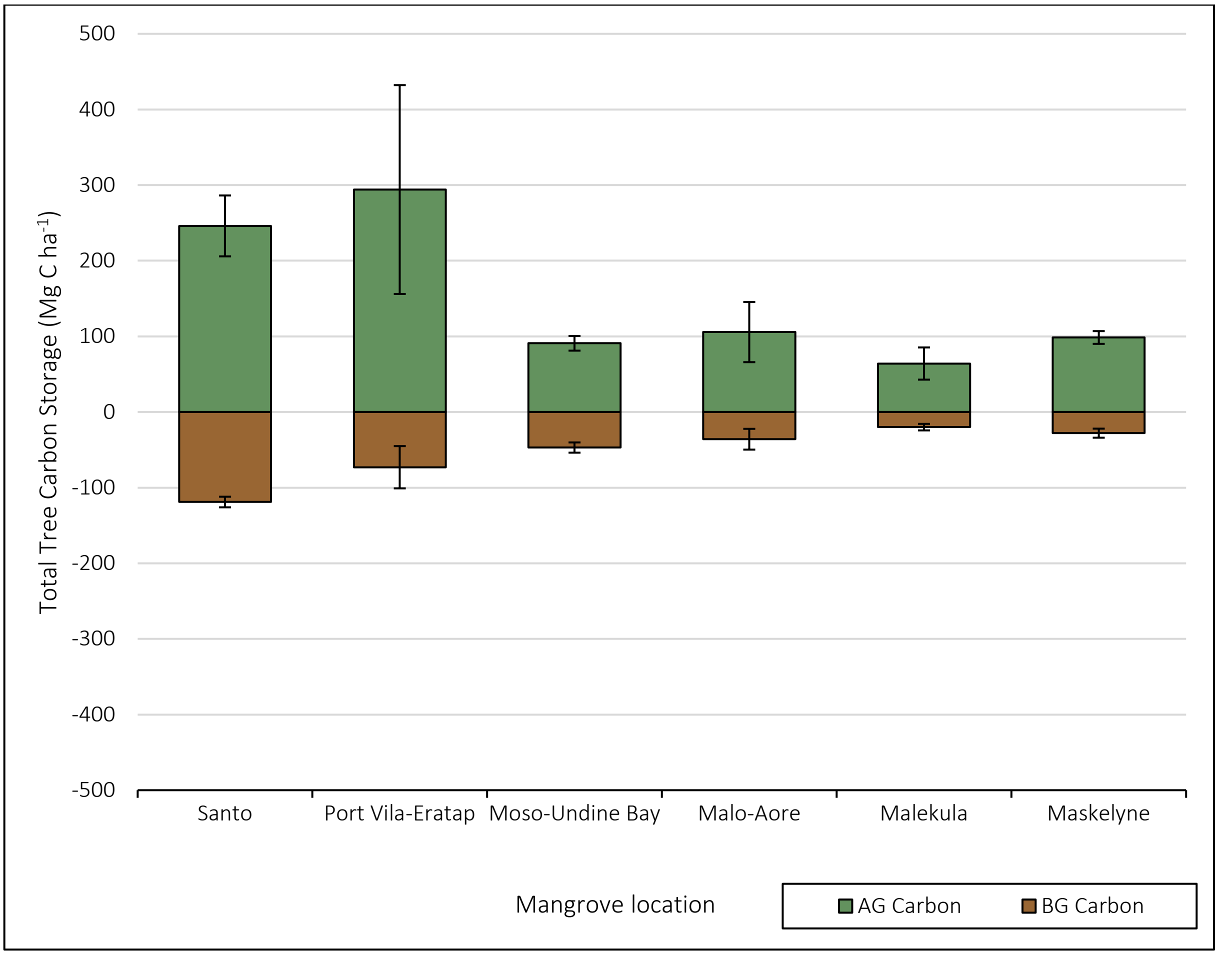
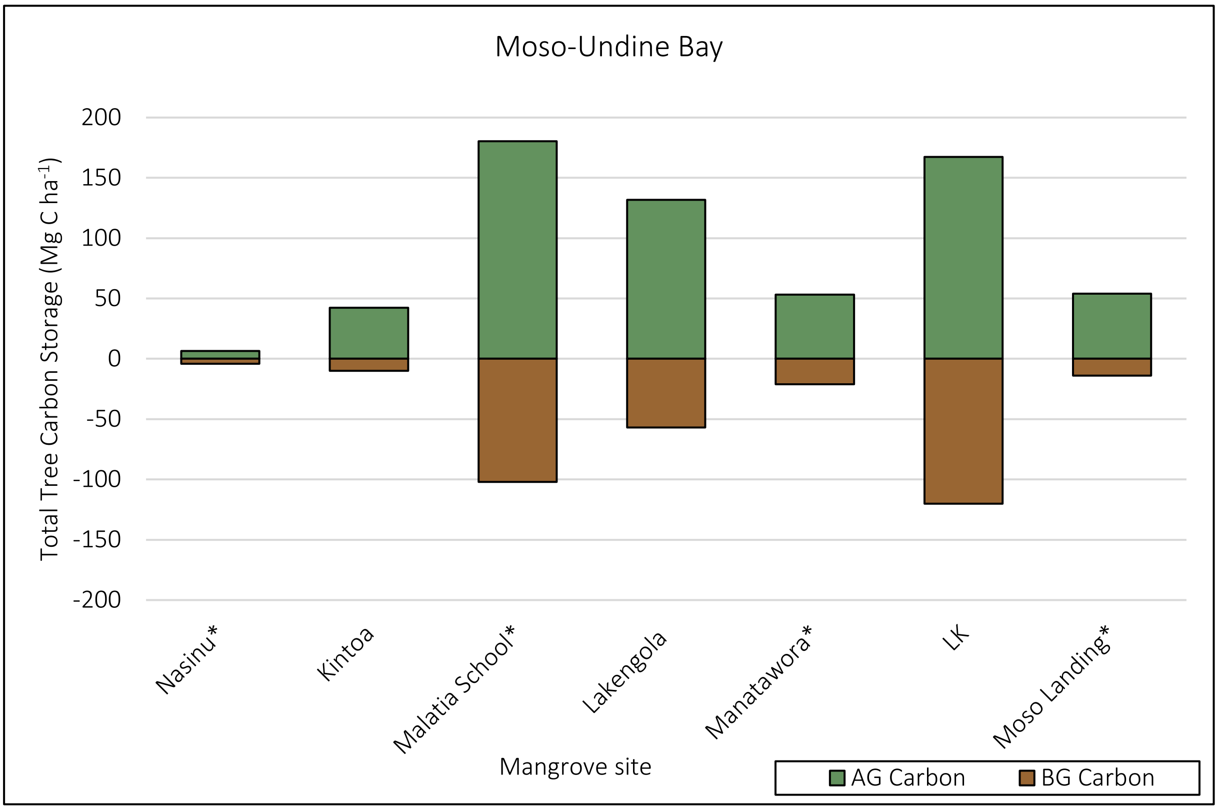


Figure 111. Mean total above-ground (AG) and below-ground (BG) tree carbon storage across study locations in Vanuatu: Port Vila-Eratap and Santo had the highest AG tree carbon storage (294 Mg C ha^{-1} and 246 Mg C ha-^{1}, respectively). Malo-Aore (106 Mg C ha-^{1}), Maskelyne (99 Mg C ha-^{1}), Moso-Undine Bay (91 Mg C ha-^{1}), and Malekula (64 Mg C ha^{-1}) had relatively lower AG tree carbon storage. Santo had the highest BG tree carbon storage (119 Mg C ha^{-1}), followed by Port Vila-Eratap (73 Mg C ha^{-1}), Moso-Undine Bay (47 Mg C ha^{-1}), Malo-Aore (36 Mg C ha^{-1}), Maskelyne (28 Mg C ha^{-1}), and Malekula (20 Mg C ha^{-1}). Error bars represent the standard error of the mean.



