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TOWARDS KENYA'S MARINE AND COASTAL ECOSYSTEM ACCOUNTS: MAPPING ECOSYSTEM EXTENT, CONDITION AND ECOSYSTEM SERVICES PHYSICAL FLOWS FOR 2021

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PREFACE AND ACKNOWLEDGEMENTS

This study forms part of a UNEP-funded study led by the University of Nairobi, which aims to quantify and value the ecosystem services and ecosystem assets of Kenya's coastal and marine areas, following the methods of the UN's System of Environmental Economics Accounts for Ecosystem Accounting (SEEA EA) in order to be able to contribute to the preparation of Kenya's ecosystem accounts. Anchor Environmental Consultants (Anchor) was commissioned by the University of Nairobi to contribute to the study by mapping ecosystem extent and condition and estimating and mapping the flows of selected ecosystem services in physical terms.

This report was authored by Jane Turpie and Tayla Dominy, with inputs from Kevin Schmidt, Zack Christensen and Luke Wilson on remote sensing analysis and GIS, Adam Rees and Lily Bovim on fisheries, Johanna Brühl on coding. We are grateful to Barry Clark for his review of an earlier draft.

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Introduction

This study forms part of a UNEP-funded study led by the University of Nairobi, which aims to quantify and value the ecosystem services and ecosystem assets of Kenya's coastal and marine areas, following the methods of the UN's System of Environmental Economics Accounts for Ecosystem Accounting (SEEA EA) in order to be able to contribute to the preparation of Kenya's ecosystem accounts. This component of the study develops a suitable ecosystem typology and uses a combination of existing maps and satellite data to generate a comprehensive map of coastal, estuarine and marine ecosystems at 1 ha resolution. The study also maps ecosystem condition and the flows of key ecosystem services, in physical terms.

Accounting framework

The ecosystem accounting area encompasses the entirety of Kenya's marine and coastal assets out to the EEZ. The maps include adjacent terrestrial land cover to about 10km inland; these terrestrial land cover classes were not accounted for.

The IUCN Global Ecosystem Typology was modified to develop a pragmatic classification of marine and coastal ecosystems, taking into account existing classifications and management systems, as follows (Table I).

The marine inner shelf realm extends from the coastline to 25m water depth and includes seagrass meadows and photic coral reefs. The marine outer shelf extends to 250m water depth and includes subtidal sediment and shelf break classes. Lastly, the marine deep-sea floor includes the continental slope (250m – 3,000m depth) and the abyssal plain (3,000-6,000m depth).

Table I. The classification system developed for Kenya's marine and coastal ecosystems.

Realm	Biome	Ecosystem Type
Coastal	Supralittoral coast	Salt Pans
		Coastal Saltmarshes and Reedbeds
		Sandy Shorelines / Dunefields
Estuarine	Estuary/Delta	Tarns
		Estuarine Saltmarshes and Reedbeds
		Estuarine Mangroves
		Estuarine Intertidal Sand/Mudflats
		Estuarine Seagrass Meadows
		Estuary Channels
Marine	Marine Intertidal	Coastal Mangroves
		Coastal Sand/Mudflats
		Rocky Shores
	Marine nearshore	Marine Seagrass Meadows
		Coral Reefs
		Subtidal Sediments
	Marine oceanic	Oceanic Continental Slope
		Oceanic Abyssal Plain

The condition of natural ecosystems was mapped using the assessment framework developed by Turpie *et al.* (2012) which assesses the level of similarity of the ecosystems to their intact, natural state (Table II).

Table II. Ecological categories to describe ecosystem health, modified from Turpie et al. (2012).

Broad category	Ecological category	Similarity to reference condition	Description
Good	A	91-100%	Unmodified, natural
	B	76-90%	Largely natural with few modifications
Fair	C	61-75%	Moderately modified
	D	41-60%	Largely modified/Somewhat degraded
Poor	E	21-40%	Highly degraded
	F	0-20%	Extremely degraded

This study focuses on the ecosystem services which are both likely to be of significant value and for which there are sufficient data and/or where it would be possible to make reasonable assumptions to provide spatial estimates. Using the SEEA EA reference list of ecosystem services as a guide, the following categories of ecosystem services are accounted for in this study (Table III).

Table III. Key marine, estuarine and coastal ecosystem services included in the study.

Broad category	Ecosystem service
Provisioning services	Wood provisioning services
	Wild fish and other natural aquatic biomass provisioning services
Regulating services	Global climate regulation services
	Coastal Protection
Cultural services	Experiential-related services (tourism/recreation).

Ecosystem extent

Coastal marine ecosystems were mapped using a combination of satellite data, publicly available GIS datasets and published maps, as follows:

1. Satellite data on the location and temporal distribution of surface water from 1984 to 2021 at 10m resolution were used to delineate high and low tide marks and the intertidal zone;

2. Ecosystem types falling within the Supralittoral Coastal Biome were mapped using 10 m resolution landcover data for 2021.

3. Estuaries and deltas were delineated based on inspection of land cover data and Google Earth imagery, as well as the literature.

4. Oceanic bathymetric data were used to delineate the two oceanic ecosystem types based on depth contours;

5. Sentinel-2 satellite data at 10 m resolution were analysed using Google Earth Engine to delineate the estimated extent of coastal and marine ecosystem types down to 25 m depth. Underwater features beyond this depth would not be picked up by satellite data. While the maps are designed to represent the situation at 2021, seven years of data were used (2016-2023) to improve accuracy and avoid gaps due to cloud cover; and

6. The above layers were compiled into a single raster map, which was then checked and validated against global datasets, Google Earth imagery and a range of published maps of Kenya's coastal areas, and manually adjusted using ArcGIS Pro where necessary.

Land cover in the adjacent terrestrial areas was also added to provide context for the maps, using European Space Agency (ESA) land cover data for 2021, also at 10 m resolution (same data as for the supratidal habitats).

Table IV presents the total area of each ecosystem type for the entire Kenyan coastal and marine area, out to the EEZ boundary. At this scale, the oceanic ecosystem types dominate, together making up 94% of the overall area. Subtidal sediments make up 84% of the remainder. Supratidal coastal habitats cover 11 263 ha, estuarine ecosystems cover 108 170 ha, with estuarine mangroves and channels predominating. Marine intertidal ecosystems cover 31 996 ha and mangroves in estuarine and coastal locations make up a total of 54 825 ha.

Table IV. Marine and coastal ecosystem extents area summary for the Kenyan coastline.

Realm	Ecosystem type	Area (ha)
Coastal	Salt Pans	4 478
	Coastal Saltmarshes and Reedbeds	3 912
	Sandy Shores / Dunefields	2 873
Estuarine	Tarn	2 584
	Estuarine Saltmarshes and Reedbeds	9 378
	Estuarine Mangroves	44 088
	Estuarine Intertidal Sand/Mudflats	12 008
	Estuarine Seagrass Meadow	4 656
	Estuary Channel	35 456
Marine	Coastal Mangroves	10 737
	Coastal Sand/Mudflats	16 176
	Rocky Shores	5 083
	Marine Seagrass Meadow	8 898
	Coral Reefs	6 582
	Subtidal Sediments	897 483
	Oceanic Continental Slope	5 959 126
	Oceanic Abyssal Plain	9 517 967
		16 541 486

Ecosystem condition

Ecosystem condition was assessed following the cumulative impact approach, whereby three main pressures (population density, fishing and shipping) were identified as proxies of a range of pressures. Spatial datasets pertaining to these three pressures and the above mapped ecosystems extents were used as inputs into the InVEST habitat quality model. The model outputs a spatial dataset scoring each pixel between 0 = good to 1 = poor. The scores were grouped and classified based on the broad categories in Table II. Ecosystems were assessed to estimate the approximate area per condition class. Most ecosystems are estimated to be in a fair condition with areas within MPAs having lower scores in comparison to areas outside of MPAs. Ecosystems such as coral reefs, estuaries and subtidal sediment have larger extents which are estimated to be in a poor condition.

Table V: Summarized ecosystem condition scores for each ecosystem type

Ecosystem	Extent per ecosystem condition (ha)		
	Good	Fair	Poor
Subtidal sediments	23 0151	567 610	77 410
Coral reef	827	13 813	1 237
Seagrass meadows	731	6 889	893
Rocky Shores	323	3 748	980
Sandy/muddy intertidal	1 262	14 095	509
Estuary (All estuary classes)	338	59 043	4 473
Mangroves (coastal and estuarine)	1 288	51 451	2 045
Total	**234 920**	**716 649**	**87 548**

Ecosystem services

Modelling of ecosystem services requires spatial information on the extent of different ecosystem types in the environment, and ideally an indication of the condition of these ecosystems. This was assessed based on the generated extent and condition datasets from this study.

Provisioning services assessed included mangrove wood (fuelwood and poles) and wild fish resources. Based on available estimates of mangrove fuelwood harvested along the entire coast, the average mangrove fuelwood harvest was approximately 4 tons/ha/y, with Kilifi having the highest average harvest of some 76 tons/ha, which would be highly unsustainable. Further research and monitoring data are needed to improve these estimates. Mangrove poles were historically harvested on a large scale for construction and export, however, several bans on pole harvesting have been instituted in recent years. A ban on all pole harvesting apart from in Lamu county was in place in the year being accounted for in this study. However, the most recent record of pole harvesting from Lamu was from 2014, when 96 842 scores of poles were harvested.

Wild fish resources were assessed for both the artisanal and industrial fisheries. The artisanal fishery derived its catches largely from within 10 km of the coast, where fisheries statistics reported a total catch of 35 600 tonnes in 2022. A heuristic model was developed to estimate the spatial distribution of catches of each species across different habitat types in different condition and distances offshore, using county-level statistics and expert opinion. Based on this, it was estimated that catches per unit area were highest on coral reef. subtidal sediment and estuary habitats in general, and were highest in Kwale county overall. The industrial fishery, which focused on the marine ecosystems approximately 12 nautical miles offshore to the boundary of the EEZ, saw 92 kg/km^2/year of catch from the crab pot fishery, 65 kg/km^2/year from the longline fishery and 233 kg/km^2/year from the trawl fishery.

The regulating services assessed were global climate regulation through carbon storage, and coastal protection from storm surges. Carbon storage in mangrove forests, seagrass meadows (above and below ground) and marine sediments were estimated based on the literature and global spatial datasets. In marine ecosystems the largest proportion of carbon is in sediments, for all ecosystem types. In total, the coastal ecosystems hold approximately 1740 million tons of carbon, the bulk of which lies in oceanic sediments. Mangrove ecosystems have the highest levels of carbon per unit area, and are also likely to be the areas most vulnerable to carbon losses.

Coastal protection was estimated using the InVEST coastal vulnerability model to determine the proportion of coastline vulnerable to coastal storms and sea level rise with all the ecosystems and then without selected ecosystems. The difference indicated the amount of protection provided by each ecosystem. Mangroves provide protection to approximately 167 km of the coastline and coral reefs provide 66 km of protection.

Cultural services were assessed in the form of nature-based tourism, using the density of photo-user-days as a proxy measure for tourism activity. Variation in the level of nature-based tourism activity was mapped along to the coast to show the relative value of each coastal stretch. Overall, the highest levels of activity are in Mombasa County. Other important areas are Malindi-Kilifi North, Lamu West, and the Matuga- Msambweni area of Kwale County. More detailed information is required to map tourism value more accurately to individual habitat types.

GLOSSARY

Biodiversity: The variability among living organisms and the ecological complexes of which they are part. This includes variation within species, the diversity of species within ecosystems, and the diversity of ecosystem types in nature.

Ecosystem services: The benefits people obtain from the earth's many life-support systems. The Millennium Ecosystem Assessment defines four categories of ecosystem services: provisioning, regulating, cultural, and supporting services.

Image classification: The process of assigning land cover classes to image pixel values.

Marine Spatial Planning: a tool to manage the use of our seas and oceans coherently and to ensure that human activities take place in an efficient, safe, and sustainable way.

Natural capital accounting: the process of calculating the total stocks and flows of natural resources and services in each ecosystem or region.

Raster: A matrix of cells (or pixels) organized into rows and columns (i.e. a grid) where each cell contains a value representing information, such as land class.

Sentinel-1x/2x: European optical imaging satellite providing global coverage 20 m resolution imagery. 1A launched in 2014, 1B in 2016. 2A launched in 2015, 2B in 2017, and 2C proposed launch date in 2024.

Spectral signature: A unique combination of values under different light wavelengths for a particular pixel in a remotely sensed image.

Supervised image classification: A procedure for identifying spectrally similar areas on an image by identifying training sites of known targets and then extrapolating those spectral signatures to other areas of unknown targets.

Training sample: Location information (either points or polygons) within or encompassing a known associated land cover class. An image classification algorithm uses the training samples, saved as a feature class, to identify the land cover classes in the entire image.

Unsupervised image classification: A process by which each pixel value in a dataset or image is identified to be a member of one of the inherent categories present in the image collection, without the use of labelled training samples.

LIST OF ABBREVIATIONS AND ACRONYMS

AGB	Above Ground Biomass
AIS	Automated Identification System
Anchor	Anchor Environmental Consultants
BGB	Below Ground Biomass
ESA	European Space Agency
EEZ	Exclusive Economic Zone
FAO`	Food and Agriculture Organization
GDP	Gross Domestic Profit
GEBCO	The General Bathymetric Chart of the Oceans
GEE	Google Earth Engine
GET	Global Ecosystem Typology
GFW	Global Fishing Watch
GIS	Geographical Information System
GOK	Government of Kenya
Ha	Hectare
IIASA	International Institute for Applied Systems Analysis
InVEST	Integrated Valuation of Ecosystem Service Tradeoffs
IUCN	International Union for Conservation of Nature
JRC	Joint Research Centre
KIMFRI	Kenya Marine Fisheries Research Institute
Km	kilometre
km^2	square kilometre
KTB	Kenya Tourism Board
m	metres
m^2	square metres
MEA	Millennium Ecosystem Assessments
MICE	Meetings, Incentives, Conferences and Exhibitions
MNaR	Marine National Reserve
MNP	Marine National Park
MPA	Marine Protected Area
MSP	Marine Spatial Planning
NASA	National Aeronautics and Space Administration
NEMA	National Environmental Management Act
PUD	Photo-user Density
RCMRD	Regional Center for Mapping of Resources for Development
SEEA EA	System of Environmental Economics Accounting – Ecosystem Accounting
SOC	Sediment Organic Carbon
UN	United Nations
UNEP	United Nations Environmental Programme
WCMC	World Conservation Monitoring Centre

1 INTRODUCTION

1.1 Background

This study forms part of a broader UNEP-funded study being led by the University of Nairobi, which aims to quantify and value the ecosystem services and ecosystem assets of Kenya's coastal and marine areas, following the methods of the System of Environmental Economics Accounts for Ecosystem Accounting (SEEA EA, UN et al., 2021) in order to be able to contribute to the preparation of Kenya's ecosystem accounts.

Preparation of the coastal and marine ecosystems account are focussed on the marine ecosystems from the high tide mark of the mainland and island coasts out to the edge of Kenya's Exclusive Economic Zone. This involved preparation of a map of the extent of different ecosystem types and their condition to inform ecosystem accounts 1 (ecosystem extent) and 2 (ecosystem condition), followed by the estimation of physical flows of ecosystem services for account 3 (ecosystem service flows in physical terms), the valuation of these flows for ecosystem account 4 (ecosystem service flows in monetary terms) and the resultant value of the ecosystem assets for account 5 (ecosystem monetary asset account).

1.2 Terms of Reference

Anchor Environmental Consultants was subcontracted to prepare the maps of ecosystem extent and condition, and to estimate and map the ecosystem service flows, as input to the co-authored output of the overall project. Thus, the terms of reference for this study were:

1. Develop a suitably typology of coastal and marine ecosystems for Kenya and based on available data, select a suitable recent year for the maps and accounts;
2. Produce a map of Kenya's coastal and marine ecosystems using a combination of existing spatial data, maps and remote sensing data from satellite imagery, also showing the adjacent terrestrial ecosystems for context, using existing landcover data;
3. Undertake a desktop spatial assessment of the condition of these ecosystems based on available spatial and non-spatial data;
4. Identify and estimate and map the flows of key ecosystem services supplied by coastal and marine ecosystems in physical terms, using rapid desktop estimation methods based on available data and information.