There was significant variation in AG and BG tree carbon storage (TCS) between sites at each location, however, the majority of sites had total TCS less than 150 Mg C ha^{-1}. Higher levels were typically found in river deltas such as Sarakata River, Port Sandwich, Malatao River, which ranged from 171 to 476 Mg C ha^{-1} (

Figure 113, Figure 115 and Figure 117). There was one site that had twice as much carbon, compared to all other sites in Vanuatu. This site, called Tuuaimatic which was on Efate near coastal Port Vila, retained very large *Bruguiera gymnorhiza* which resulted in exceptionally high live tree carbon (942 Mg C^{-1}) (Figure 114). Many of the sites assessed were considered degraded, due to widespread cyclone damage across Vanuatu, in addition to localised wood harvesting pressures. At the most significantly degraded sites lowest TCS were found, ranging from 10 to 98 Mg C ha $^{-1}$ (

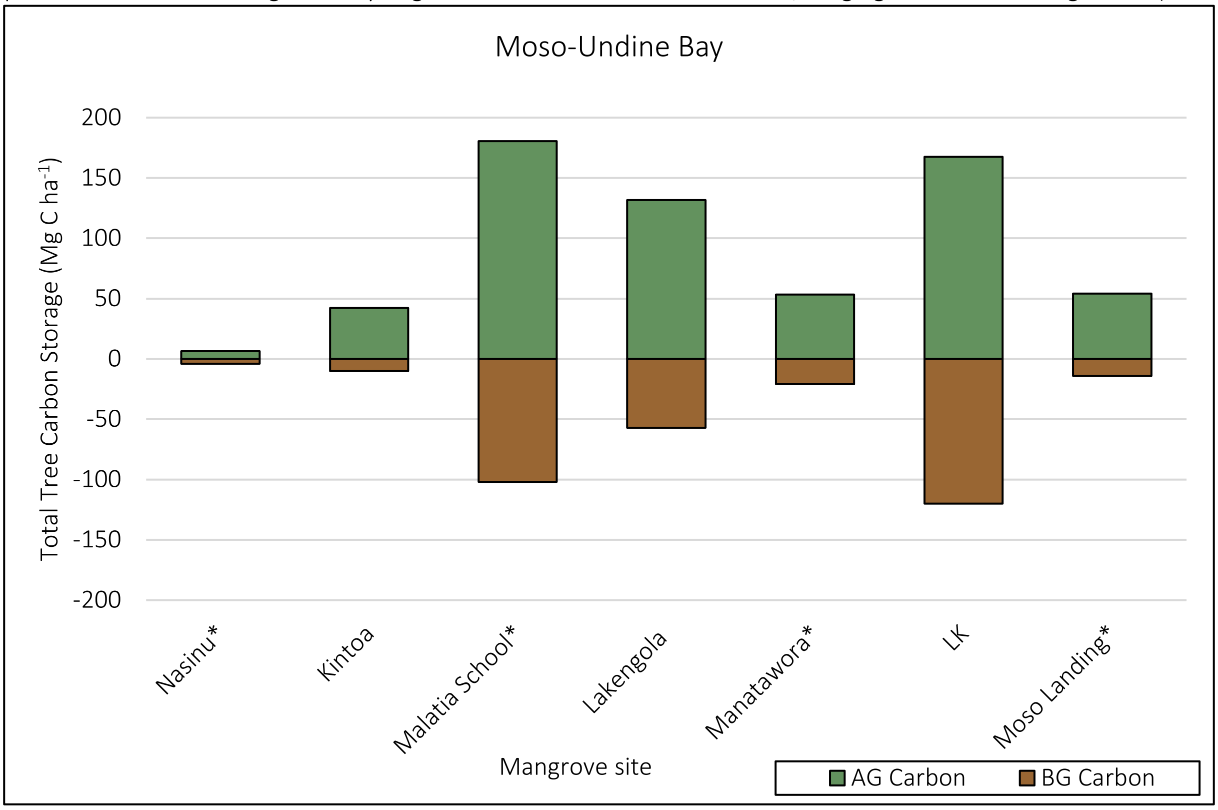


Figure 113 to Figure 118).

Figure 112. Two large *Ceriops tagal* that were measured at one degraded site in Santo. These were the only large trees at this site; the surrounding area was a settlement and generally quite disturbed.

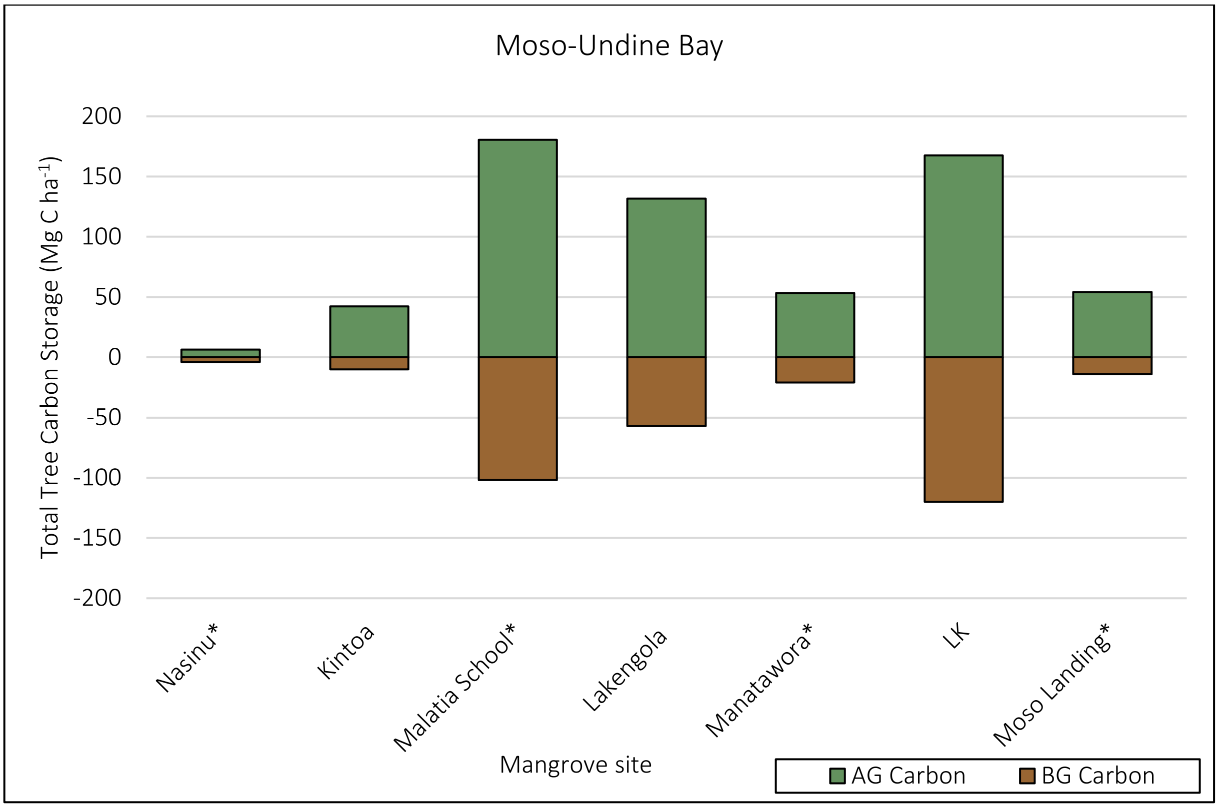


Figure 113. Above-ground (AG) and below-ground (BG) mangrove tree carbon storage at each mangrove assessment site for the Moso-Undine Bay location. An asterisk (*) is indicative of a degraded site. Four assessment sites were classified as degraded, due to significant cyclone impacts and various levels of wood harvesting, three of which were associated with lower levels of live tree carbon storage.

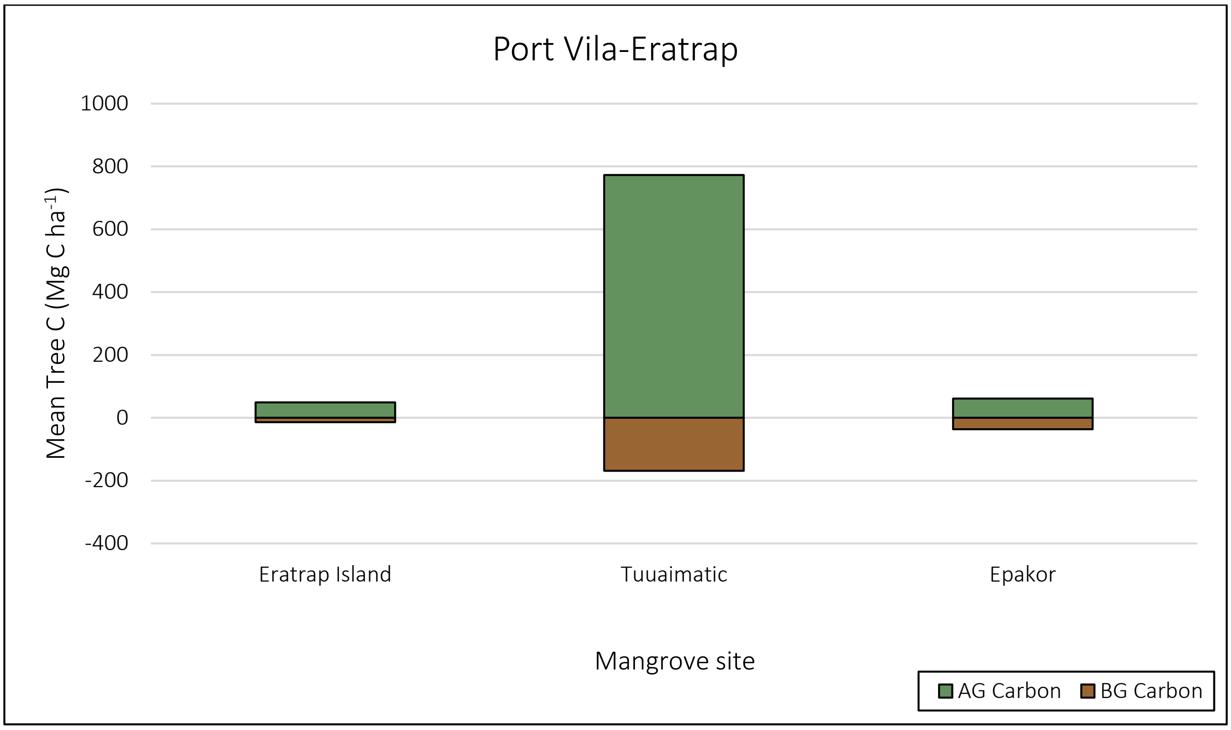


Figure 114. Above-ground (AG) and below-ground (BG) mangrove tree carbon storage at each mangrove assessment site for the Port Vila-Eratap Bay location. The site called Tuuaimatic retained very large *Bruguiera gymnorhiza* trees, which resulted in exceptionally high live tree carbon (941 Mg C ha^{-1}) compared to other sites at this location.

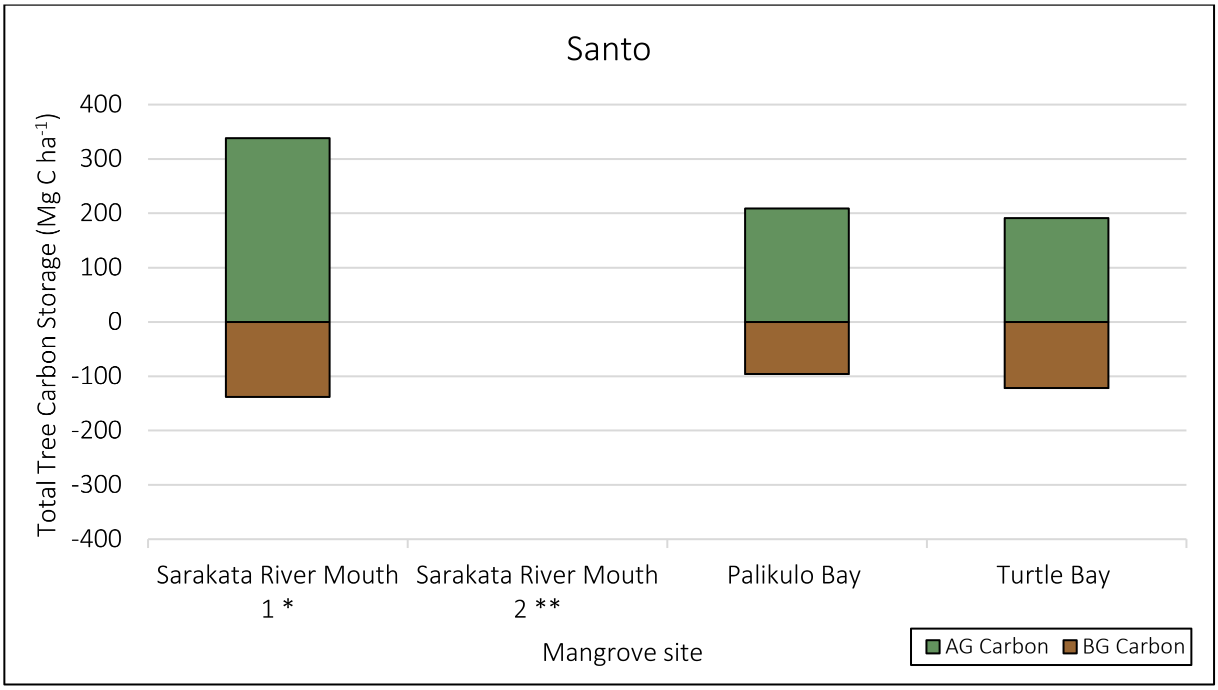


Figure 115. Above-ground (AG) and below-ground (BG) mangrove tree carbon storage at each mangrove assessment site for the Santo location. One asterisk (*) is indicative of a degraded site. Two asterisks (**) is indicative of a converted site. The assessment site, Sarakata River Mouth 2, was classified as converted, due to cyclone impacts and pressure from adjacent urban land-use.

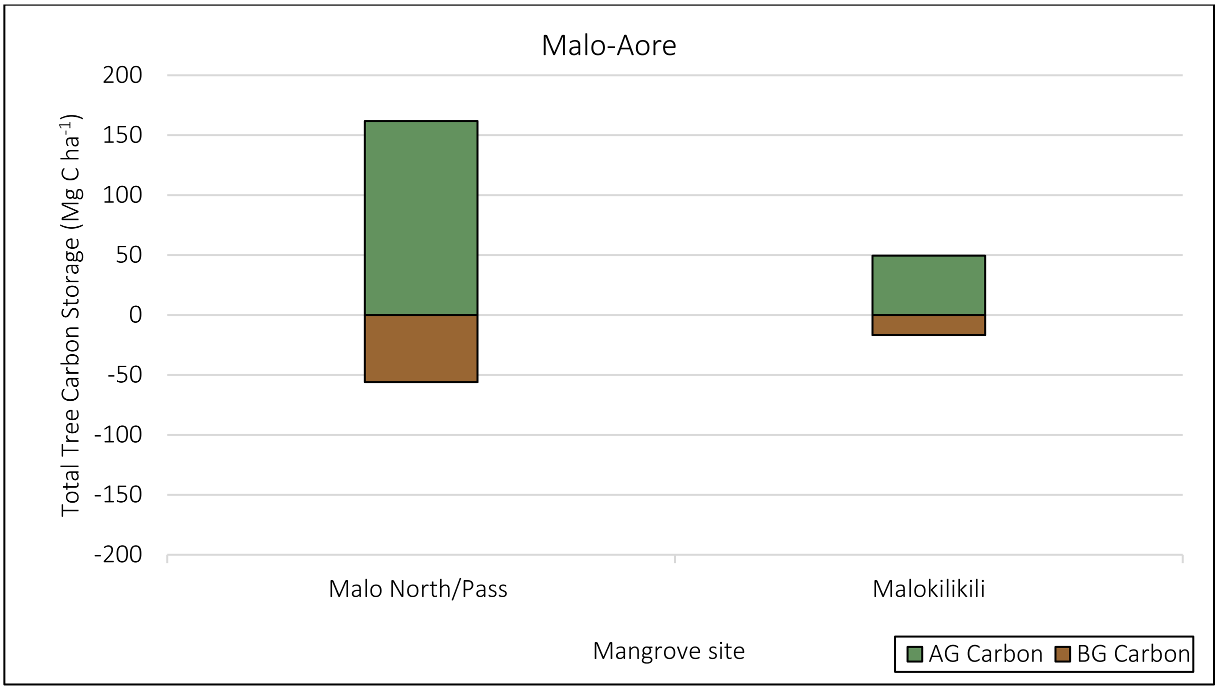


Figure 116. Above-ground (AG) and below-ground (BG) mangrove tree carbon storage at each mangrove assessment site for the Malo-Aore location. Both mangrove sites had a level of cyclone impact.