2 ACCOUNTING FRAMEWORK

2.1 Ecosystem accounting area, spatial resolution and year

The ecosystem accounting area encompasses the entirety of Kenya's marine and coastal assets, from its coastal habitats through to the outer limits of exclusive economic zone (EEZ), including the portion of the EEZ off the northern Kenyan coast also claimed by Somalia. This includes coastal habitats that sometimes extend above the high tide mark, such as dunes, estuaries and mangrove forests. More detail is provided on the onshore and nearshore coastal and marine ecosystems, where there is higher diversity of habitats and use of ecosystem services. The maps provided include detail of the terrestrial land cover up to approximately 10 km from the coast for context. The accounts are prepared using a grid with cell dimensions of 100 x 100 m (one hectare).

The accounts represent the situation in the year 2021. This year was chosen as it is the most recent year for which many of the key datasets were available.

2.2 Classification of marine and coastal ecosystems

An ecosystem is a community of plants and animals interacting with each other in a given area, and also with their non-living environments. As such, ecosystems can be defined at a variety of spatial scales or levels of detail. Therefore, in mapping ecosystem extent, it is important to first decide on the level at which ecosystems are to be defined. In ecosystem accounting, where mapping of ecosystem extent, condition and services takes place at large (regional or national) scales, the SEEA EA recommends that one uses the second or third level of the IUCN Global Ecosystem Typology (GET) as a guide. The IUCN GET is a comprehensive classification framework for Earth's ecosystems that integrates their functional and compositional features (Keith, Ferrer-Paris, et al., 2020). This typology was developed over more than two years, with an extensive development and review process initiated and co-ordinated by the IUCN Commission on Ecosystem Management. In this categorisation, the first level corresponds to realms (terrestrial, marine, freshwater etc), the second to biomes, and the third to broad functional groups within biomes, that we will refer to as ecosystem types.

The IUCN GET has developed maps of Level 3 ecosystem types which are hosted online[1] (Keith, Ferrer-Paris, et al., 2020). These are at a relatively coarse scale and can be refined. The set of Level 3 Ecosystem Types included in Kenya's coastal and marine zones was used as a basis for devising a suitable typology of coastal and marine ecosystem types for Kenya's ecosystem accounts, considering local literature and understanding of ecosystem services.

This study area corresponds to four realms of the IUCN GET, the Marine Realm plus three transitional realms that encompass the coastal area: Freshwater-Marine; Marine-Terrestrial; and Marine-Freshwater-Terrestrial. These four realms are broken down into nine biomes, which are further subdivided into 35 Ecosystem Functional Groups (Appendix 1). Of these, seven of the biomes and 21 of the Ecosystem Functional Groups are found in Kenya (Table 1).

[1] global-ecosystems.org

It should be noted that in the Marine Realm, the Pelagic Open Waters biome (M2) overlies the Marine Shelf and Deep Sea Floor biomes (M1 and M3).

Table 1 Marine and coastal realms, biomes and ecosystem functional groups of the IUCN Global Ecosystem Typology (Keith *et al.* 2020) that occur within Kenya.

Realm	Biome	Ecosystem Functional Group (EFG)
Freshwater-marine	FM1. Semi-confined transitional waters	FM1.2 Permanently open riverine estuaries and bays
		FM1.3 Intermittently closed and open lakes and lagoons
Marine-freshwater-terrestrial	MFT1. Brackish tidal systems	MFT1.1 Coastal river deltas
		MFT1.2 Intertidal forests and shrublands
		MFT1.3 Coastal saltmarshes and reedbeds
Marine-terrestrial	MT1. Shoreline systems	MT1.1 Rocky shores
		MT1.2 Muddy shores
		MT1.3 Sandy shores
	MT2. Supralittoral coastal systems	MT2.1 Coastal shrublands and grasslands
Marine	M1. Marine shelfs	M1.1 Seagrass meadows
		M1.3 Photic coral reefs
		M1.4 Shellfish beds and reefs
		M1.6 Subtidal rocky reefs
		M1.7 Subtidal sand beds
		M1.8 Subtidal mud plains
	M2. Pelagic ocean waters	M2.1 Epipelagic ocean waters (~0-200m)
		M2.2 Mesopelagic ocean waters (~200-1000m)
		M2.3 Bathypelagic ocean waters (~1000-3000m)
		M2.4 Abyssopelagic ocean waters (~3000-6000m)
	M3. Deep sea floors	M3.1 Continental and island slopes
		M3.3 Abyssal plains

For this study, the IUCN GET classification was used to inform the development of a classification of coastal and marine ecosystems that would be practical for Kenya, taking into account existing classifications and management systems. For example, this required more explicit recognition of estuaries and mangroves.

The classification system used for this study is summarised in Table 2. This divided the area into three realms that complement the terrestrial realm, viz. Coastal, Estuarine and Marine. The Coastal and Estuarine realms have no further subdivision at biome level, i.e. can also be regarded as biomes. The Marine Realm is further subdivided into Marine Intertidal, Marine Nearshore and Marine Oceanic. The Coastal biome is subdivided into three ecosystem types that are found above the high tide mark. The Estuary/Delta Biome is subdivided into six ecosystem types. Note that we combine Estuary/Delta in this classification to avoid repetition of the ecosystem types for Estuaries and Deltas. Kenya's coast has one delta, the Tana River Delta. While the geomorphological processes that shape a delta are different to an estuary, the ecosystem types within a delta are functionally the same for estuaries. The marine biomes were subdivided into three, three and two ecosystem types, respectively as per Table 2. The methods used to map ecosystem extent are described in Section 3.

Table 2 Classification of Kenya's marine and coastal ecosystems derived in this study for the purpose of ecosystem accounting.

Realm	Biome	Ecosystem Type	Description
Coastal	Supralittoral coast	Salt Pans	Man-made salt evaporation pans located along the coastline.
		Coastal Saltmarshes and Reedbeds	Areas located in the sheltered coastlines that comprise of brackish, shallow water with salt-tolerant plants such as herbs, grasses and shrubs
		Sandy Shorelines / Dunefields	Includes beaches, sand bars and splits and adjacent unvegetated dunefields. These systems have a low productivity, sand being the main component.
Estuarine	Estuary/Delta	Tarns	Fringe zones of the estuarine zone which is characterized by a hyper-saline environment with little to no productivity.
		Estuarine Saltmarshes and Reedbeds	Areas located in the estuarine zone that comprise of brackish, shallow water with salt-tolerant plants such as herbs, grasses and shrubs
		Estuarine Mangroves	Taxonomically diverse, salt-tolerant tree and other plant species which thrive in intertidal zones of estuaries.
		Estuarine Intertidal Sand/Mudflats	Transitional water (tidal) zone in estuaries where sand or mud extents are exposed during low tides. Limited vegetation cover exists.
		Estuarine Seagrass Meadows	Any semi-submerged to submerged patches of seagrass or submerged vegetation cover found in the estuarine zone. Characterised based on spectral range and classification efforts.
		Estuary Channels	Estuarine channels where flow is constant during the full tidal cycle. The bottom sediment is unknown and may transition from mud to sand throughout the reaches of an estuary.
Marine	Marine Intertidal	Coastal Mangroves	Taxonomically diverse, salt-tolerant tree and other plant species which thrive in intertidal zones of sheltered tropical shores and "overwash" islands.
		Coastal Sand/Mudflats	Transitional water (tidal) zone where sand or mud extents are exposed during low tides. Limited vegetation cover exists.
		Rocky Shores	Rock extents that are exposed during the low tides. Marine life does still occur in these areas, however exposed rock is the main feature. Includes Fossil Pleistocene reef rock formations.
	Marine nearshore	Marine Seagrass Meadows	Any semi-submerged to submerged patches of seagrass or submerged vegetation cover. Characterised based on spectral range and classification efforts. This zone includes the overlying epipelagic ocean waters.
		Coral Reefs	Photic coral reefs, including fringing reef habitats which may be exposed during very low tides. This zone includes the overlying epipelagic ocean waters.
		Subtidal Sediments	Subtidal seabed down to 250 m depth. Including small subtidal rock or reef features which may be present periodically in the subtidal sediment class. This zone includes the overlying epipelagic ocean waters.
	Marine oceanic	Oceanic Continental Slope	The deep-sea floor from 250 m to 3 000 m depth. This includes drop-off features such as the shelf break. This zone includes meso- and bathypelagic ocean waters.
		Oceanic Abyssal Plain	Oceanic area from 3000 and 6000 m deep. This zone includes the benthic sediments and the overlying abyssopelagic ocean waters.

2.3 ECOSYSTEM CONDITION

Ecosystem condition can be broadly classified as the health or state of the ecosystem in reference to its natural state prior to any measurable anthropogenic impact (Smit et al., 2021; Stephens et al., 2015). Modern definitions are based off three main approaches depending on the information and data available (Smit et al., 2021). The first approach relies on the ability to detect degradation within the ecosystem and includes aspects of ecosystem structure and functioning (Smit et al., 2021). The second approach is underpinned by the ecosystem resilience concept and the ecosystems capacity to handle stress (Smit et al., 2021). The third approach, the most applicable in the context of the Kenyan coast, relies on the identification of threats impacting on an ecosystem and incorporates the degree of modification from anthropogenic impacts (Smit et al., 2021). Smit et al., (2021) developed a structured framework that aids in the process of defining and assessing ecosystem condition. The most suitable definition of ecosystem condition for the context of this assessment relies on the identification of threats to the marine ecosystems (Smit et al., 2021).

Marine ecosystem condition is complex to measure, thus it is necessary to have a structured framework that is adaptable and widely applicable (Smit et al., 2021; Western Indian Ocean & Symphony, 2022). Smit et al., (2021) suggests assessing a marine ecosystems condition stems from how ecosystem condition is defined and the capacity and complexity of available indicators. They described a simple framework to assess condition. The first step is to determine which indicators are applicable based on the available data and project requirements. It is important to note that most indicators are a proxy for ecosystem condition and do not represent the exact condition (Smit et al., 2021; Stephens et al., 2015; Western Indian Ocean & Symphony, 2022). Indirect measurements rely on a demonstrated relationship existing between ecosystem functioning and structural components of biota (Smit et al., 2021). Ex situ measurements are particularly useful in instances where biological data are lacking or do not cover the full study extent (Smit et al., 2021). In these instances, ex situ measurements of pressures, typically originating from human activities, can be used as a proxy for ecosystem condition (Smit et al., 2021; Western Indian Ocean & Symphony, 2022).

Pressure mapping has been found to be particularly suitable for inferring condition at national or regional scales, particularly in data poor scenarios (Smit et al., 2021; Western Indian Ocean & Symphony, 2022). An example of where this approach has been successfully applied and accepted was in the creation of the South African National Biodiversity Assessment of the marine environment at a national scale (Smit et al., 2021). Western Indian Ocean & Symphony, (2022) have created a web tool (WIO Symphony) which follows these same broad principles, the tool was developed to support marine spatial planning in assessing the impacts arising from human activities in the Western Indian Ocean (https://www.nairobiconvention.org/wio-symphony/)..

The national scale of this study, limited spatially applicable ecological data, limited financial capacity, and growing coastal populations indicate a simple ex situ cumulative impact approach would be the most suitable to infer condition for the coastal ecosystems. The system for categorisation used in this study is summarised in Table 3. In this desktop study, the assessment was based on available information and due to the lack of scientific data, was done at the level of broad categories only.

Table 3 Ecological categories to describe ecosystem health, modified from Turpie et al. (2012).

Broad category	Ecological category	Similarity to reference condition	Description
Good	A	91-100%	Unmodified, natural
	B	76-90%	Largely natural with few modifications
Fair	C	61-75%	Moderately modified
	D	41-60%	Largely modified/Somewhat degraded
Poor	E	21-40%	Highly degraded
	F	0-20%	Extremely degraded

2.4 ECOSYSTEM SERVICES

This focused on the ecosystem services that were both likely to be of significant value and for which there was sufficient data and/or where it was possible to make reasonable assumptions to provide spatial estimates.

Ecosystem services have been described in many typologies, of which one of the most well-known is that of the Millennium Ecosystem Assessment (MEA 2003), which grouped services into Provisioning, Regulating, Cultural and Supporting services. Since then, several alternative classifications have been proposed, all of which have dropped the "Supporting Services" category to focus on what are known as "final services" (to avoid double-accounting). This approach has also been adopted by the SEEA EA (UN et al. 2021), which avoids any particular classification system, but is loosely based on the CICES system.

Aligning with the more recent literature, this study classifies major types of ecosystem services[2] listed by the SEEA EA (Table 6.3 in UN et al. 2021) into Provisioning, Regulating and Cultural services (Appendix 2), with slight modifications following Turpie et al., (2022). The key services that are described in this study are listed in Table 4. These were selected based on their applicability, importance and/or availability of information. The methods for their quantification and mapping are described in Chapter 5.

[2] Note that it can be misleading to state or compare the "number" of ecosystem services included in a study, since the types of services discussed are nearly always groupings that could be subdivided in various ways.

Table 4. Key marine, estuarine and coastal ecosystem services included in the study, based on the SEEA-EA reference list and Turpie *et al.*, (2022). A brief explanation is provided of how the service flow can be measured in physical terms. See Appendix 2 for the full list from which these were selected.

Broad category	Ecosystem service	Description	Physical measure (all per ha and per year) and notes
Provisioning services	Aquaculture provisioning services	In situ ecosystem inputs to aquaculture production	Total harvested production (kg) as a proxy measure for the various ecosystem inputs which are difficult to quantify
	Wood provisioning services	Ecosystem contributions to the growth of trees and other woody biomass in both cultivated (plantation) and uncultivated production contexts.	Total output in terms of m^3 per ha per year of wood for fuelwood, charcoal, poles and timber. For coastal-marine context this comprises mangrove wood only.
	Wild fish and other natural aquatic biomass provisioning services	Ecosystem contributions to the growth of fish and other aquatic biomass harvested in uncultivated production contexts	Total output in terms of m^3 per ha per year of fish, grouped by major fishery type. Note that the contribution of nursery areas in different ecosystem types is subtracted and allocated under regulating services.
Regulating services	Global climate regulation services	Ecosystem contributions to reducing concentrations of GHG in the atmosphere	Stocks of carbon in each period, expressed as tonnes of carbon per ha
	Nursery population and habitat maintenance services	Provision of critical habitat for populations that are utilised in other locations, such as fish nursery areas, wildlife breeding areas or migratory staging areas. As for the above service, this requires attributing some of the ecosystem inputs to these activities to the critical habitat areas rather than the areas in which the activities take place.	Very preliminary estimate of proportion of marine catches originating in estuaries (data are lacking)
	Flood control: coastal protection services	Contributions of linear elements in the seascape, for instance coral reefs, sand banks, dunes or mangrove ecosystems along the shore, in protecting the shore and thus mitigating the impacts of tidal surges or storms on local communities. Final ecosystem service.	Score pertaining to estimated protection provided by each ecosystem. Determined through scoring the vulnerability of the coast with and without ecosystems. .
Cultural services	Experiential-related services	Experiential fulfilment associated with active or passive use, through any type of or purpose including recreation, education, scientific research, spiritual, artistic, or other cultural activities (typically some combination of these).	This manifests as contributions to tourism value, recreation/experiential activities, and to property value. Since user days cannot be mapped on a continuous grid the relative use is expressed as an index that relates directly to monetary value.

3 ECOSYSTEM EXTENT

3.1 OVERVIEW

Kenya's coastal, estuarine, and marine ecosystems were mapped using a combination of existing spatial data, satellite imagery, and bathymetric data. Within the last decade, satellite data have improved significantly in terms of their spatial and temporal resolution and have also become more readily accessible through open-source databases and catalogues. Furthermore, the release of Google Earth Engine (GEE) software has facilitated efficient, cloud-based geospatial processing of these very large datasets. This web-based platform provides access to publicly available remote sensing imagery, as well as high-speed parallel processing and machine learning algorithms using Google's computational infrastructure. Within this infrastructure, a library of Application Programming Interfaces (APIs) can be utilized and modified for a multitude of environmental analysis such as ecosystem classification. In addition, there are global maps of the IUCN GET ecosystem types, although some of these are coarse or vague, and several global maps have also been produced from satellite data for ecosystem types such as mangroves and coral reefs. Because the latter are produced at global scale, they are often rather inaccurate at local scale, as was confirmed in this study.

This study started by using satellite data on water cover to delineate high and low tide marks and used bathymetric data to delineate oceanic ecosystem types, then made use of Sentinel-2 satellite data at 10 m resolution to delineate the estimated extent of nearshore and inshore ecosystem types as of 2021. The latter were checked and validated against global datasets, Google Earth imagery and a range of published maps of Kenya's coastal areas. These steps and the data sources are explained in more detail below.

3.2 DATA AND METHODS

3.2.1 DELINEATING THE INTERTIDAL AREA

Since the existing GIS maps of administrative boundaries for Kenya were not accurate at the coastline, the first step in the mapping process was to delineate the high tide mark and the intertidal area. To do this, a permanent water feature was generated in GGE based off code developed by Pekel, Cottam, Gorelick, & Belward (2016) for the Joint Research Centre (JRC) Global Surface Water Mapping Layers v1.4. This contained the location and temporal distribution of surface water from 1984 to 2021 at a 10 m spectral resolution, and a 5 to 10 day temporal resolution, and provided statistics on the delineated extent and various changes in the extent. The high tide mark was defined by the full extent of the ocean-connected area that had water present at any time (i.e. water was present for >0% of the time). The low tide mark was defined as the landward extent of the area that had water coverage for 100% of the time. This resulted in a highly accurate map of the intertidal area along the entire coast. These extents were employed to clip the satellite imagery used in the steps below.

Figure 1. Rasterised permanent water feature (high-tide) delineated using code developed by Pekel et al. (2016)

3.2.2 MAPPING SUPRALITTORAL COASTAL BIOME ECOSYSTEM TYPES

Ecosystems forming part of the Supralittoral Coast biome were mapped based on the European Space Agency (ESA) land cover data for 2021(ESA WorldCover 10 m 2021 V2.0; Zanaga et al., 2022). This is a freely available global landcover and landuse dataset which was generated at 10 m resolution and an accuracy of 76.7 % (Zanaga et al., 2022).

3.2.3 DELINEATING THE OCEANIC ECOSYSTEMS

Oceanic bathymetric data were used to delineate the two oceanic ecosystem types based on depth contours. The Oceanic Continental slope occurs from 250 m – 3 000 m depth, and the Oceanic Abyssal extends from 3 000-6 000 m depth (Keith, Ferrer-paris, et al., 2020). These two ecosystem groups were derived based on the publicly available GEBCO bathymetry data; the bathymetry lines were used as the cut off points for each ecosystem. The Oceanic Continental slope was delineated from the GEBCO 25 0m bathymetry line to the 3 000 m bathymetry line, the Oceanic Abyssal Plain was delineated from the 3 000 m bathymetry line to the full extent of the EZZ boundary. In both cases shapefiles of each extent were delineated based off the GEBCO bathymetry lines and then converted into a raster format to be merged with the other raster datasets.

3.2.4 Delineation of estuaries

Estuaries and deltas were delineated based on inspection of land cover data and Google Earth imagery, as well as the literature. These systems were identified as those in which there is significant mixing of freshwater with seawater, and thus inlets that were visibly fed by rivers. The outer extents were defined by areas that had intertidal or supratidal mangroves, tarns or marshes that were clearly hydrologically linked to the estuary channel. In two cases, an arbitrary division had to be made between estuarine and coastal mangroves.

The estuarine extents were taken from the mouth of the estuary, or the point at which it reaches the coastline, to its uppermost extent which was determined using a combination of known factors. The first factor considered was literature on the Tana River and the Sabaki estuary which defined the exact estuary extents for these systems (Kitheka & Mavuti, 2016). The ground elevation for these locations in both estuaries were noted, to be drawn on in other estuaries as needed. The upstream boundary of an estuary is defined by the tidal variation and the salinity gradient, whichever is furthest (Republic of South Africa, 2008). Additionally, a good visual identification of the estuarine boundary is the presence of tarn (hypersaline tidal flat) which is a supratidal flat generally located in an intermediary position between mangroves or saltpans and the terrestrial environment (Brown et al., 2021). For estuarine systems where there was no literature and no clear evidence of tarn, an elevation of 6 m was used as a cut off for the estuarine boundary. This elevation was selected based off expert opinion.

The delineation of estuarine ecosystem types happened in two steps. The more terrestrial ecosystems like the estuarine tarn, estuarine saltmarshes and reedbeds and estuarine mangroves were derived from the ESA WorldCover 10m 2021 V2.0 (Zanaga et al., 2022). The estuarine sandy / muddy intertidal, estuarine seagrass and estuarine channels were determined based on the classification methodology described in the section below.

3.2.5 Mapping of intertidal and nearshore ecosystem types

The intertidal and nearshore ecosystem types within the estuarine and marine realms down to 25 m depth were mapped using Sentinel-2 satellite data at 10 m resolution. The previously delineated extents from section 3.2.1 were used in conjunction with the 25 m bathymetry line to clip the imagery to improve processing power for the upcoming analysis. Underwater features beyond this depth would not be picked up by satellite data. While the maps are designed to represent the situation in 2021, seven years of data were used (2016-2023) to improve accuracy and avoid gaps due to cloud cover. The data and processes are described in more detail below. The subtidal sediment ecosystem was extended from the 25 m bathymetry line and adjusted ensuring it reached its known outermost extent of the 250 m bathymetry contour.

Satellite Imagery

Satellite imagery and aerial photography has progressed significantly in the last decade, with improvements in the resolution, frequency, and accessibility of the imagery (Figure 2). Open-source satellite imagery was limited to a resolution of 30 m for many years. However, in 2014, Sentinel 1 and in 2015, Sentinel 2 satellite were launched with the ability to produce satellite imagery at 10 m resolution (Figure 2). Figure 3 shows a visual comparison between the two types of open-source satellite imagery applicable for the required analysis. This image highlights the importance of imagery with a higher resolution when detecting features. Imagery from other sources such as the PlanetLabs Dove Satellites or from UAVs would provide higher resolution imagery, however, these are costly and would have required a significantly more processing capacity.

In this work, multispectral satellite imagery (harmonized Sentinel-2 MSI: MultiSpectral Instrument, Level-2A) from the period of 2016-2023 (7-years) was pre-processed based on cloud cover probability and exported for spectral and image analysis in ArcGIS. Sentinel-2 is a wide-swath, high-resolution, multi-spectral imaging mission supporting Copernicus land monitoring studies, including the monitoring of vegetation, soil, and water cover, as well as observation of inland waterways and coastal areas (European Space Agency (ESA), 2023).

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Figure 2. Differences in spatial resolution (m^2) for the various satellites launched by the LANDSAT and Sentinel earth observation from space campaigns from 1972 - 2023. The highest resolution imagery available to date is from the most recent Sentinel 1 and 2 satellites which were deployed in 2014 and 2015, respectively.

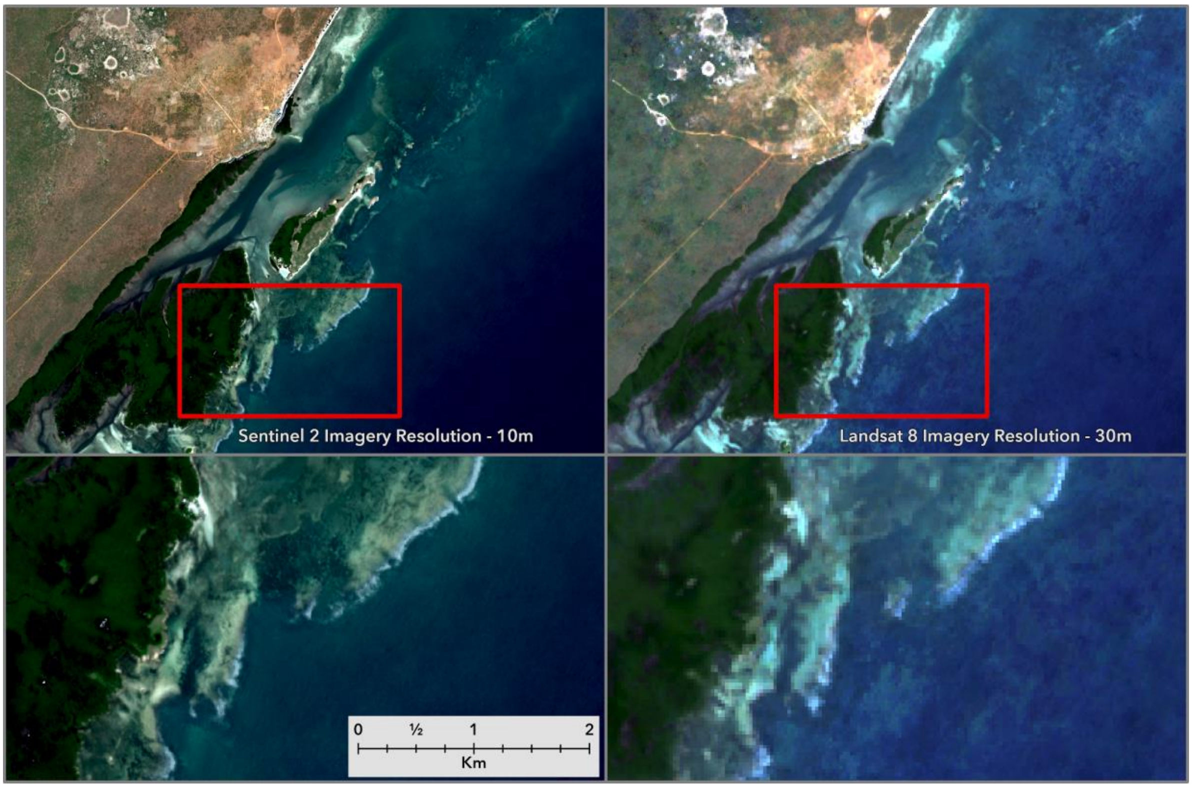

Figure 3. Comparison between Sentinel 2 (10m resolution) and Landsat 8 (30m resolution).

Image classification

Image classification is a machine learning process whereby satellite imagery is analysed, and pixels are grouped into classes based on their natural spectral signature. There are two approaches to image classification, the first of which is a supervised classification and the second unsupervised classification. Both approaches follow the same principles, however, training samples or known features are used to guide the process and influence the outcomes in the supervised classification process. The second approach is an unsupervised classification where pixels are grouped based on the similarity of their spectral signatures. In this approach, a statistical machine learning method known as "clustering" is applied to each segmented image composite. Clustering is an unsupervised learning method that attempts to combine objects into clusters based on similarity criteria of input variables. This can be defined as a case where a statistical relationship is established between the spectral bands or frequencies used and the variable measured without there necessarily being a causal relationship (Holloway & Mengersen, 2018).

By specifying multiple groups (clusters) per ecosystem class, spectral profiles can be generated to facilitate classification at a large geographical extent. From this exercise the spectral signatures or spectral response curves of the known and likely ecosystem classes are observed to differ substantially from the random points around them (Figure 4). Once satisfied with the isolated spectral signature for each ecosystem class, band value ranges are targeted for each image segment of the cloud-free Sentinel-2 satellite images. All image pixels with band values within the expected spectral range were isolated and reclassified into a single value raster surface and assigned to an ecosystem class based on the reference table in section 3.3.

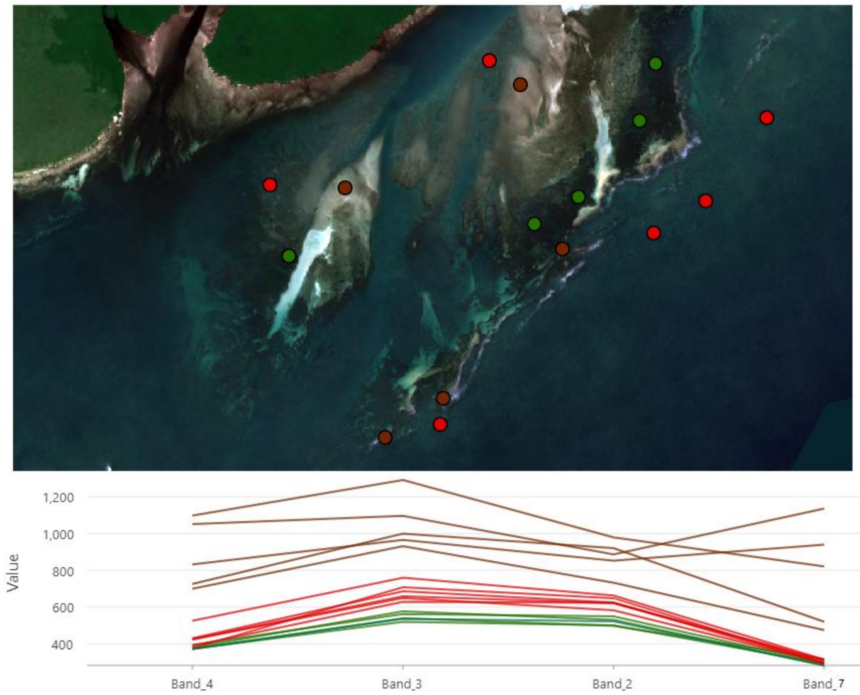

Figure 4. Spectral signature analyses example performed on segmented satellite imagery. Seagrasses (green), corals (red), intertidal sediment (brown) spectral profiles with variable frequency distributions.

The results of the preliminary unsupervised classification effort, spectral analysis, and the publicly available GIS layers from the Regional Center for Mapping of Resources for Development (RCMRD); SERVIR Eastern and Southern Africa, the Allen Coral Reef Atlas (Allen Coral Atlas, 2022) and the study by Traganos et al. (2022) were used as the basis for developing training polygons for the subsequent supervised classification effort. Training polygons are selected areas of known cover which were used in the supervised classification process to train the model on which spectral signatures to select for each class. Typically, supervised classifiers utilise training samples of known entity (ground-truthed) to classify pixels of unknown entity. Supervised classification entailed manually (user defined) isolating imagery into different unique classes. In this way, image pixels with similar characteristics were grouped together to represent distinct ecosystem classes. Training polygons were created for each major segmented image collection along the coast of Kenya and used to generate a rasterised classification result for the ecosystem types identified in Table 2. No quantitative accuracy assessment has been undertaken at this stage. Further ground-truthing across as much of this range as possible will enhance the accuracy and reliability of mapping in the future.

3.2.6 VALIDATION AND FINALISATION OF THE MAPS

The outcomes of the supervised classification were compared to known literature comparing area estimates per ecosystem and visual comparison of the mapped extents. The mangrove cover of the Kenyan coastline has been relatively well studied and there are several documented estimates of the total cover. This study has determined mangrove cover to be a total of 54 8218 ha, this estimate is in line with the mangrove cover determined by Doute, Ochanda, & Epp (1981) at 54 000 ha, as well as Mohamed, et al. (2009) at 52 980 ha and hamza & Esteves, (2022) at 52 356 ha. Hamza & Esteves, (2022) had a county breakdown of total mangrove cover which has been compared with this study's estimates (Table 5). The county mangrove extents for both studies are similar with the results differing overall by 13%. In all instances, this study's estimates are larger than that from Hamza & Esteves, (2022), this could be attributed to the higher resolution (10 m) that was used in determining the mangrove cover in this study versus the 30 m resolution data that was used to estimate the mangrove extent in hamza & Esteves, (2022).

Table 5: Per county comparison of mangrove extent between this study and the study by Hamza & Esteves, (2022)

Kenya County	**Area per county (ha)**	
	Hamza & Esteves, (2022)	This study
Kwale	9203.8	9520
Mombasa	1458.5	1821
Kilifi	5439.7	5840
Tana River	2128.1	3331
Lamu	34125.5	34247

Our classification efforts were visually compared to similar studies which focused on smaller specific regions along the Kenya coastline. There has been significant work done on the mapping of habitats and ecosystems of Mida Creek (Figure 5, Owuor et al., 2017). Although their classes differ from ours, features of importance such as the mangroves and intertidal sand and mud flats were mapped. Mangroves were found to cover a similar extent in both studies, with majority of the mangroves occurring along the eastern side of the Mida Creek estuary with patches other vegetation types such as shrubland or bare areas. Sandy beaches were the dominant feature along the estuary banks in both scenarios, with small patches of other non-mangrove vegetation being detected along the estuary in the study by Owuor et al. (2017), which correlates to our classification of seagrass.