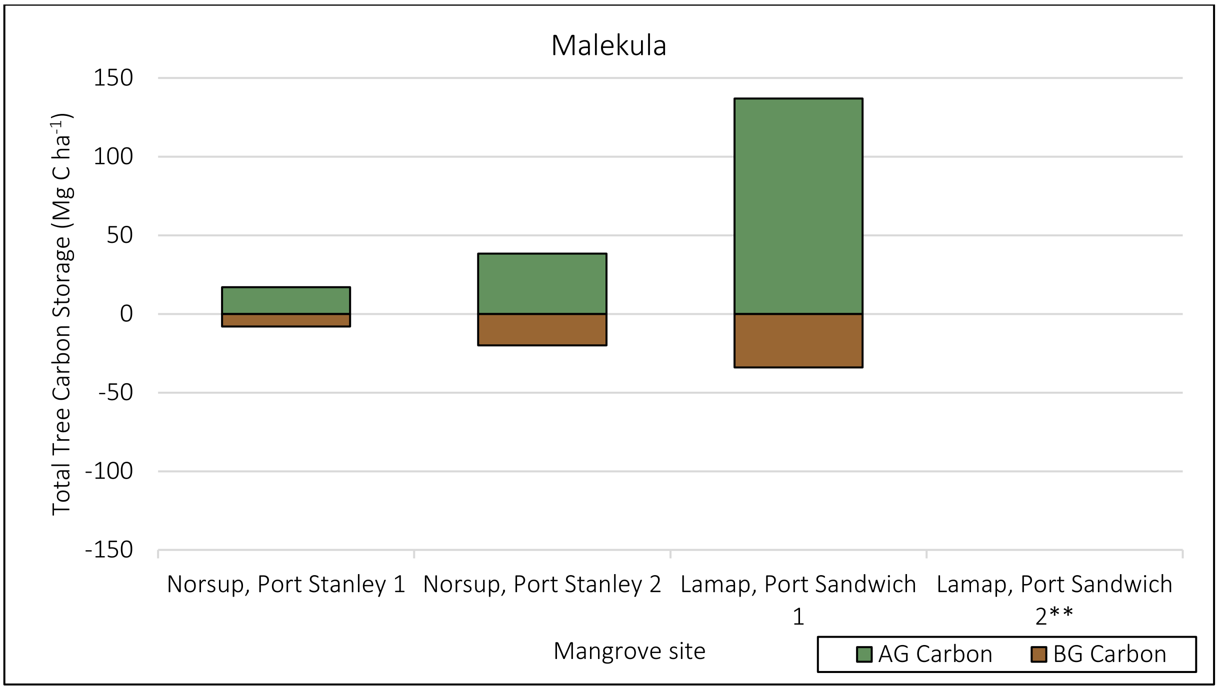


Figure 117. Above-ground (AG) and below-ground (BG) mangrove tree carbon storage at each mangrove assessment site for the Malekula location. There was evidence of cyclone impact at all sites, and timber harvesting at the Port Stanley sites. Two asterisks (**) are indicative of a converted site. The assessment site, Lamap Port Sandwich 2, was cleared of all mangrove trees.

Figure 118. Above-ground (AG) and below-ground (BG) mangrove tree carbon storage at each mangrove assessment site for the Maskelyne location. An asterisk (*) is indicative of a degraded site. At both sites, there was evidence of cyclone impact. The Peskarus site was classified as degraded due to clearing for village use.

7.3.3 Soil organic carbon

Mangrove soil organic carbon (SOC) sampling in Vanuatu represents the first meter of the sediment profile at most sites. However, due to field constraints, challenging conditions, or shallow bedrock at some locations, obtaining deeper samples was not always possible, therefore, the results from those sites represent only the top 50 cm or less of the soil profile. Sand dominated sediments were prevalent in Vanuatu mangrove sites which are difficult to sample to depth. Sampling depths at each site are represented between Figure 120 and Figure 125.

Across all study locations, mean SOC was relatively consistent within depth intervals. At 0-15 cm depths, mean SOC ranged from 44 to 65 Mg C ha^{-1}. This pattern was similar within other depth intervals. However, Port Vila-Eratap and Moso-Undine Bay generally had slightly higher SOC than other sites within each depth interval.

Overall, mean SOC totals were highest in Moso-Undine Bay at 378 Mg C ha^{-1}, followed by Port Vila-Eratap with 360 Mg C ha^{-1}, and Santo with 292 Mg C ha^{-1}. This may be attributed to sampling reaching depths greater than 50 cm. Mean SOC totals were slightly lower in Maskelyne (164 Mg C ha^{-1}), Malo-Aore (161 Mg C ha^{-1}), and Malekula (137 Mg C ha^{-1}).

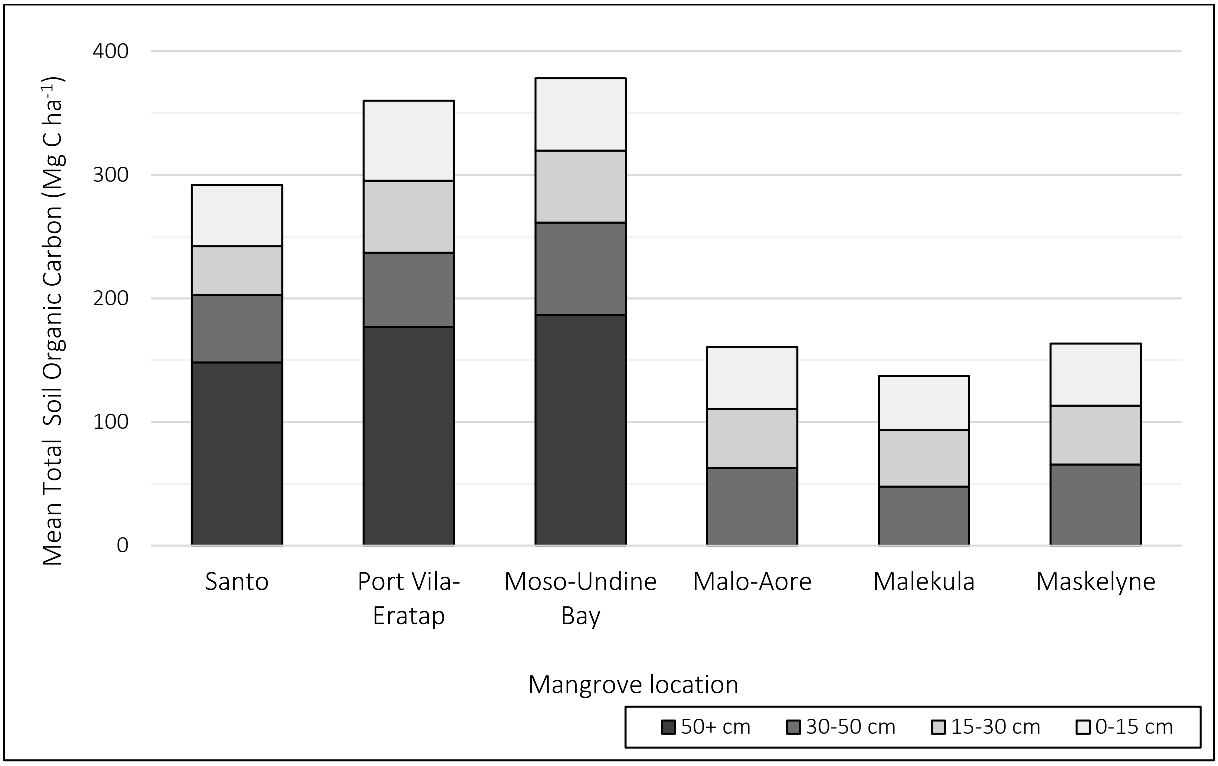


Figure 119. Mean total soil organic carbon (SOC) stocks at different soil depths at six mangrove study locations in Vanuatu.