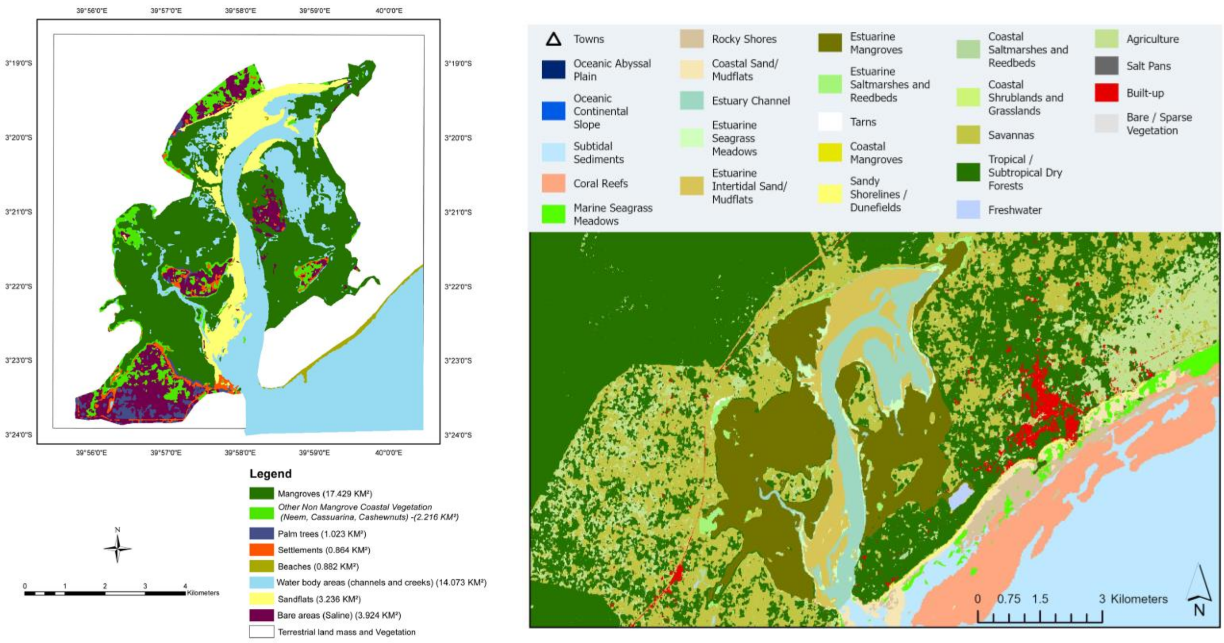

Figure 5 Left: LULC map taken from Owuor et al. (2017), Right: this studies classification outputs for the Mida Creek region

Several studies have looked at the extent of seagrass meadows along the Kenyan coastline. The literature all suggests varying extents of seagrass cover along the coastline. Traganos et al., (2022) conducted a high resolution machine learning classification of seagrass extents along the coastline and predicted a total cover of 679.6 km², which is significantly higher than our estimate of 134 km². However, our estimates are more in line with the estimates determined by UNEP-Nairobi Convention/WIOMSA, (2020) 113.2 km². Harcourt et al. (2018) and NEMA (2017) calculated seagrass estimates 308.4 km² (30 840 ha) and 336 km² (33600 ha), respectively. Seagrass meadows are very sensitive ecosystems and have been documented to be showing significant declines in their extents (Daudi, 2010; Harcourt et al., 2018; NEMA, 2017). This well documented decline in seagrass extent probably goes a long way to accounting for the lower estimated extent in this study. The additional coverage determined by Traganos et al., (2022) could also be attributed to their improved detection in the subtidal zones as well as their occasional detection of seagrass in the terrestrial environments which was not corrected for.

Cowburn et al., (2018) mapped habitats in the Watamu National Park between the reef crest and the terrestrial boundary (Figure 6). These findings suggest a similar picture of sandy beaches and sandy bottom at the mouth of the estuary, with patches of intertidal seagrass, including a sizable seagrass meadow on the eastern bank of the estuary mouth. Cowburn et al., (2018) detected more seagrass meadows than in this study; but our classification attempt indicates that much of the area they identified as seagrass was now dominated by rocky intertidal. The decline in seagrass meadow extent can be explained by the variety of threats they are exposed to, including sedimentation impacts from upstream catchments, trampling, eutrophication and over grazing (UNEP-Nairobi Convention/WIOMSA, 2020). In the Watamu National Park, overgrazing of seagrass meadows is a major concern. Daudi, (2010) estimated that losses associated with sea urchin overgrazing in this region were in the order of 4.6 % per year. This, along with other factors affecting seagrass growth, can explain the discrepancy between our study and earlier attempts at mapping seagrass extent. This is again supported by the declining populations of seagrasses observed by (harcourt et al., 2018) along the whole Kenya coastline.

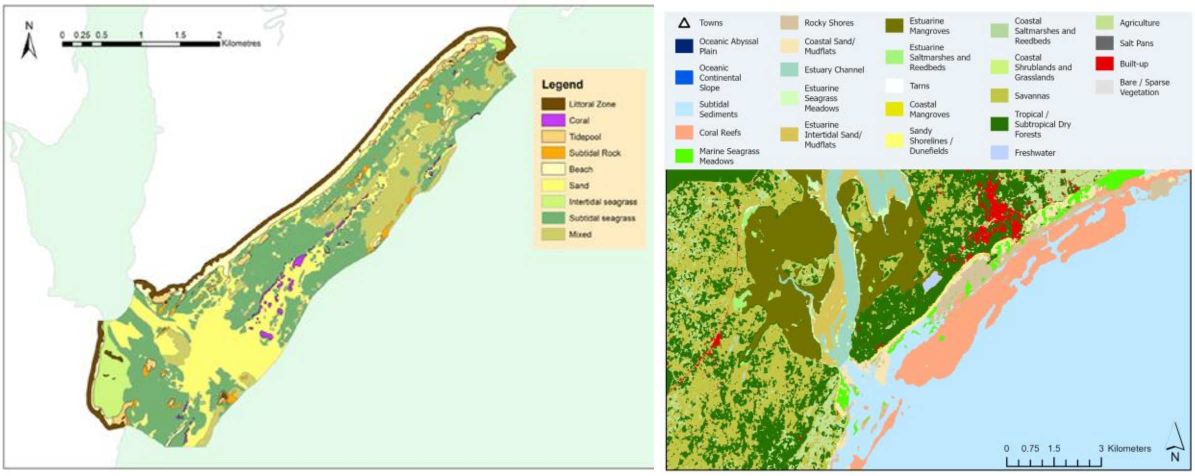

Figure 6. Left Watamu National Parks habitat classification taken from Cowburn et al. (2018), Right: this studies classification outputs for the Watamu National Park.

The seagrass extents were visually compared to the high resolution machine learning based outcomes from Traganos et al., (2022). Traganos et al., (2022) harnessed big satellite data, machine learning and region-specific reference data to produce the seagrass extent in Kenya, Tanzania, and Mozambique. We were able to visually compare our classification results for seagrass with the published and available interactive online map of the results from Traganos et al., (2022). Based on our visual comparison in particular focusing on the Gazi Bay region (Figure 7), our classification estimates are similar to that of Traganos et al., (2022). Traganos et al., (2022) was able to detect more seagrass in the subtidal zones that what we were. This could be addressed in future using additional training samples of known subtidal seagrass extents along the coastline.

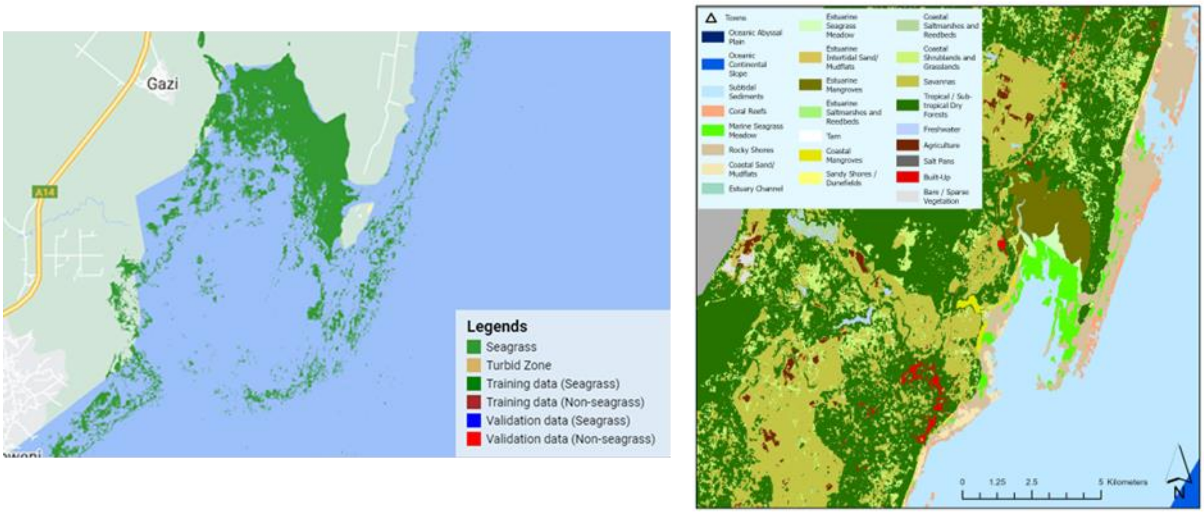

Figure 7: Left Gazi Bay seagrass extent taken from *Traganos et al., (2022)*, Right: this studies classification outputs for the Gazi Bay region.

Coral reef extent and distribution was compared to the mapped coral reef extents in Tychsen (2006). The mapped extents in Tychsen (2006) were broad and generalized delineations of known coral reefs along the coastline. Coral reefs identified from our analysis are found in the same locations, however, the extent is smaller. Our assessment was based on a finer resolution and more comprehensive dataset that included the most recent satellite imagery, and is thus considered superior to that developed by Tychsen (2006). This allowed us to provide a more detailed view of the coral reef extents. The classified extent of the coral reef from this study was also compared to the adjusted reef extent dataset developed by (Allen Coral Atlas, 2022) which is a global coral reef extent dataset created through remote sensing and AI. Their classifications were guided by validated training samples and was mapped at a maximum resolution of 15 m (Allen Coral Atlas, 2022, Kennedy et al., 2021). Our extents cover a similar area to what they have classified as the reef crest. However, their coral/algae dataset covers a much larger extent than our coral reef extent. Coral reefs along the Kenyan coast have been found to have a high proportion of algal coverage (Karisa et al., 2020). On average most sites assessed by Karisa et al. (2020) had a 42% algal coverage in comparison to hard and soft corals which had a coverage of approximately 32%. These coverage estimates support the reduced coral reef extents of this study in that they represent living coral reefs and not portions of the reefs covered by algae.

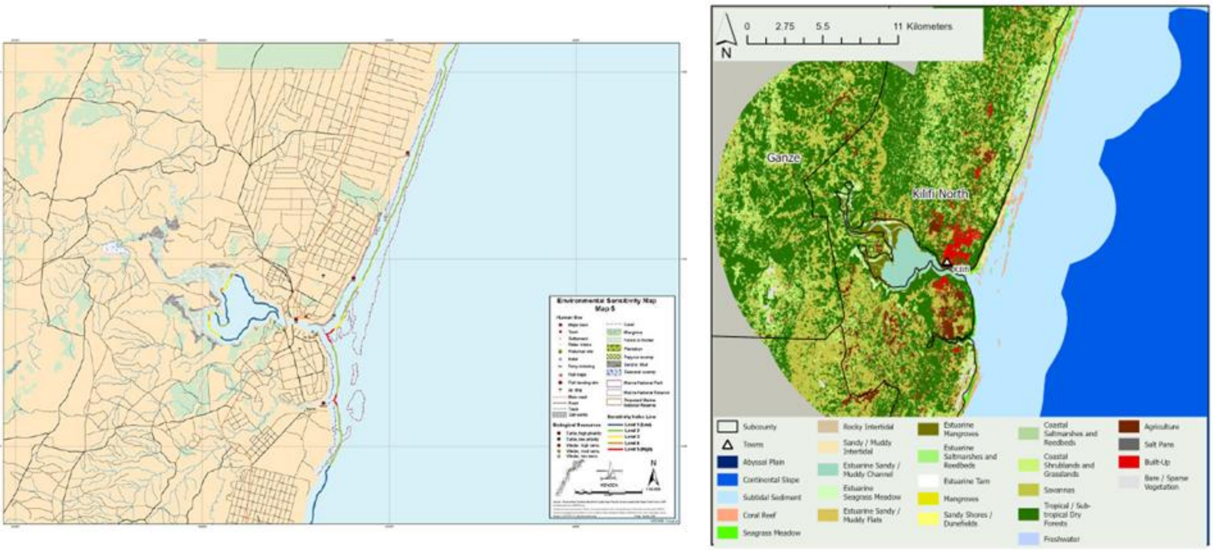

Figure 8. Coral reef extent mapped by Tychsen (2006) (left) and this studies classification of the marine ecosystems off the coast of Kilifi (right).

3.3 ECOSYSTEM EXTENT

3.3.1 OVERVIEW

Maps of ecosystem extent were compiled using the classification classes listed in Table 2. Figure 9 provides an example of the mapping for part of the coast, while Figure 10 shows the full extent of the mapped area. Appendix 3 presents the more detailed maps at 1:250 000 scale in a series of 17 maps from the Tanzanian border in the south to the Somalia border in the north (see Figure 22 for a key to the map series).

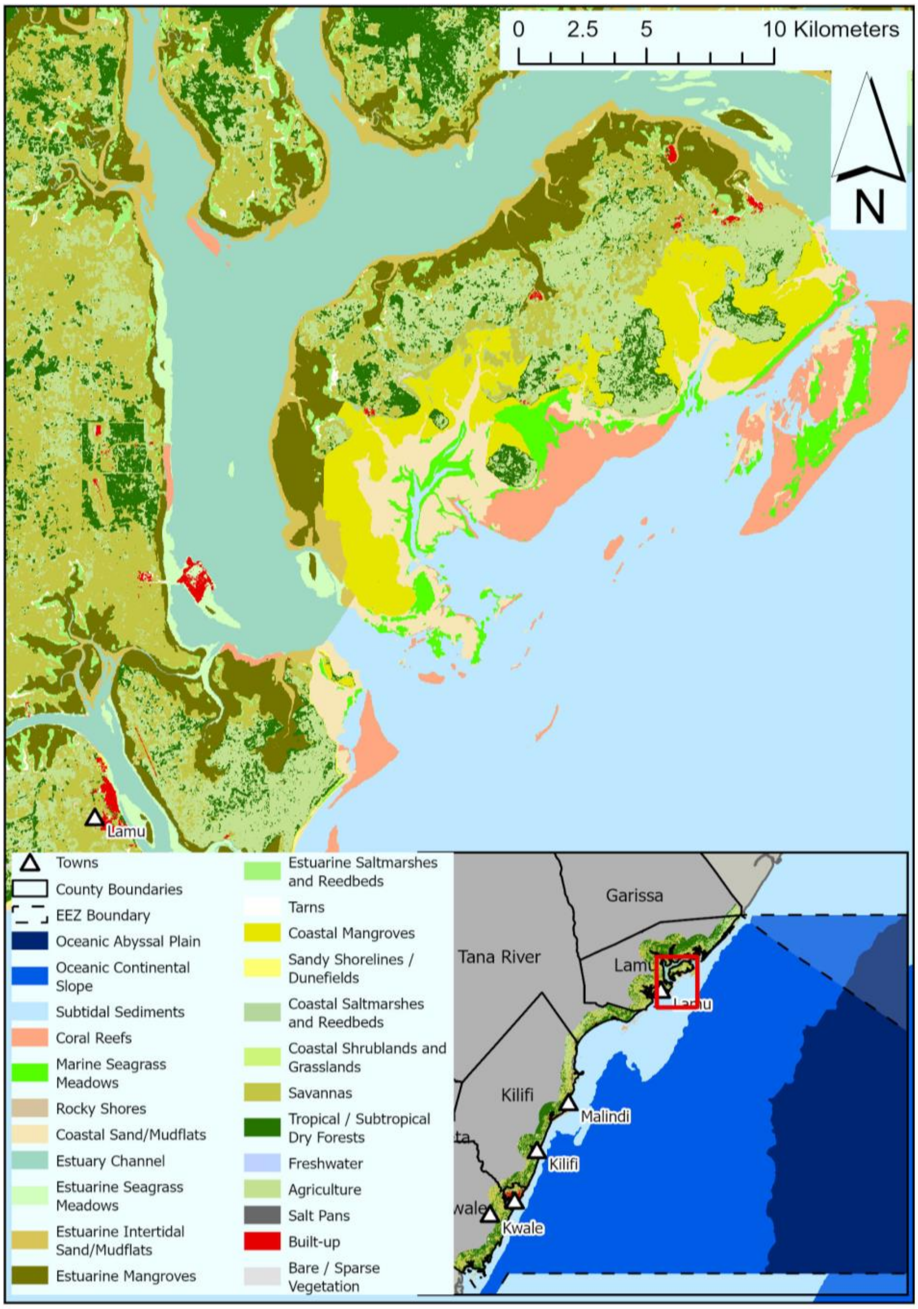

Figure 9: Map of coastal, estuarine, and marine ecosystems and adjacent terrestrial land cover in the vicinity of Lamu Island.