Across all mangrove survey sites in Vanuatu, carbon content ranged from 1.3% to 36.6%, with stocks ranging from 89 to 449 Mg C ha^{-1}. Figure 120 to Figure 125 summarise SOC stocks at each mangrove assessment site and demonstrate the variability between sites at different depths. Soil organic carbon stocks varied between sites reflecting differences in soil properties, organic matter inputs and rates of organic matter decomposition.

The highest SOC was found in survey site LK in Moso-Undine Bay (449 Mg C ha^{-1}), where SOC from the 50+ cm depth interval contributed significantly with 212 Mg C ha^{-1} to the total SOC for this site (Figure 122). This site is associated with a riverine system which may contribute to higher SOC levels.

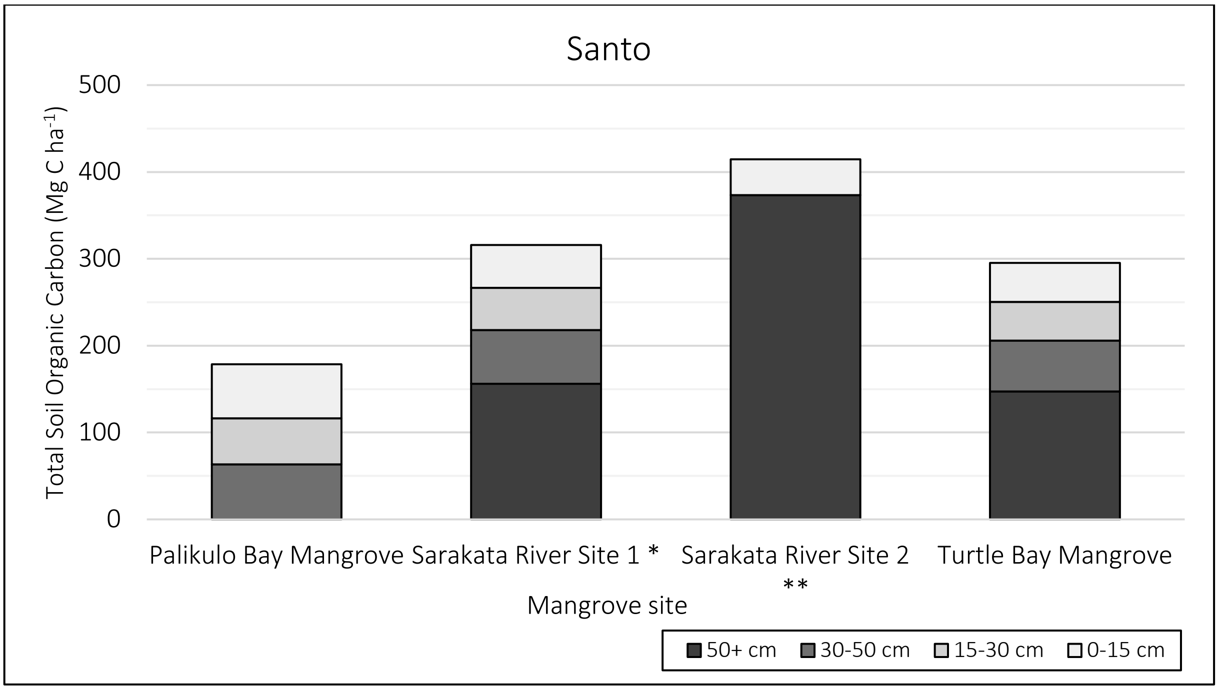


Figure 120. Mangrove soil organic carbon at different soil depths at four mangrove sites on Santo, Vanuatu. One asterisk (*) is indicative of a degraded site. Two assessment sites were classified as degraded. Sarakata River sites were degraded due to cyclone impacts, pressure from adjacent urban land-use and clearing for alternate land uses.

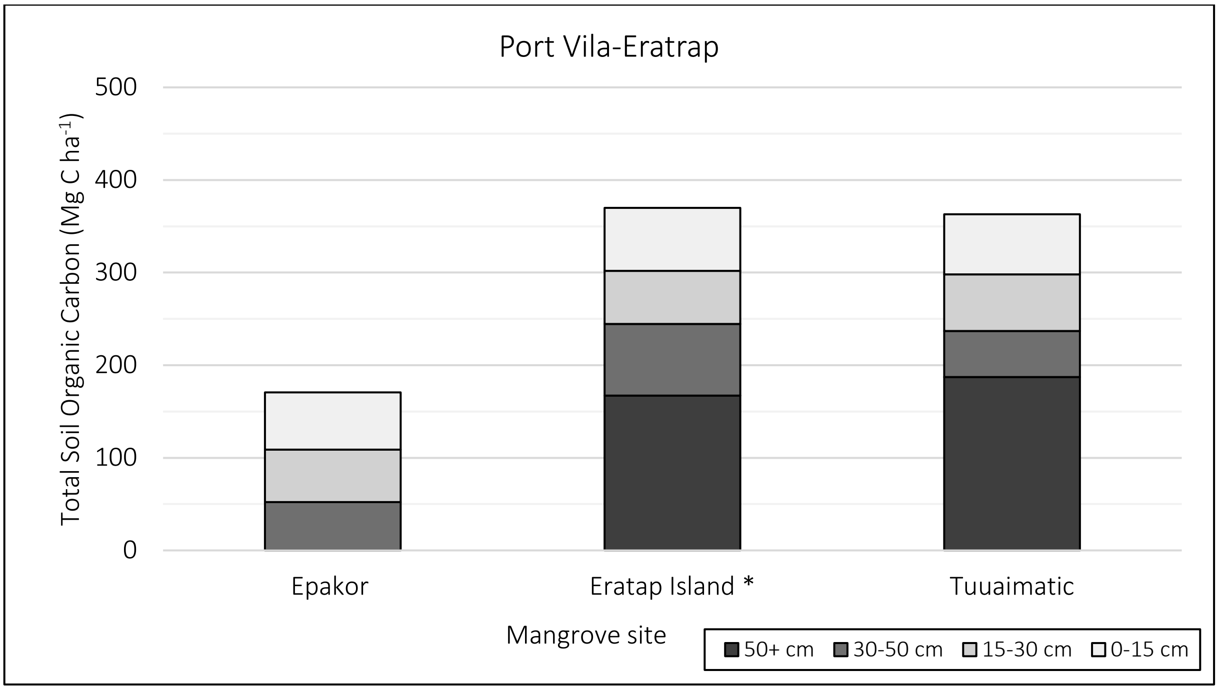


Figure 121. Mangrove soil organic carbon at different soil depths at three mangrove sites in Port Vila-Eratap, Vanuatu. An asterisk (*) is indicative of a degraded site. One assessment site was classified as degraded, due to clearing for tourism, wood harvesting and cyclone impact (Eratap), this site was associated with lower levels of live tree carbon storage.