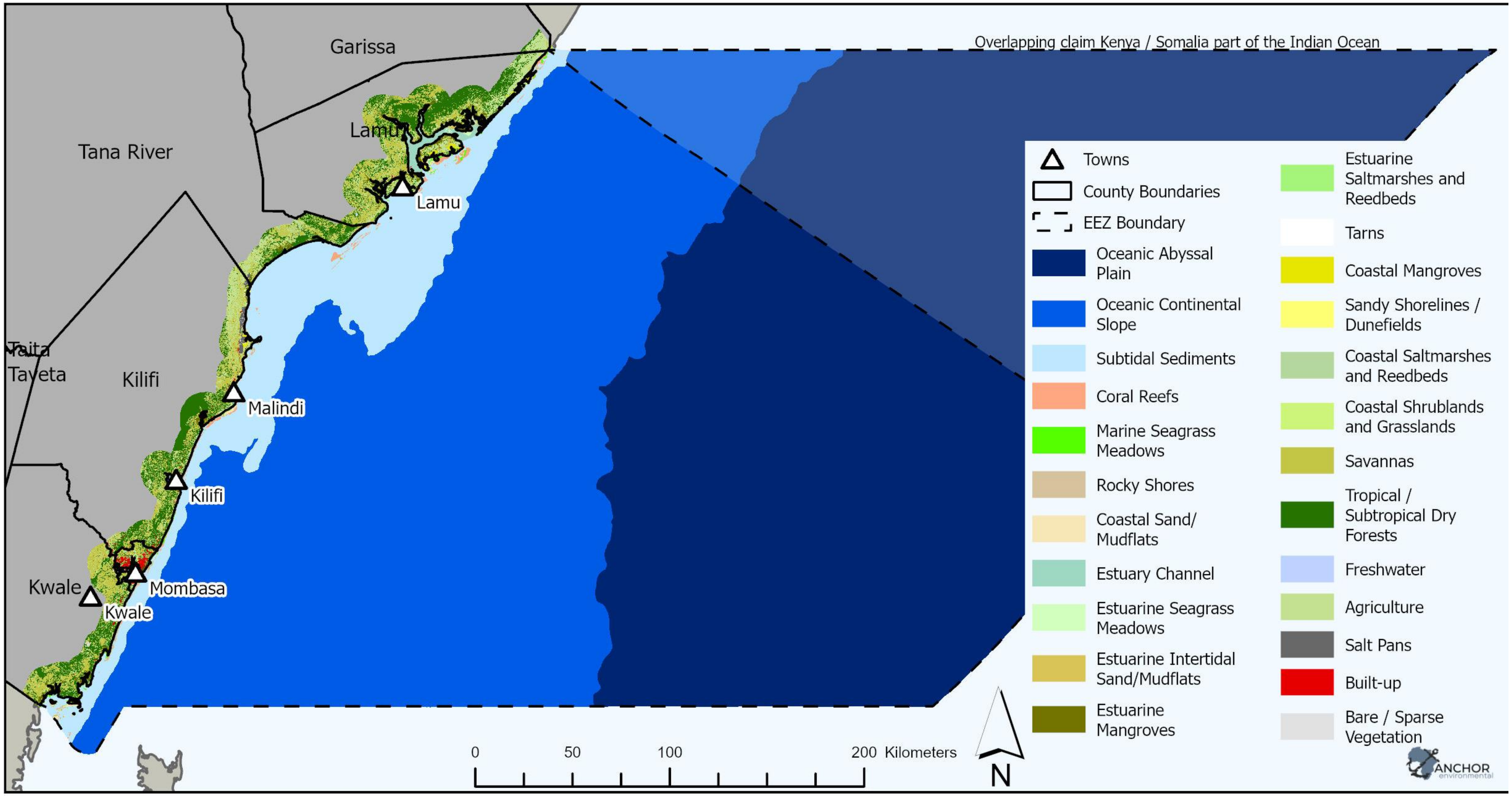

Figure 10: Ecosystem map of the Kenyan Coastline, Terrestrial ecosystems mapped to 10km inland and marine ecosystems mapped to the EEZ boundary. The partially greyed out EEZ zone represents the contested EEZ area between Kenya and Somalia.

3.3.2 ECOSYSTEM EXTENT AT NATIONAL SCALE

Table 6 presents the total area of each ecosystem type for the entire Kenyan coastal and marine area, out to the EEZ boundary. At this scale, the oceanic ecosystem types dominate, together making up 94% of the overall area. Subtidal sediments make up 84% of the remainder. Supratidal coastal habitats cover 11 264 ha, estuarine ecosystems cover 107 958 ha, with estuarine mangroves and channels predominating, and marine intertidal ecosystems cover 32 000 ha. Mangroves in estuarine and coastal locations make up a total of 54 818 ha.

Table 6. Marine and coastal ecosystem extents area summary for the entire coastline.

Realm	Ecosystem type	Area (ha)
Coastal	Salt Pans	4 479
	Coastal Saltmarshes and Reedbeds	3 912
	Sandy Shores / Dunefields	2 873
Estuarine	Tarn	2 582
	Estuarine Saltmarshes and Reedbeds	9 373
	Estuarine Mangroves	44 079
	Estuarine Intertisal Sand/Mudflats	11 973
	Estuarine Seagrass Meadow	4 530
	Estuary Channel	35 421
Marine	Coastal Mangroves	10 739
	Coastal Sand/Mudflats	16 179
	Rocky Shores	5 082
	Marine Seagrass Meadow	8 890
	Coral Reefs	16 485
	Subtidal Sediments	887 757
	Oceanic Continental Slope	5 959 093
	Oceanic Abyssal Plain	9 517 797
		16 541 246

3.3.3 ECOSYSTEM EXTENT AT COUNTY SCALE

Ecosystem areas (excludng oceanic ecosystems) were also summarised at the county level as per the extents depicted in Appendix 4, Figure 40. The county-level areas are shown in Table 7 below. Lamu has the largest extents of several of the important ecosystem types, the highest seagrass coverage (Estuarine Seagrass Meadows 3 881 ha, Marine Seagrass meadows 4 024 ha), the highest mangrove coverage (Estuarine Mangroves 26 391 ha and Coastal Mangrove 7 856 ha) and coral coverage at 7 056 ha. Kilifi County has the largest Sandy Shores/ Dunefields extent, covering 1 322 ha.

Table 7: Coastal, estuarine and marine ecosystem extent area in hectares (ha) per county situated along the coast.

Ecosystem	Kwale	Mombasa	Kilifi	Tana River	Lamu
Salt Pans	0	0	4 217	262	0
Coastal Saltmarshes & Reedbeds	291	25	616	2 778	199
Sandy Shores / Dunefields	117	44	1 322	670	686
Tarn	376	499	391	43	1 272
Estuarine Saltmarshes and Reedbeds	1 021	683	535	746	6 373
Estuarine Mangroves	8 513	1 821	3 964	3 330	26 391
Estuarine Intertisal Sand/Mudflats	301	67	885	412	10 309
Estuarine Seagrass Meadow	355	125	169	0	3 881
Estuary Channel	1 973	3 176	1 877	257	28 137
Coastal Mangroves	1 007	0	1 876	0	7 856
Coastal Sand/Mudflats	2 803	610	4 286	1 777	6 398
Rocky Shores	3 153	921	929	53	3
Marine Seagrass Meadow	2 273	359	1 751	101	4 024
Coral Reefs	1 392	310	4161	2 957	7 056
Subtidal Sediments	66 824	20 039	229 508	323 650	235 137
	90 400	**28 679**	**256 488**	**337 037**	**337 720**

3.3.4 Ecosystem extent at subcounty scale

Ecosystem areas (excludng oceanic ecoysstems) were also summarised per subcounty as per the extents depicted in Appendix 4, Figure 41. The subcounty-level areas are shown in the tables below, with subcounties listed from south-west to north-east.

Table 8: Coastal, estuarine and marine ecosystem extent area in hectares (ha) per sub-county situated along the coast.

	Kwale				Mombasa	
Ecosystem	Lunga lunga	Msam-bweni	Matuga	Kinango	Likoni	Chang-amwe
Salt Pans	0	0	0	0	0	0
Coastal Saltmarshes & Reedbeds	113	130	47	0	15	0
Sandy Shores / Dunefields	20	84	13	0	9	0
Tarn	185	0	42	150	75	2
Estuarine Saltmarshes and Reedbeds	857	15	37	113	35	16
Estuarine Mangroves	6 626	624	318	946	363	234
Estuarine Intertisal Sand/Mudflats	256	5	6	34	14	30
Estuarine Seagrass Meadow	259	96	0	0	30	25
Estuary Channel	1 413	15	65	480	622	1 158
Coastal Mangroves	949	58	0	0	0	0
Coastal Sand/Mudflats	2 411	218	171	3	320	0
Rocky Shores	992	1 941	220	0	488	0
Marine Seagrass Meadow	1 670	519	84	0	66	0
Coral Reefs	568	544	281	0	85	0
Subtidal Sediments	37 753	19 138	9 933	0	6 901	0
	54 070	**23 387**	**11 217**	**1 726**	**9 022**	**1 464**

Table 7 cont'd

	Mombasa				Kilifi		
Ecosystem	**Jomvu**	**Mvita**	**Nyali**	**Kisauni**	**Rabai**	**Kilifi south**	**Ganza**
Salt Pans	0	0	0	0	0	0	0
Coastal Saltmarshes & Reedbeds	0	3	5	2	0	19	3
Sandy Shores / Dunefields	0	1	18	16	0	41	0
Tarn	91	0	0	331	0	77	0
Estuarine Saltmarshes and Reedbeds	118	1	0	513	3	95	0
Estuarine Mangroves	406	8	0	811	0	344	0
Estuarine Intertisal Sand/Mudflats	0	17	0	6	0	17	0
Estuarine Seagrass Meadow	0	57	1	13	0	8	0
Estuary Channel	367	413	12	604	0	36	0
Coastal Mangroves	0	0	0	0	0	0	0
Coastal Sand/Mudflats	0	37	118	134	0	334	0
Rocky Shores	0	45	198	189	0	294	0
Marine Seagrass Meadow	0	2	80	212	0	583	0
Coral Reefs	0	9	196	19	0	450	0
Subtidal Sediments	0	2 747	5 847	4 543	0	11 961	0
	982	**3 340**	**6 476**	**7 395**	**4**	**14 259**	**3**

Table 7 cont'd

	Kilifi			Tana River	Lamu		Garissa
Ecosystem	**Kilifi north**	**Malindi**	**Magarini**	**Garsen**	**Lamu west**	**Lamu east**	**Ijara**
Salt Pans	0	0	4 217	262	0	0	0
Coastal Saltmarshes & Reedbeds	45	188	361	2 778	33	166	0
Sandy Shores / Dunefields	99	25	1 157	670	560	125	34
Tarn	127	0	187	43	717	555	0
Estuarine Saltmarshes and Reedbeds	298	0	139	746	3 107	3 266	0
Estuarine Mangroves	2 232	0	1 387	3 330	10 669	15 721	0
Estuarine Intertisal Sand/Mudflats	540	0	328	412	1 364	8 945	0
Estuarine Seagrass Meadow	161	0	0	0	1 549	2 332	0
Estuary Channel	1 728	0	112	257	8 818	19 319	0
Coastal Mangroves	1	0	1 875	0	34	7 823	0
Coastal Sand/Mudflats	1 538	298	2 116	1 777	1 230	5 167	102
Rocky Shores	635	0	0	53	3	0	0
Marine Seagrass Meadow	778	243	147	101	117	3 907	334
Coral Reefs	2 425	514	772	2 957	1 306	5 750	405
Subtidal Sediments	88 475	14 129	114 943	323 650	137 867	97 270	7 227
	99 086	**15 397**	**127 746**	**337 035**	**167 367**	**17 0351**	**8 103**

4 ECOSYSTEM CONDITION

4.1 Overview

In developing countries, it is particularly challenging to assess the condition of marine ecosystems due to the vast extent of the marine environment and complexity of the ecosystems coupled with limited current or historical data. In the absence of spatially explicit condition assessments for the Kenya coast, a simple pressure indicator approach was followed to estimate the likely condition of marine ecosystems, which was validated as far as possible using qualitative or location-specific information in the literature. The InVEST Habitat Quality model was used to assess the relative condition of ecosystems, based on the expected impacts of three key pressure indicators. Indicators were determined based on for which spatial data were available, namely coastal population density, shipping traffic and industrial fishing intensity.

4.2 Existing information on ecosystem condition

Several studies have been conducted on the assessment of ecosystem condition along the Kenyan coast in the last two to three decades, most of which have focussed on coral reefs, mangroves, and seagrass meadows (Table 9). Few studies have been carried out at scale, however, with most focusing on relatively small areas and/or a particular habitat type. Nevertheless, these studies can help to inform a national-scale assessment. The findings for the three main habitat types assessed can be summarised as follows:

- ***Coral reefs*** are considered to be stressed and bleached following the last mass bleaching event in 1998 due to much higher than normal sea temperatures which severely impacted Kenya's coral reefs (Obura et al., 2001; Obura, 2006). Although some recovery has been documented, most reefs have become algae dominated, particularly those along the central and northern coast (Karisa et al., 2020; Gudka et al. , 2018). Coral reefs are also being smothered from increased sediment outputs from the major rivers in the area. In particular, the elevated sediment outputs from the Tana River is smothering the coral reefs around Malindi (Mohamed et al., 2009; Obura, 2006; Obura, 2001). Gazi Bay and Mombasa north coast reefs are reportedly in a reduced condition following impacts from fishing pressure, tourism and pollution (Mangi & Roberts, 2006; Obura, 2006). Fish populations in unprotected reefs along the coast are considered to be severely overexploited, with fisher density documented as well above the allowed thresholds (Obura, 2001).

- ***Mangrove forests*** are considered degraded and severely overexploited, so much so that the government has banned mangrove wood harvesting twice in the past three decades (GOK., 2017). In addition to a reduction in the area of mangrove habitat, overexploitation impacts on the condition of remaining mangrove areas. In Lamu, it is reported that mangroves have experienced a very noticeable decline in condition and extent in recent years (Hamza et al., 2022; Okello et al. , 2022; Riungu et al., 2022). Mangrove forests in Mida Creek were documented as being "somewhat degraded" by 40% of survey recipients (Owuor et al., 2019). In Makupa Creek, Mombasa, mangroves had not fully recovered by 2017 following an oil spill which destroyed the entire system (GOK., 2017).

- ***Seagrass meadows*** in Malindi and Gazi Bay have shown a pronounced decline, purportedly linked to the increasing coastal population (Harcourt et al., 2018). An assessment in Gazi Bay showed that the seagrass meadows outside of the marine protected area had a lower species diversity than the protected area and were dominated by short lived species, also a sign of degradation (Juma et al., 2020).

Table 9: Summary of the literature reviewed and main findings relating to the condition of the ecosystem.