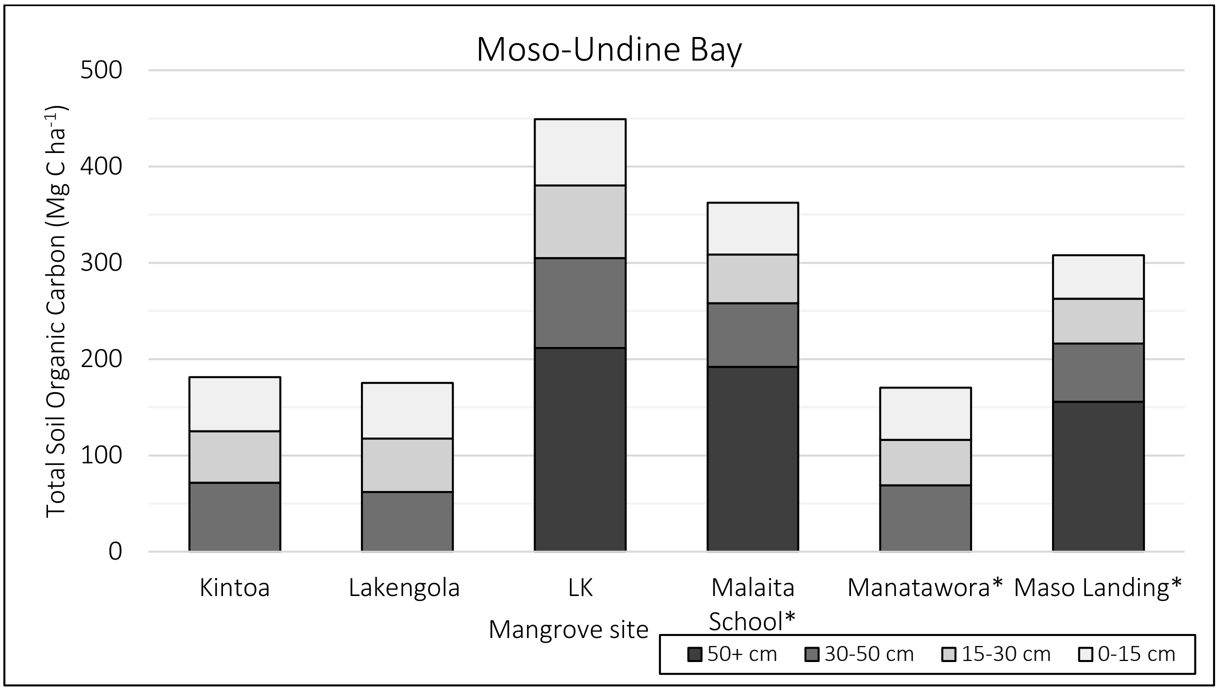


Figure 122. Mangrove soil organic carbon at different soil depths at four mangrove sites in Moso-Undine Bay, Vanuatu. An asterisk (*) is indicative of a degraded site. Three assessment sites were classified as degraded, due to significant cyclone impacts and various levels of wood harvesting.

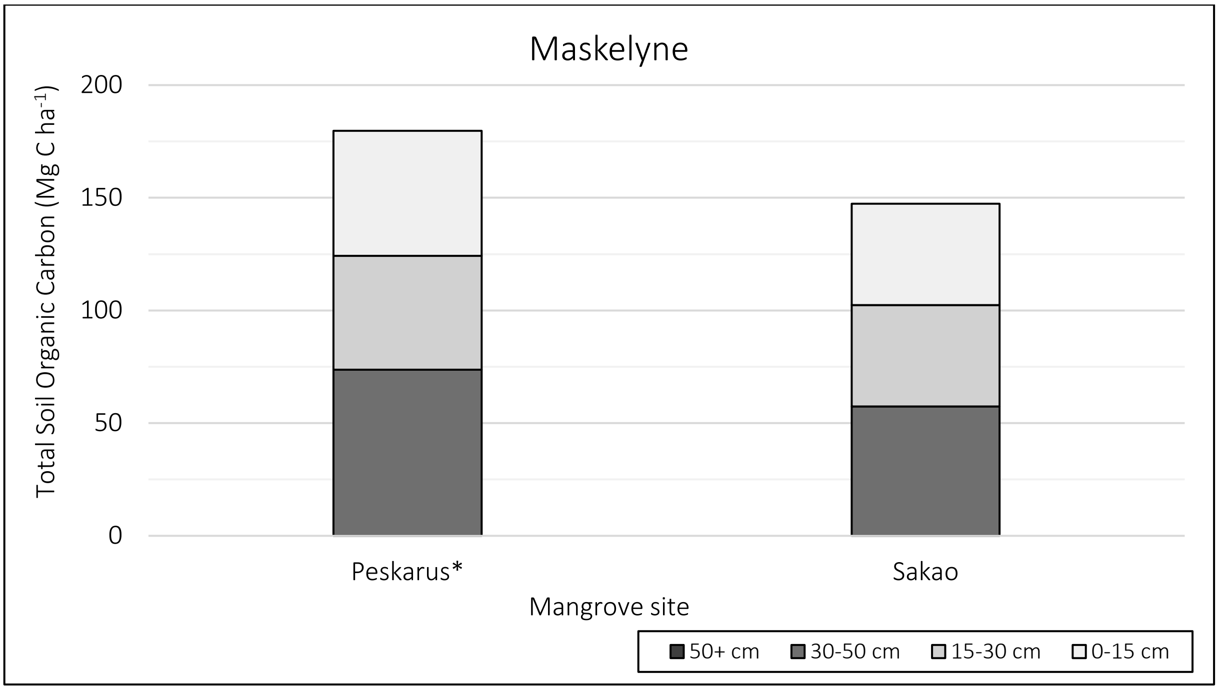


Figure 123. Mangrove soil organic carbon at different soil depths at two mangrove sites in the Maskelyne Islands, Vanuatu. An asterisk (*) is indicative of a degraded site. The site in Peskarus was classified as degraded due to clearing for village use and cyclone damage.

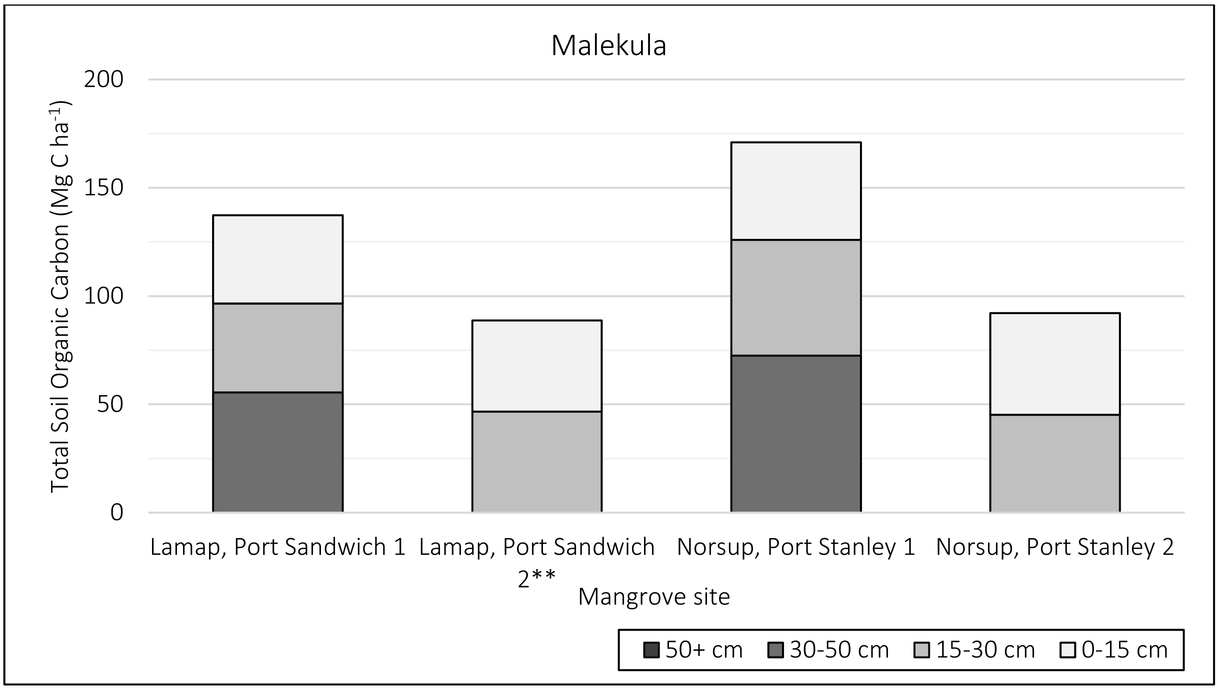


Figure 124. Mangrove soil organic carbon at different soil depths at four mangrove sites on Malekula, Vanuatu. An asterisk (**) is indicative of a converted site. One assessment site, Lamap Port Sandwich 2, was cleared of all mangrove trees.