Ecosystem	Source	Location	Ecosystem Condition Findings
Coral Reefs	Gudka et al., 2018	Kenya	Ecosystems shifting to predominately algal dominated. Suggesting a less than ideal condition.
	Karisa et al., 2020	South Coast, Central Coast, North Coast	High presence of algal cover on reefs and low density of reefs in the North and Central sites.
	Obura, 2001	Malindi National Park	Reefs are stressed
		Malindi Bay, Malindi Town	Corals stressed and smothered from increased sediment export from rivers.
	Mangi & Roberts, 2006	Gazi Bay and Mombasa Northern reefs	Fishing pressure has resulted in decline in reef condition.
	Obura, 2006	Mombasa North Coast	Tourism has resulted in the pollution of the associated marine ecosystems. Intentional wastewater discharge, damage to reefs by tourists and attendant threats.
Mangroves	Owuor et al., 2019	Mida Creek	Surveyed household felt mangroves were somewhat degraded (40%).
	Okello et al., 2022	Lamu, Kiunga and Pate Island	General decline in cover observed, 22.6% decline over 19 years.
	Riungu et al., 2022	Lamu	Annual stock data indicates the forest is at risk of degradation.
	Hamza & Esteves, 2022	Mombasa, Kilifi, Tana River and Lamu counties	Net loss in cover across the country. Mombasa, Kilifi and Tan River slight increase in cover. Lamu highest decline in cover.
Seagrass	Harcourt et al., 2018	Malindi	Pronounced decline in coverage. Potential driver is the increasing coastal population.
		Gazi Bay	Signs of damage from boat anchors
	Juma et al., 2020	Gazi Bay	Western Creek is dominated by small-leaved and short lived species and have a lower Shannon index for species diversity and species evenness in comparison to the eastern creek.
Coastal waters	Obura, 2001	Kenya	Unprotected reefs are exploited well beyond their MSY. Average fisher density well above threshold.

4.3 Estimation and mapping of condition based on pressures

In the absence of large-scale field assessments, the state of ecosystems can be estimated based on spatial data on known pressures, combined with expert understanding of the types, intensity, and extent of the impacts of these pressures. The demand for mapping marine ecosystem condition at scale has intensified in recent years both because of the increased application of marine spatial planning, ecosystem service assessments and natural capital accounting. Because of the paucity of empirical data, modelling tools have been developed that can estimate likely ecosystem condition. Ideally, such maps would be validated with field data and improved over time. This desktop study does not include a field component, and thus could only be validated in broad terms based on the studies discussed above. Nevertheless, a preliminary estimate of condition is likely to be better than omitting this parameter in such assessments.

In this study we considered two existing tools – the Symphony tool developed for marine spatial planning (MSP), and the InVEST Habitat Quality model, both of which deliver spatial outputs on relative condition. These tools use spatial data on human pressures that are usually more readily available than spatial data on ecosystem characteristics, making them useful in situations where pre-existing research and financial capacity are limited (Smit et al., 2021). The Symphony tool is designed for estimating changes in ecosystem condition resulting from the cumulative pressures and impacts under different spatial planning scenarios (Smit et al., 2021; Western Indian Ocean & Symphony, 2022). In the marine environment, the pressures considered typically include human activities such as boating, fishing, pollution from land-based sources and shipping (Smit et al., 2021; Western Indian Ocean & Symphony, 2022), but can also include environmental conditions like turbidity (from degraded river outflows) and changes in sea temperature (due to climate change).

The condition of Kenya's marine ecosystems have been impacted by a range of direct pressures[3] (Cowburn et al., 2013; Mangi & Roberts, 2006; Mwangi et al., 2001; NEMA, 2017; Obura, 2001; Tychsen, 2006). These pressures are summarised into eight types below, noting that there are some interrelationships between these:

- ***Ocean warming events*** are known to have had a major impact on Kenya's coral reefs (see above).
- ***Overharvesting*** of resources is widely considered as one of the most important threats to the health of marine ecosystem. In the case of overharvesting of plants (e.g. mangroves, seaweed) or minerals (e.g. sand, salt), it leads to direct degradation of habitats. In the case of fisheries, it disturbs the community structure and functioning, which also contributes to the overall degradation of ecosystem health.
- ***Destructive fishing methods*** such as dynamite fishing or pulling nets across sensitive habitats (e.g. seine nets, trawl nets), negatively impact coral reefs, seagrass meadows and any sandy bottomed ecosystems (Mangi & Roberts, 2006). Some methods, such as the use of gill nets, are also considered destructive to ecosystems because of their tendency to facilitate overexploitation.
- ***Physical disturbance*** from tourism and recreational boats (Benjamin Cowburn et al., 2013; Obura, 2006) and fishing boats (Mangi & Roberts, 2006), especially due to anchoring (Harcourt et al., 2018), can damage habitats.
- ***Noise pollution*** from large vessels is increasingly recognised globally for its damaging effects on ecological communities and populations because of the disruption of animal communication systems (Rutherford et al., 2021; Wildlife Conservation Society &

[3] Note that the loss of habitat, e.g. due to developments such as hotels, housing, or salt pans is already accounted for in changes in ecosystem extent.

Madagascar & Western Indian Ocean Program, 2016). This includes international shipping as well as fishing and recreational vessels.

- ***Wastewater discharge*** and other pollution from growing coastal populations leads to nutrient pollution, encourages microalgal and macroalgal growth, and leads to deoxygenation and smothering of marine habitats (Mwangi et al., 2001; C. Okello et al., 2022).

- ***Increased sediment outputs*** from rivers draining increasingly eroded catchment areas increases water turbidity, reduces light penetration and smoothers corals and seagrass, reducing their ability to function (Mohamed et al., 2009; Obura, 2006; Obura, 2001).

- ***Invasive species*** brought in my cargo and cruise ships in the form of biofouling and in ballast water also represents an important threat to marine ecosystems globally. Monitoring in the Mombasa harbour indicates an upward trend in presence of alien species in Kenyan waters (Awad, 2011).

The above pressures were then linked to seven key drivers: climate change, major river outflows, coastal development, tourism activity, inshore/artisanal resource harvesting, industrial fishing activity and shipping activity (Figure 11). These drivers were, in turn, linked to three cumulative indicators for which spatial data were available: population density (to capture shore-based pressures including pollution and the pressures associated with inshore artisanal fishing and tourism), industrial fishing activity and shipping activity. Two drivers excluded were climate change, as we had no spatial information on variation in sea temperature changes or its effects along the coast, and sediment outflows, both of which should be considered in future studies. The three cumulative indicators used were similar to those used by Skein et al. (2022) who ranked various pressures impacting on the marine environment in South Africa based on stakeholder inputs. In South Africa, fishing was ranked as having the greatest relative impact, followed by shipping and then various human induced activities such as harvesting/collecting, wastewater discharge, industry impacts and tourism. Shore-based pressures were grouped and thus ranked the highest followed by fishing and shipping for this study.

The effects of these pressures were mapped using the InVEST Habitat Quality model. For each cumulative pressure indicator (population density, industrial fishing activity and shipping activity), the model considered: (1) the relative impact of the threat, (2) the relative sensitivity of each ecosystem to the threat (from 0 = very low to 1 = high), (3) the level of protection (based on protected area boundaries and types in this study) and (4) the maximum distance from the source that the pressure has an impact, and whether this changes linearly or exponentially. This model was designed for application in terrestrial ecosystems, but has been used by Admasu et al. (2023) and Zhang et al., (2022) to assess the ecosystem condition for aquatic and marine ecosystems as well.

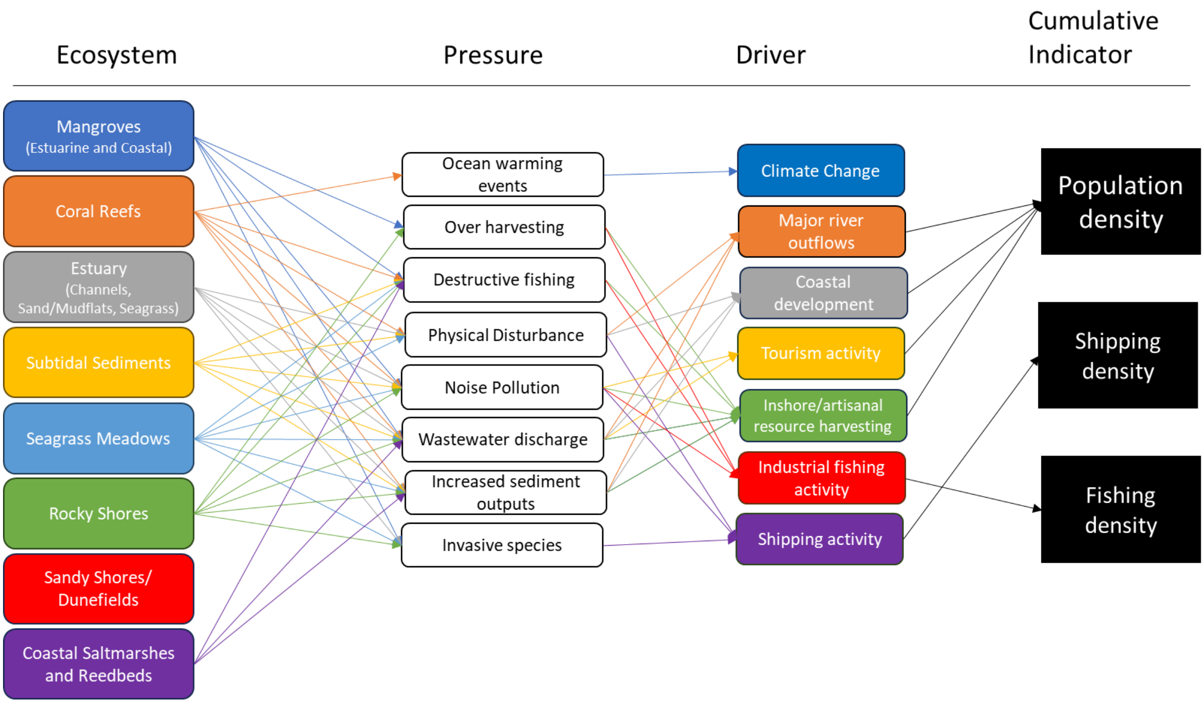

Figure 11: Process flow diagram showing the process used to determine the cumulative indicators used.

The inputs for the model included the ecosystem raster map, a table representing the sensitivity of the ecosystems to each threat (Appendix 5), a shapefile of the protected areas with a field indicating the level of protection provided by each MPA, a population density raster[4], and industrial fishing vessel density and shipping vessel density rasters.[5]

The output of the model is a score from 0 to 1 for each grid square of the study area, where 0 represents the absence of pressures, resulting in good condition, and 1 represents the highest level of pressures, resulting in very poor condition. Ecosystems with a score of 0 – 0.25 were classified as likely being in good condition, those scoring 0.25 – 0.6 were classified as likely in fair condition, and those with scores 0.6 – 1 were classified as likely in poor condition (based on Table 3).

4.4 Estimated Ecosystem Condition

The resulting condition map is shown in Figure 12. Most of the ecosystems considered to be in a poor condition were located immediately along the coastline near the major cities; these are areas which have a high occurrence of sensitive ecosystems and are in closer proximity to high population densities and ports or harbours. The mostly heavily impacted ecosystems included the subtidal sediments, coral reefs, marine seagrass meadows, rocky shores, and

[4] WorldPop; https://www.worldpop.org/

[5]https://globalmaritimetraffic.org/gmtds.html?$root.map.zoom=3&$root.map.center={%22lat%22:0,%22lng%22:0}&$root.projectionSelect=%22EPSG:3857%22

intertidal sand/mudflats, all with a pressure score of 0.9 (Table 11). Estuarine ecosystems also had high pressure scores (average 0.8) and are also likely in a poor state of health. These ecosystems are all extensively used by people for fishing, harvesting, tourism and recreation. Protected areas afford some protection to marine ecosystems by restricting access and by limiting consumptive activities within their boundaries. Protected areas providing the best overall protection to ecosystems included the Watamu MNP, Mombasa MNP, and Kisite MNP (Figure 12, Table 10). These protected areas offer the highest level of protection to marine ecosystems through established no-take zones. The average pressure score across all protected areas did not exceed 0.5, with majority having an average score of less than 0.4 (Table 10). The positive effects of protected areas are visible in Watamu National Marine Protected Area (Figure 12, inset map 2), and Gazi Bay (Figure 12, inset map 4), where ecosystems on the eastern side of the bay are estimated to be in much better condition than those on the western half of the bay which are not afforded any protection. This is supported by the findings of Juma (2020) who assessed the condition of seagrass meadows in these areas (see above). The mangrove forests in Lamu are estimated to be in a fair condition (Figure 12, inset map 1), which is supported by the findings of Hamza & Esteves, (2022), Riungu et al., (2022) and Okello et al., (2022), all of whom observed that mangrove forests in this area were in a declining state of health. Across the whole country, mangrove forests were estimated to be generally in a poor state of health, with estuarine mangroves being worse off (average 0.8, poor) than coastal mangroves (average 0.7, fair; see Table 11). This is likely attributable to estuarine mangroves being more accessible to human pressures than the coastal mangroves, which mostly occur on the islands along the coast.

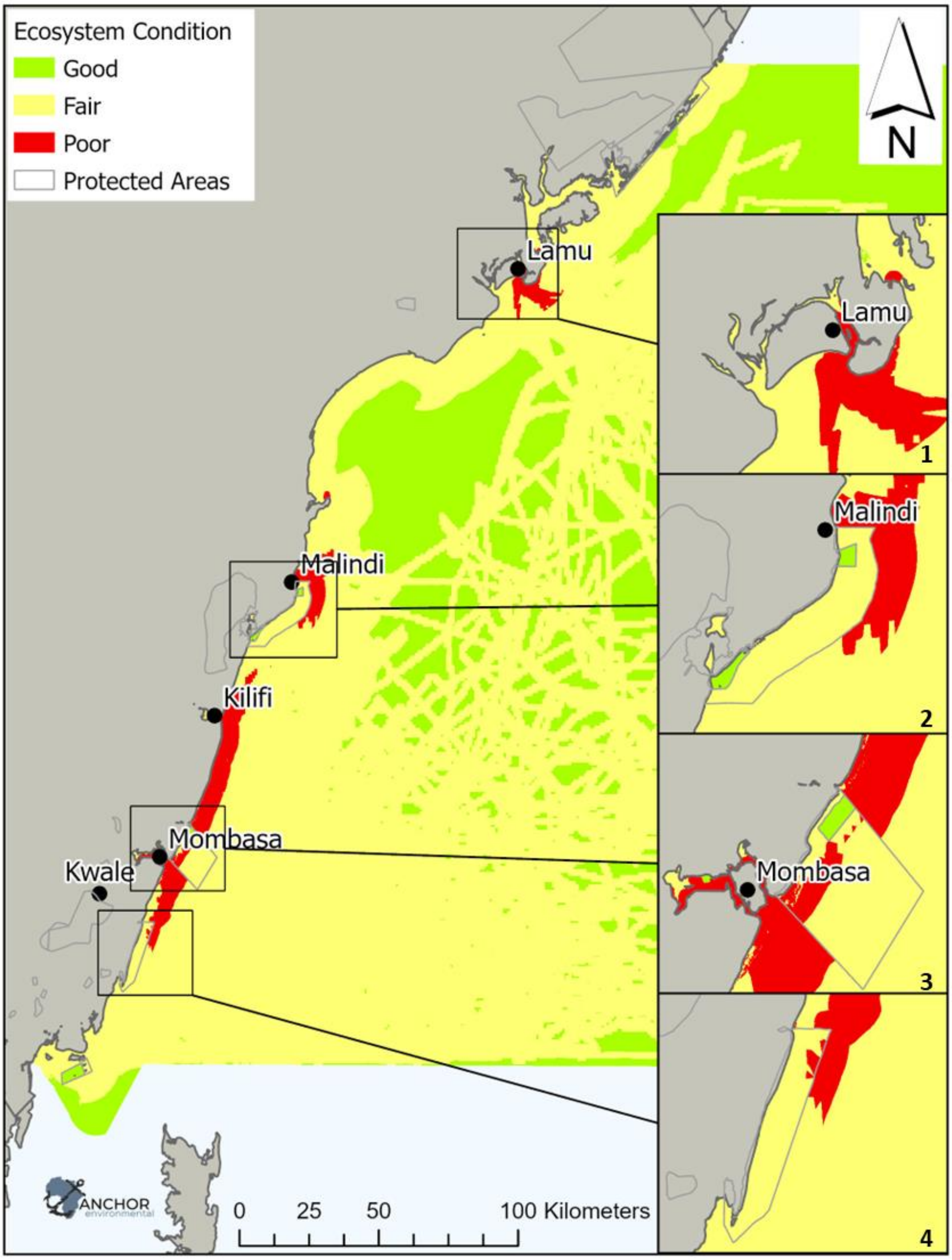

Figure 12. Map of the estimated/likely ecosystem condition for the Kenya Coast. Inset maps (top to bottom) display Lamu Island, Mida Creek and Watamu Marine National Park to Malindi Town, Mombasa and Mombasa Marine National Reserve and Marine National Park, and Gazi bay and Diani-Chale Marine Reserve

Table 10. Summary of the estimated ecosystem condition scores within protected areas.