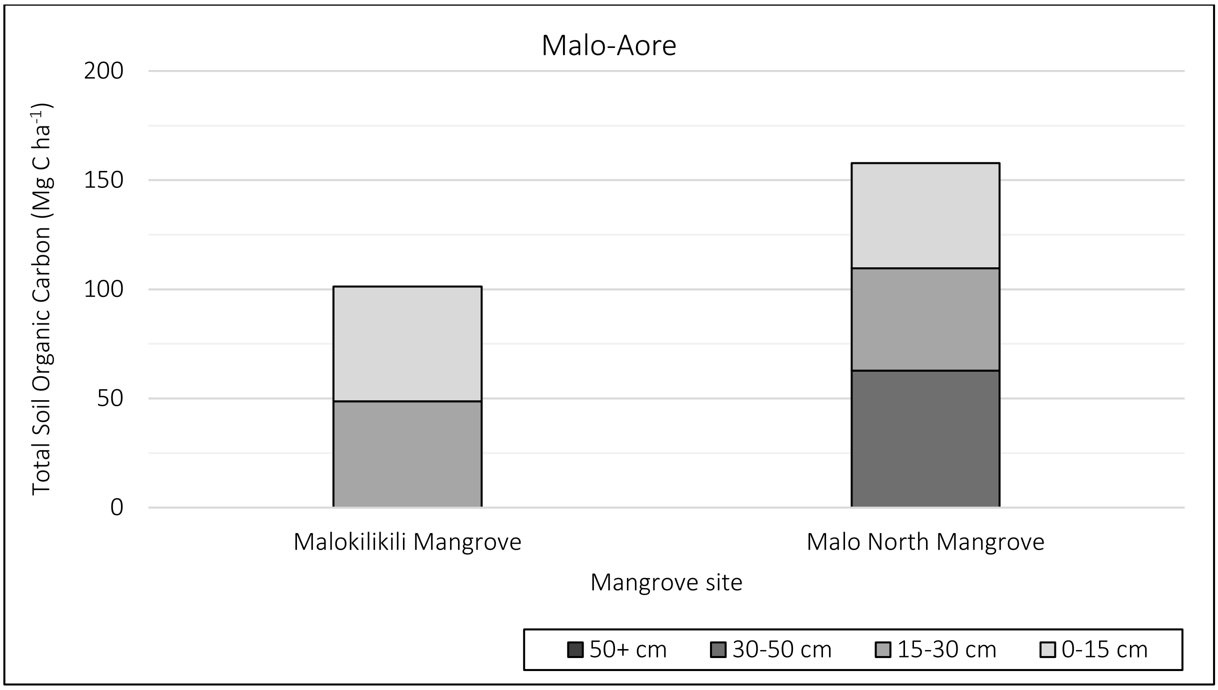


Figure 125. Mangrove soil organic carbon at different soil depths at two mangrove sites at Malo-Aore, Vanuatu.

7.3.4 Total ecosystem carbon

Mean total ecosystem carbon stocks (TECS) showed significant variation between study locations in Vanuatu (Figure 126). Mean TECS were significantly higher at study locations in Port Vila-Eratap (727 Mg C ha^{-1}) and Moso-Undine Bay (515 Mg C ha^{-1}) on Efate, as well as at sites on Santo (656 Mg C ha^{-1}). By comparison, the mean TECS were considerably lower at Malo-Aore (302 Mg C ha^{-1}), Maskelyne (291 Mg C ha^{-1}), and Malekula (221 Mg C ha^{-1}).

Across all locations, soil carbon was the dominant carbon pool (45-73% of TECS). Many of the sites in Port Vila-Eratap, Moso-Undine Bay, and Santo locations were typically influenced by riverine systems and had significant contributions from soil organic carbon (SOC).

Port Vila-Eratap had the largest mean TECS, with SOC and tree carbon storage (TCS) contributing equally to TECS with 360 Mg C ha^{-1} each. Live trees contributed 290 Mg C ha^{-1} from above-ground TCS and 70 Mg C ha^{-1} from below-ground TCS. This is likely due to the presence of extremely dense stands of *Rhizophora stylosa* (Figure 126).

Santo followed a similar trend, with live trees contributing significantly to TCS. Above-ground TCS contributing 240 Mg C ha^{-1} and below-ground TCS contributing 113 Mg C ha^{-1}. The next largest carbon pool was SOC (292 Mg C ha^{-1}) followed by dead TCS (11 Mg C ha^{-1}) (Figure 126).

In Moso-Undine Bay, SOC was the greatest contributor at approximately 73% and 378 Mg C ha^{-1} to TECS at this location. Live TCS contributed considerably less, with 84 Mg C ha^{-1} from above-ground biomass and 41 Mg C ha^{-1} from below-ground biomass. Dead TCS contributed the least at 12 Mg C ha^{-1} (Figure 126).

The remaining locations had little or no riverine inputs and showed similar TECS composition structures to Moso-Undine Bay. In Malo-Aore, SOC contributed the most (161 Mg C ha^{-1}), followed by live TCS (64 Mg C ha^{-1} above-ground and 35 Mg C ha^{-1} below-ground), and dead TCS contributing the least. Maskelyne showed similar results, with SOC being the highest (164 Mg C ha^{-1}), then live TCS (95 Mg C ha^{-1} above-ground and 25 Mg C ha^{-1} below-ground) and minimal amounts from dead TCS. Malekula had high SOC storage, relative to live TCS, as it made up 62% of TECS at 137 Mg C ha^{-1}. This was followed by live trees contributing 64 Mg C ha^{-1} above-ground and 20 Mg C ha^{-1} below-ground. Dead trees contributed negligible amounts (Figure 126).