Protected Area	Highest Score	Category	Average Score	Category
Diani-Chale	0.6	Poor	0.4	Fair
Dodori	0.5	Fair	0.01	Good
Kisite MNP	0.2	Good	0.1	Good
Kiunga MNaR	0.5	Fair	0.3	Fair
Malindi MNP	0.5	Fair	0.2	Good
Mombasa MNaR	0.7	Poor	0.5	Fair
Mombasa MNP	0.2	Good	0.2	Good
Mpunguti MNaR	0.5	Fair	0.4	Fair
Watamu	0.6	Fair	0.4	Fair
Watamu MNP	0.2	Good	0.1	Good

Table 11. The extent (ha) and percentage of different ecosystem types in each condition category. Note that these should not be totalled across the broad types, as some groups overlap.

Ecosystem type	Good		Fair		Poor	
	ha	%	ha	%	ha	%
Subtidal sediments	230 151	26	567 610	65	77 410	9
Coral reef	827	5	13 813	87	1 237	8
Seagrass meadows	731	9	6 889	81	893	10
Rocky Shores	323	6	3 748	74	980	19
Sandy/muddy intertidal	1 262	8	14 095	89	509	3
Estuary (All estuary classes)	338	1	59 043	92	4 473	7
Mangroves (coastal and estuarine)	1 288	2	51 451	94	2 045	4

5 ECOSYSTEM SERVICES

5.1 OVERVIEW

This section estimates and maps the physical flows of five broad types of provisioning, regulating and cultural ecosystem services from coastal and marine environments in Kenya, namely mangrove wood harvesting, fisheries, carbon storage, coastal protection, and nature-based tourism.

The provisioning and cultural services are the most visible flows and are generally the types of flows that are monitored and recorded. In Kenya, this includes the subsistence/small-scale and commercial/industrial harvesting of mangrove wood and a variety of fish and invertebrates (collectively referred to as fisheries) which are important both for local livelihoods (Manzi et al., 2021; Owuor et al., 2017) and for the economies of the coastal counties. Tourism is also known to be an important contributor to the coastal economies. However, the source areas of fisheries and tourism ecosystem service flows are not well mapped, and this required specialist knowledge and innovative methods to map the flow to ecosystems, taking condition into account.

Carbon storage is increasingly well studied globally and this assessment benefits from a series of earlier studies from the Kenyan coast. However, coastal protection is far more challenging to assess, and is provisionally estimated in this study using InVEST modelling software.

5.2 MANGROVE WOOD

Mangroves reportedly provide about 70% of the wood requirements of coastal communities in Kenya (Manzi & Kirui, 2021a). It is used for firewood, charcoal, building poles and fishing gear (Manzi & Kirui, 2021a). Several studies have assessed the importance of mangroves in providing wood for coastal communities and found that communities ranked it as a highly important service (Huxham et al., 2015; Ochieng et al., 2023; Owuor et al., 2017). While mangrove forests are also used for the provisioning of non-wood products such as honey, tannins for dyes and medicinal products (Manzi & Kirui, 2021a), these are not included in this assessment.

5.2.1 MANGROVE POLES

The main wood product of value is construction poles. Mangrove poles have historically been a major export for Kenya, with records dating back to the 9th Century (GOK., 2017; Manzi & Kirui, 2021a). In the early 20th century, Kenya exported approximately 483 000 poles (24 150 scores) of mangrove poles, which then dwindled to around 13 744 scores by the early 90s. The decline in output was attributed to the overexploitation of the resource, and led to a national ban of mangrove pole harvesting in 1997 (GOK., 2017). The ban was later lifted, after which harvesting of mangrove poles again reached unsustainable levels, leading to a second national ban in 2018 (Hamza et al., 2023). This second ban led to a mass public outcry from communities in Lamu county, whose economy was particularly dependent on this activity. In 2019, the GOK lifted the mangrove pole harvesting ban for Lamu County only, leaving the ban in place for the rest of the country. This ban on mangrove wood harvesting apart from in Lamu was still in place during the accounting year for this study (2021), but was lifted in June 2023 (Fuchs, 2023; Hamza et al., 2023). Small-scale informal harvesting continued in many areas in spites of the ban, and is considered a bigger threat than has been assumed (Manzi & Kirui, 2021a).

For this study, Lamu was the only county where mangrove pole harvesting was legally allowed in 2021. The most recent literature pertaining to the quantity of harvested mangrove poles is the GOK., (2017) National Mangrove Management Plan. Based on the (potentially unrealistic) assumption that the quantity harvested in 2014 (96 103 scores from 34 247 ha; Table 12**Error! Reference source not found.**) was a managed long-term sustainable harvest that would therefore be similar in 2021. Data on the historical mangrove pole harvest from each county prior to the national ban is presented in Table 12, which suggests that Lamu county historically accounted for almost 99% of the national harvest. It is recommended, however, that future assessments are based on more up-to-date management/monitoring data for the applicable production areas.

Table 12. Quantity of harvested mangrove poles. Note that one score is 20 poles. Source: *GOK., (2017)*.

County	Mangrove area (ha)	Scores of poles		
		2012	2013	2014
Kwale	9 520	472	478	454
Mombasa	1 821			103
Kilifi	5 840	96	100	95
Tana River	3 330	82	92	87
Lamu	34 247	23 224	96 531	96 103
Total	**54 758**	**23 874**	**97 201**	**96 842**

5.2.2 MANGROVE FUELWOOD

Manzi & Kirui, (2021) estimated the value of charcoal and firewood harvested from 11 different mangrove forest areas using a combination of reported statistics and household survey results. The monetary values were converted to mass in kg using the prices per kg given in the report, and then into total wood use by converting the charcoal mass to its wood equivalent using a ratio of 0.142:1(Okello, et al., 2001; Table 13). These data were mapped and interpolated to mangrove areas not included in the study.

Based on the above, the total harvest per subcounty is summarised in Table 14. The results suggest that Kilifi South had a significantly higher average mangrove fuelwood harvest rate than in other sub-counties of some 76 358 kg/ha/y, while Kisauni, Mombasa had the second highest harvest rate of about 21 229 kg/ha/y (Table 14). These results appear to be overestimates of fuelwood harvest, as the amount of fuelwood extracted from mangrove forests would suggest significant biomass removal, with total biomass for mangrove forests typically between 180 - 260 tonnes/ha (Kairo, et al., 2021). Further research is required to provide better assessments of the fuelwood harvest from mangroves.

Table 13. The value of mangrove wood harvested per year for firewood and charcoal as reported in Manzi & Kirui, (2021), and the total fuelwood abstraction rates derived therefrom. Prices given as Ksh30 and 45 for firewood and charcoal, respectively, throughout.

Mangrove Forest	Area (ha)	Wood for charcoal		Firewood		Total	
		Ksh '000s / y	kg wood /ha/y	Ksh '000s /y	kg wood /ha/y	kg wood /ha/y	Total tons/y
Vanga	3 880	36 876	1 487	212 918	1 829	3 317	12 868
Gazi	545	17 975	5 164	103 789	6 351	11 516	6 273
Funzi	1 306	27 455	3 291	158 527	4 047	7 338	9 581
Tudor	767	28 083	5 727	4 775	207	5 934	4 554
Mida	1 814	35 180	3 035	203 130	3 733	6 768	12 276
Mtwapa	597	214 835	56 307	359 175	20 051	76 358	45 593
Takaumgu	371	59 938	25 256	100 209	8 994	34 250	12 720
Kilifi	1 026	127 877	19 514	213 793	6 949	26 464	27 139
Ungwana Bay	2 062	56 005	4 250	93 633	1 514	5 764	11 886
Ngomeni	2 530	157 234	9 724	262 874	3 463	13 187	33 369
Lamu	32 791	94 457	451	172 050	175	626	20 517
Total	**47 689**						**196 775**

Table 14. Estimated average mangrove wood harvested for firewood or charcoal per subcounty, based on estimates in Table 13 plus interpolation.

County	Sub county	Mangrove area (ha)	Harvest rate kg/ha/y	Total harvest tons/y
Lamu	Lamu East	23 520	626	14 724
	Lamu West	10 672	626	6 681
Tana River	Garsen	3 320	13 187	43 781
Kilifi	Magarini	3 275	8 858	29 009
	Kilifi North	2 242	11 823	26 507
	Kilifi South	344	76 358	26 267
Mombasa	Kisauni	815	21 229	17 301
	Mvita	7	5 934	42
	Jomvu	409	5 934	2 427
	Changamwe	231	5 934	1 371
	Likoni	364	5 934	2 160
Kwale	Kinango	954	5 934	5 661
	Matuga	321	5 934	1 905
	Msambweni	680	11 516	7 831
	Lunga Lunga	7 580	4 985	37 789
Total		**54 734**		**223 455**

5.3 FISHERIES

Kenyan marine ecosystems support several fisheries which make an important contribution to the national economy and coastal livelihoods (Kamau et al., 2021). The marine fishery can be broadly split across two main fishing zones, the coastal inshore zone and the offshore zone or EEZ (Kamau et al., 2021). Both artisanal and industrial fishing take place in the inshore zone, while the offshore fishery is predominately industrial. The artisanal fishery includes small-scale fisheries, subsistence and recreational fishers, and the industrial fishery includes commercial trawling, pot fishing and longlining (Kamau et al., 2021).

5.3.1 ARTISANAL FISHERIES

The Kenyan marine fisheries are predominantly operated by artisanal fishers (Kamau et al., 2021). The dominance of artisanal fishers has resulted in the bulk of fishing effort being expended in the inshore waters along the coastline, with offshore coastal waters being largely unexplored by local fishers (Kamau et al., 2021). For communities living along the coastline, fishing is a pillar of their livelihoods and makes a significant contribution towards ensuring food security (Kamau et al., 2021).

The artisanal fishery can be divided into two main categories based on gear used: small-scale commercial fishers and the subsistence or recreational fishers. Small-scale commercial fishers make use of a variety of seine nets, longlines and ring nets, while subsistence and recreational fishers generally make use of spearguns, hooked sticks, basket traps, gillnets and monofilament lines (Republic of Kenya & KeFS, 2022). The target ecosystems and accessibility of offshore waters differ between each category. Small-scale fishers tend to have access to vessels with some form of propulsion, whereas subsistence and recreational fishers tend to utilize the resources available on or close to the shore only.

Methods

Artisanal fish landings data for each county (Kwale, Mombasa, Kilifi, Tana River, Lamu) in 2022[6] were obtained from (Republic of Kenya & KeFS, 2022); the data taking the form of weight (kgs) of fish caught for each of 35 taxonomic groups (Table 15). These catches amounted to some 35 600 tonnes of fish caught by artisanal fishers in 2022.

A heuristic model was developed to estimate the spatial distribution of catches of each species across different habitat types in different condition and distances offshore, using county-level statistics and expert opinion. The model took into account the relative abundance of and/or likely relative fishing effort for each taxonomic group in each of seven different habitat types (estuaries, coastal mangroves, intertidal sand/mudflats, rocky intertidal, seagrass meadows, coral reefs, subtidal sediments) using expert knowledge and sources such as FAO (2010) and Fishbase (https://www.fishbase.se/). Ecosystem areas within MPAs or MNaRs which are classified as no-take zones were assumed to have zero fishing effort. Ecosystems in poor or

[6] Note that although these accounts are for 2021, we used the 2022 data as data collection methods had significantly improved in 2022.

fair condition were assumed to have proportionally lower potential catches than those in good condition, for all other things equal.

Table 15. Catch data for each species/taxonomic grouping by County for 2022, expressed in kilograms. Source: (Republic of Kenya & KeFS, 2022). Spellings are as per the report.

Species caught	Kwale	Mombasa	Kilifi	Tana river	Lamu	Total
Rabbit fish	1 517 489	415 587	350 079	15 136	1 156 500	3 454 791
Scarvenger	979 053	201 035	264 930	81 324	1 001 491	2 527 833
Snapper	474 163	91 687	391 369	296 367	404 366	1 657 953
Parrot fish	686 145	96 936	356 385	41 211	898 422	2 079 098
Surgeon fish	205 213	82 312	101 274	13 678	54 884	457 361
Unicorn fish	277 203	62 428	78 800	634	42 697	461 761
Grunter	79 931	75 816	35 251	936	184 988	376 923
Pouter	298 209	33 029	52 161	0	187 281	570 679
Black skin	252 748	145 919	187 371	20 743	242 606	849 387
Goat fish	298 941	63 902	87 425	1 403	124 981	576 652
Steaker	76 923	853	18 543	1 115	26 373	123 808
Rock cod	318 769	75 608	304 517	41 477	166 673	907 044
Cat fish	156 079	30 186	127 179	37 226	102 716	453 387
Mixed dermasal	209 622	48 163	1 199 235	19 644	155 984	1 632 649
Cavalla jacks	684 648	80 017	218 231	63 810	87 047	1 133 753
Mullets	107 946	30 489	61 377	3 271	129 481	332 564
Little mackerels	470 569	65 361	1 056 881	5 617	0	1 598 428
Barracudas	366 167	60 659	366 070	9 763	72 802	875 460
Milk fish	73 270	11 387	41 095	39 625	46 915	212 291
King fish	172 868	39 359	493 855	40 565	24 792	771 439
Queen fish	72 108	39 650	109 676	21 475	35 625	278 534
Sail fish	97 905	4 241	197 017	75 459	13 781	388 403
Bonitos/Tunas	767 091	365 922	1 353 265	767 091	536 698	3 790 066
Dolphin Fish	92 885	0	46 577	0	0	139 463
Mixed Pelagics	347 992	21 619	475 231	12 229	63 065	920 136
Sharks &Rays	593 058	133 319	243 332	33 390	77 208	1 080 308
Sardines	1 569 041	169 771	301 655	8 402	0	2 048 869
mixed fish/Others	158 103	110 563	0	27 787	53 583	350 036
Lobsters	235 044	26 022	96 592	15 456	193 926	567 040
Prawns	526 439	317 155	105 269	10 953	52 296	1 012 113
Crabs	248 850	46 844	94 555	6 484	217 720	614 454
Oysters	69 376	0	8 406	0	0	77 781
Beche-de-mer	80 152	0	15 658	4 892	34 090	134 791
Octopus	1 579 057	103 582	343 513	63 728	130 343	2 220 224
Squids	651 728	99 300	124 095	28 593	17 163	920 880
TOTAL	**14 794 787**	**3 148 721**	**9 306 868**	**1 809 486**	**6 536 495**	**35 596 357**

County catches of each taxonomic group were disaggregated spatially by habitat type and condition in a series of calculation steps.

First, the likely relative catchability (H) for each habitat type was scored, mainly considering where the species was likely to be more common, but possibly also the degree to which it would be fishable in that habitat. Then the proportional impact of condition of a particular habitat on catchability was provided as a modifier (i.e. poor condition and fair condition catchability as a percentage of good condition catchability). The relative catchability (H) and relative habitat condition (R) was used to create the $FDFactor_{h,c,f}$ which estimates the relative density of fish species (f), per habitat (h), and per habitat condition (c), with habitat condition being either good, fair, or poor.

$$FDFactor_{h,c,f} = \frac{H_{h,c,f} \times R_{h,c,f}}{R_{good}}$$

with H being relative catchability, R being a categorical variable taking the value of 25 (poor condition), 50 (fair condition), 80 (good condition), and R_{good} representing a habitat in a good condition.

Then, the relative abundance of each habitat under each condition was considered, to ultimately spread the recorded catches across the seascape. A fish allocation factor $FAFactor_{h,c,f}$ was calculated to determine how fish landings should be allocated, considering fish species' habitat preferences and how much of these habitats of different conditions are present in the relevant county (with A being the total area of habitat; ha):

$$FAFactor_{h,c,f} = \frac{FDFactor_{h,c,f} \times A_{h,c}}{\sum_h (FDFactor_{h,c,f} \times A_{h,c})}$$

Total fish landings per fish species, habitat, and habitat condition were then calculated by multiplying the fish allocation factor ($FAFactor_{h,c,f}$) with the fish landings per fish species (L_f):

$$TFL_{h,c,f} = FAFactor_{h,c,f} \times L_f$$

Fish landings per habitat and habitat condition are calculated by summing the total fish landings per fish species, habitat condition and habitat:

$$TFL_{h,c} = \sum_f (TFL_{h,c,f})$$

A further adjustment was made for catches from subtidal sediments which extend into much deeper waters than other nearshore ecosystem types which tend to be located well within reach of the shore. For fish catches allocated to subtidal sediments, we assumed that fishing effort would be greater closer to shore, dropping off rapidly after about 5 km from shore (based on a study in Kenya by Daw et al., 2011), but with some effort extending up to 10km (or the edge of the shelf, whichever is closer). This inverse sigmoid function was calculated as:

$$E = \frac{E_m}{1 + (\frac{D}{D_{50}})^P}$$

where E = effort relative to maximum level (as a proportion out of 1), E_m = maximum level of effort (close to shore), D = distance from shore, D_{50} = distance at which effort level declines to 50% of maximum (set as 3 km), and P = exponent determining curve shape, set to 3.5.