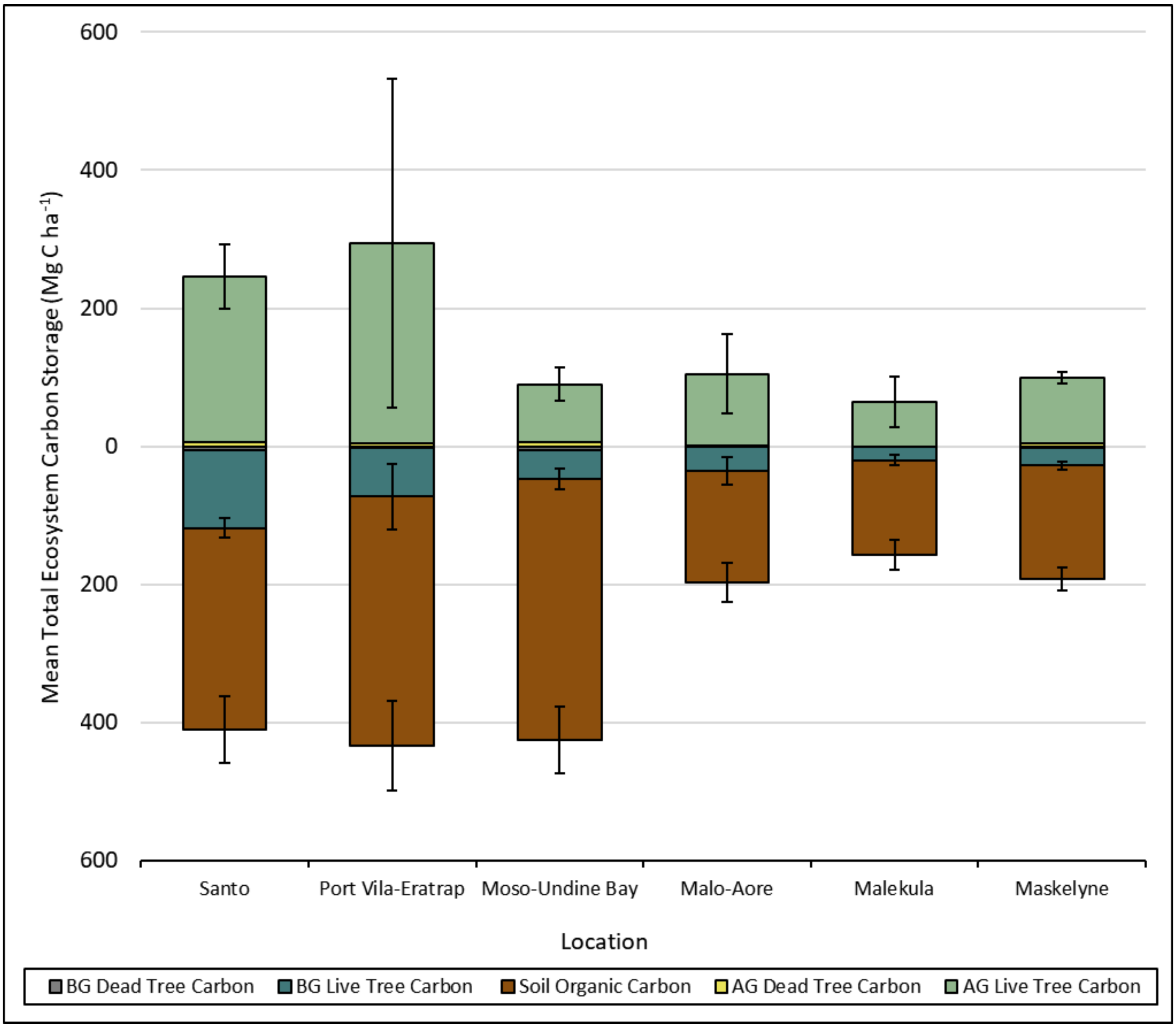


Figure 126. Mean total ecosystem carbon stocks (TECS) across six locations in Vanuatu, partitioned by carbon pools: soil organic carbon, above-ground (AG) and below-ground (BG) live tree carbon, and dead tree carbon. Soil carbon was the dominant pool at all sites, with TECS highest in Santo and relatively similar in other locations. Error bars represent the standard error of the mean.

7.4 Summary

The seagrass and mangrove ecosystems of Vanuatu provide essential ecosystem services, including biodiversity support, coastal protection, carbon sequestration, food production, and resources such as firewood and construction materials. This study represents the most extensive field-based carbon assessment conducted in Vanuatu to date, covering 19 mangrove and 14 seagrass sites across Efate, Espiritu Santo, and Malekula Islands.

There are limited previous carbon studies from Vanuatu for comparison. However, Baereleo et al. (2025) conducted localized biomass surveys in Amal/Crab Bay (Malekula) and Eratap (Efate), reporting live tree carbon levels ranging from 155 to 747 Mg C ha^{-1} in forests dominated by *Bruguiera gymnorrhiza*, *Rhizophora* spp., *Xylocarpus granatum*, *Ceriops tagal*, and *Avicennia marina*. [54] Our study found a broader range of live tree carbon (10 to 942 Mg C ha^{-1}), with high densities of *Rhizophora stylosa*, *Ceriops tagal*, *Avicennia marina*, and *Sonneratia alba* at many sites.

Consistent with global Blue Carbon literature, the highest total ecosystem carbon stocks (TECS) were typically associated with riverine and deltaic mangrove systems, such as those at the Sarakata River, Malateo River, and Port Sandwich. High carbon levels were also observed in forests dominated by *Rhizophora stylosa*, a species known for its large biomass and extensive root systems.

Seagrass soil organic carbon (SOC) was found to be higher than expected based on past literature, potentially due to differences in methodology, but also likely influenced by the structural complexity and species diversity of Vanuatu's mixed-species meadows.

Key Findings

Seagrass ecosystems

- Across the seagrass study sites, surface SOC levels at 0-15 cm depths ranged from a mean of 38 to 60 Mg C ha^{-1}, which is comparable to previously reported values from Fiji (31-47 Mg C ha^{-1}) [55] and Palau (48 Mg C ha^{-1}) [56]. The relatiely high SOC levels observed in this study likely reflect the dominance of *Cymodocea rotundata* and *Enhalus acoroides*, species known for dense root-rhizome structures and high carbon burial efficiency.
- Across the study locations, mean total SOC (across all depths) ranged from 77 to 161 Mg C ha^{-1}. These values are significantly higher than those reported in previous studies from Indonesia, which measured stocks up to 1 m and ranged from 0.32 to 65.8 Mg C ha^{-1}. [57]
- While methodological differences may partly explain the elevated SOC levels, the lower disturbance levels and higher species diversity and structural complexity of Vanuatu's seagrass meadows are also likely contributing factors.

Mangrove ecosystems

- Live tree carbon storage across the survey sites ranged from 10 to 942 Mg C ha^{-1}, demonstrating a wider range than reported in a past Vanuatu study (155-747 Mg C ha^{-1})[54].

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[54] Baereleo, R., Kalfatak, D., Kanas, T., Bulu, M., Ham, J., Kaltavara, J., Sammy, E., Dovo, P., Duke, N., MacKenzie, J., Sheaves, M., Johnston, R., & Yuen, L. (2025). *Mangrove EcoSystems for Climate Change Adaptation and Livelihoods (MESCAL) Biodiversity Assessments Technical Report*. Viliame Pita Waqalevu (Ed.). Vanuatu: MESCAL Project.
[55] Singh, S., Lal, M. M., Southgate, P. C., Wairiu, M., & Singh, A. (2022). Blue carbon storage in Fijian seagrass meadows: First insights into carbon, nitrogen and phosphorus content from a tropical southwest Pacific Island. *Marine Pollution Bulletin, 183*, Article 113432. https://doi.org/10.1016/j.marpolbul.2022.113432
[56] Kauffman, J. B., Heider, C., Cole, T. G., Dwire, K. A., & Donato, D. C. (2011). Ecosystem carbon stocks of Micronesian mangrove forests. *Wetlands, 31*(2), 343–352. https://doi.org/10.1007/s13157-011-0148-9
[57] Stankovic, M., Mishra, A. K., Rahayu, Y. P., Lefcheck, J., Murdiyarso, D., Friess, D. A., ... & Prathep, A. (2023). Blue carbon assessments of seagrass and mangrove ecosystems in South and Southeast Asia: Current progress and knowledge gaps. *Science of the Total Environment*, *904*, 166618.

- Mangrove forests assessed were dominated by *Rhizophora stylosa, Ceriops tagal, Avicennia marina*, and *Sonneratia alba.*
- Mean TECS were highest in Port Vila-Eratap (727 Mg C ha^{-1}) and Moso-Undine Bay (515 Mg C ha^{-1}) on Efate, as well as at sites on Santo (656 Mg C ha^{-1}). By comparison, the mean TECS were considerably lower at Malo-Aore (302 Mg C ha^{-1}), Maskelyne (291 Mg C ha^{-1}), and Malekula (221 Mg C ha^{-1}).
- Riverine and deltaic systems (e.g., Sarakata River, Malateo River, Port Sandwich) supported the highest TECS.
- Sites in Port Vila–Eratap and Santo showed elevated live tree carbon storage, corresponding with high *Rhizophora stylosa* densities.
- Soil organic carbon was the dominant carbon pool across all sites, representing 45 to 73% of TECS.
- Disturbed sites (e.g., Moso and Undine Bay), impacted by cyclones and wood harvesting, had lower live tree carbon storage but retained moderate to high SOC, reflecting the resilience of below-ground tree carbon storage pools.