Results

The estimated distribution of catches among ecosystem types in each county is summarised in Table 16. Within Kwale, 87% of catches were estimated to come from the subtidal sediment ecosystem, and 3% from coral reefs (Table 17). In Kilifi the corresponding proportions were 97% and 1% (Table 17). A similar trend was observed across Tana River with majority of the catches coming from the subtidal sediment ecosystem followed by coral reefs. In Lamu and Mombasa, a substantial number of catches also came from estuaries. In terms of catch per unit area, coral reefs and subtidal sediments have the highest estimated catch rates compared to the other ecosystems (Table 16). Overall, coral reefs in Kwale County had the highest estimated catch rates, with up to 334 kg/ha (Table 16). Subtidal sediments in Kwale also had a relatively high catch rate, followed by estuaries (Table 16).

These findings correspond with the literature which indicated artisanal fishing effort to be concentrated within few kilometers of the coast, approximately 5 km (Daw et al., 2011) mostly around the fringing coral reefs (Kamau et al., 2021). In particular, the coral reefs along the southern border and in the nearshore waters around Funzi Island, Vanga and Shimoni, all of which are within Kwale county. Mugnier (2021) indicated that Kwale accounted for the highest quantity of fish which corresponds with our findings. The high quantities of catch arising from these ecosystems should not be taken to represent the condition of the ecosystems, rather an indication of the high pressure these ecosystems endure and the increased potential for overexploitation, resulting from artisanal fishing pressure.

Table 16. Weighted average artisanal catch (kg/ha) per ecosystem type for each county. Note that these habitats area all inside the continental shelf.

Ecosystem	**Catch kg/ha**				
	Kwale	**Mombasa**	**Kilifi**	**Tana River**	**Lamu**
Estuaries	100	83	10	1	9
Coastal mangroves	45	45	4	0	5
Intertidal sand/mudflats	97	83	9	2	5
Rocky intertidal	67	40	5	1	8
Seagrass meadows	76	70	4	1	11
Coral reefs	334	223	33	8	34
Subtidal sediments	202	131	40	5	23
Across all habitats	**171**	**114**	**37**	**5**	**19**

Table 17. Estimated distribution of total artisanal catches per ecosystem for each county.

Ecosystem	Catch (tonnes)				
	Kwale	Mombasa	Kilifi	Tana River	Lamu
Estuaries	399	380	40	2	459
Coastal mangroves	431	82	21	0,9	187
Intertidal sand/mudflats	261	47	37	3	110
Rocky intertidal	208	32	4	0,07	0,08
Seagrass meadows	170	22	7	0,05	45
Coral reefs	446	70	125	24	242
Subtidal sediments	12 881	2 515	9 072	1 779	5492
Total	**14 796**	**3 148**	**9 306**	**1 809**	**6 535**

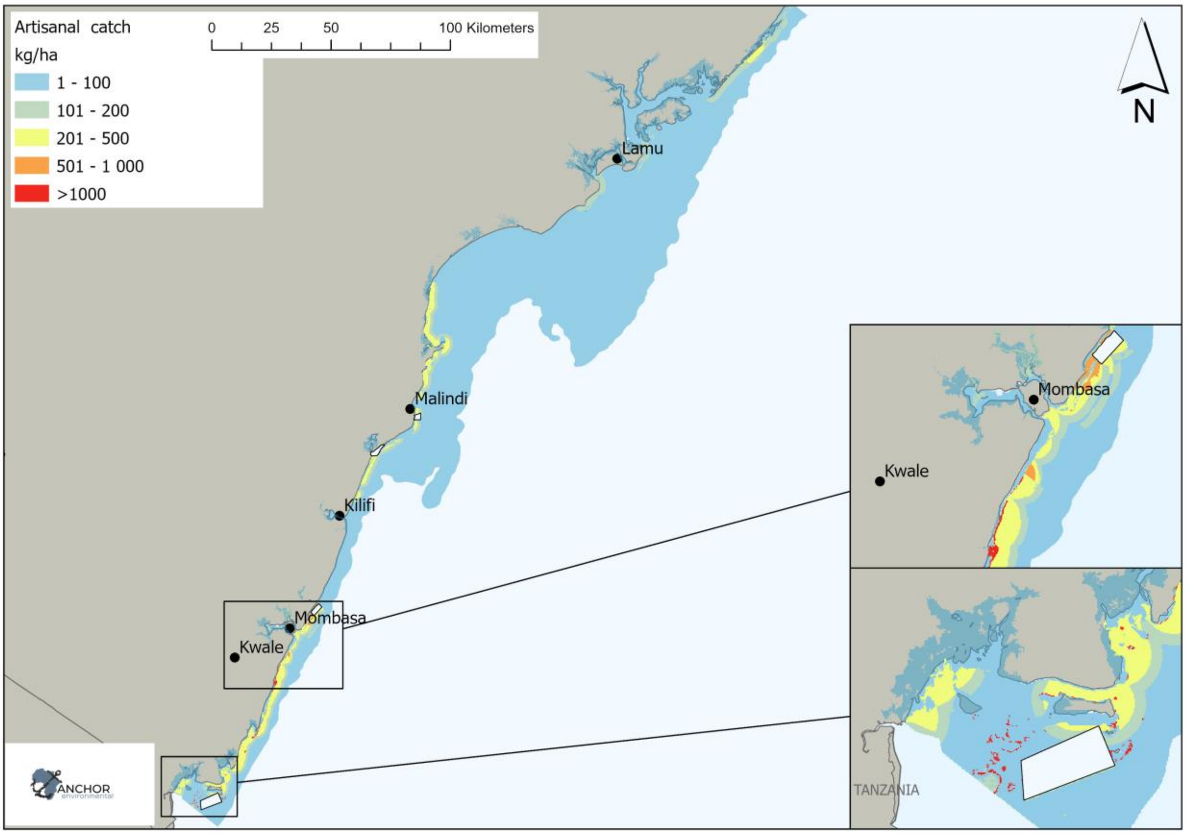

Figure 13: Map displaying the estimated variation in artisanal fishing catch rates (kg/ha/y) across different ecosystems.

5.3.2 INDUSTRIAL FISHERIES

The industrial fisheries in Kenya make up a small component of the total national fishing activity, and are dominated by three main fisheries: the trawl, longline and pot fisheries

(Republic of Kenya & KeFS, 2022). Kenya's offshore fishing sector is considered to be underdeveloped, with most of fishing effort coming from artisanal fishers who rarely target the productive offshore waters (Kamau et al., 2021). Nevertheless, it is also argued that the size of the industrial fisheries and their economic impact may be underestimated (Kamau et al., 2021).

Methods

For this study, total catch data for 2021 (in kg; Republic of Kenya & KeFS, 2022) were mapped using spatial data on fishing vessel activity within the Kenyan EEZ boundary. Maps of trawl and pot fishing activity were obtained from Republic of Kenya & KeFS, (2022). Data for longline fishing activity were obtained from Global Fishing Watch (GFW; GFW, 2023), an open-source portal with datasets mapping fishing effort globally. The assumption was made that all point locations were indicative of places where fishing took place. For each fishery, the point data were used to create a map of relative activity level. This was then used to spread the total catch weight (kg) across the fishing area. In the absence of further information (e.g. variation in stocks or catch per unit effort), this assumed that catchability was constant across the area.

Results

The crab pot fishery is a relatively small fishery operated by just two vessels which focus their efforts approximately 12 nautical miles offshore (Republic of Kenya & KeFS, 2022). The oceanic continental slope ecosystem accounts for 98% (Table 18) of the crab pot fishery catching 104 tonnes of crabs in 2022, with most of this between Mombasa and Kilifi. Estimated catches per ha varied up to about 0.5 kg/ha/year (Figure 14).

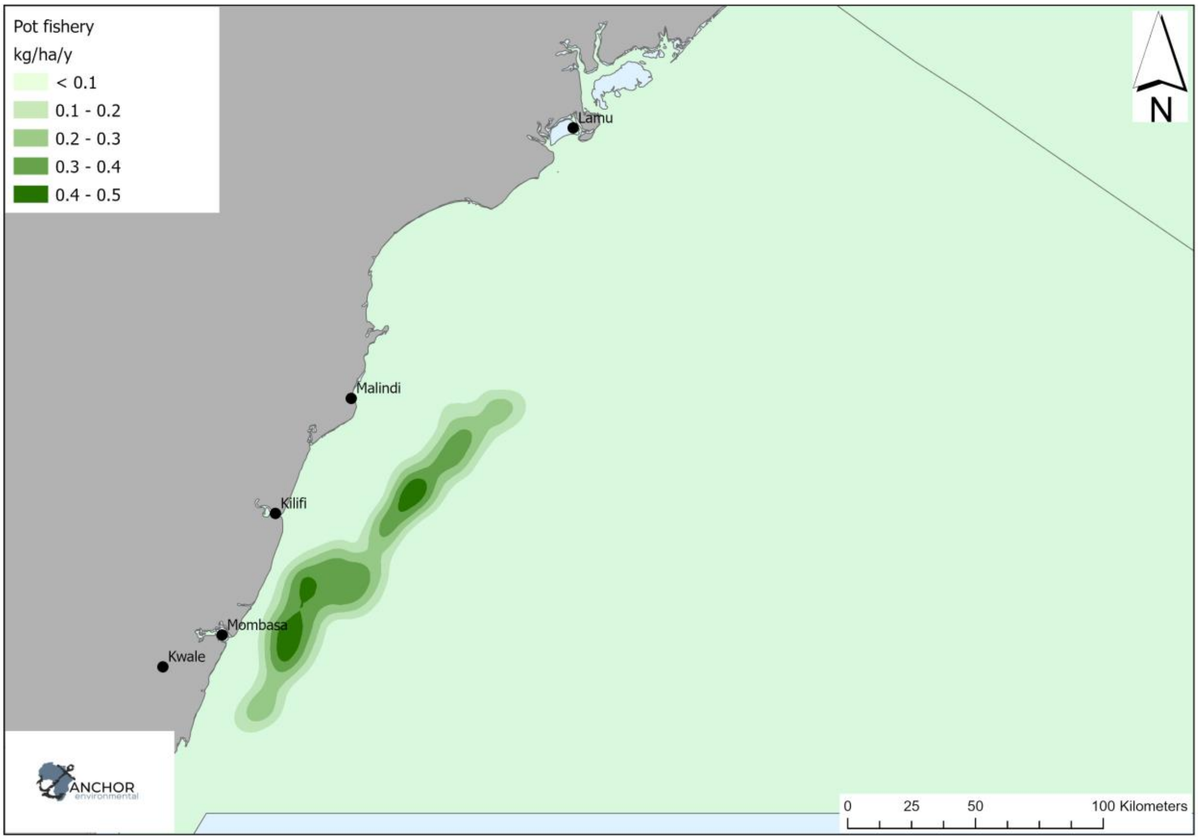

Figure 14. Estimated spatial distribution of the provisioning of crabs caught in the industrial pot fishery, based on data in Republic of Kenya & KeFS, (2022).

Longline fishing mostly occurs between 12 nautical miles from shore and the EEZ boundary in the subtidal sediment, oceanic continental slope, and oceanic abyssal plane ecosystems (Republic of Kenya & KeFS, 2022) (Figure 15). Most of the longline fishery catches occur in the southern coastal waters, off the coast of Mombasa with catches of up to about 0.6 kg/ha/year. Very little of the catch comes from the northern waters (Figure 15). The oceanic continental slope accounts for 85% of the longline catches, 12% from the oceanic abyssal plain and 3% from the subtidal sediment ecosystem (Table 18).

The longline fishery is a relatively underdeveloped fishery in Kenya, and it is believed that the majority of the available stock is lost to foreign fishing vessels, in particular those targeting tuna off the continental shelf of the north coast (Kamau et al., 2021). The Kenyan longline fishery landed some 527 tonnes of fish in 2022, with game fish - swordfish (49.46%), yellowfin tuna (3.55%), big-eye tuna (2.20%), black marlin (0.28%) - and finfish (24.45%) accounting for 80% of the total catch (Republic of Kenya & KeFS, 2022).

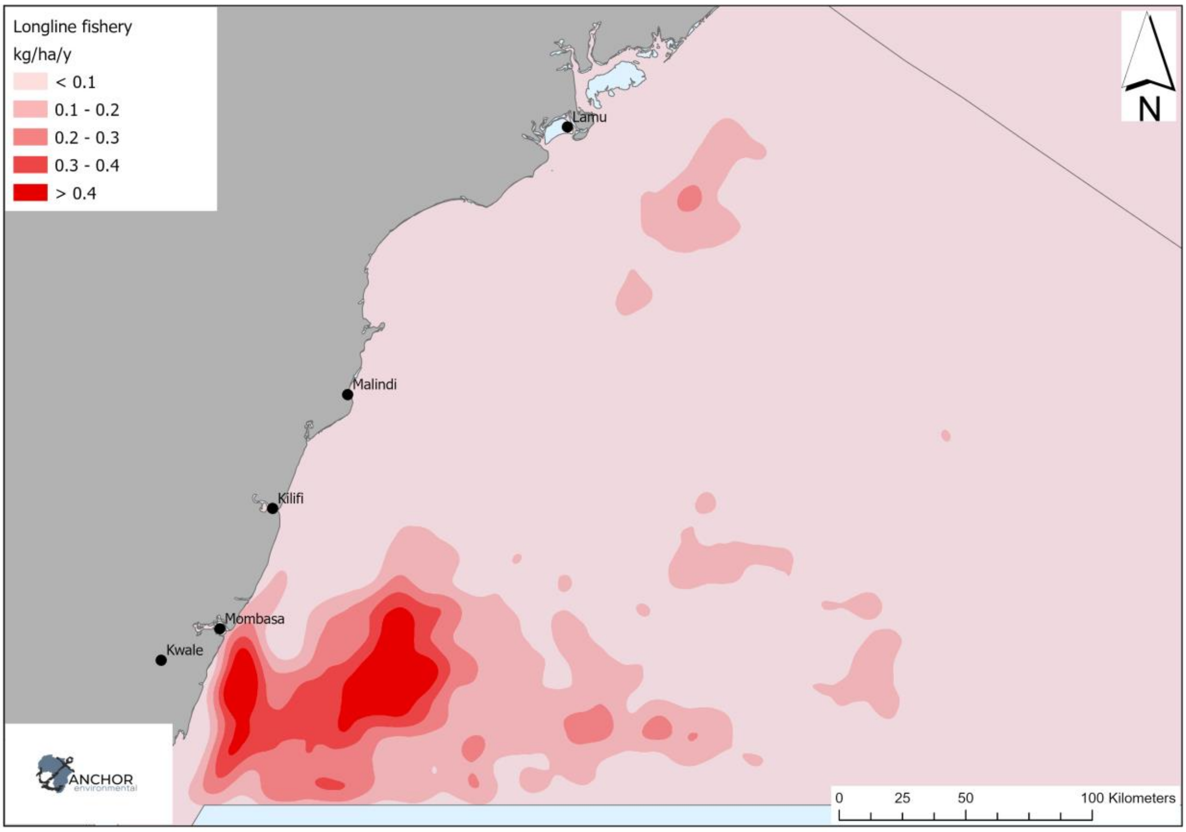

Figure 15. Estimated spatial distribution of the provisioning of fish caught in the industrial longline fishery, based on data in Republic of Kenya & KeFS, (2022) and Global Fishing Watch, (2023)

The industrial trawl fishery has a fleet of six registered vessels mostly targeting finfish (87% of recorded landings) and prawns (9% of recorded landings; Republic of Kenya & KeFS, 2022). The trawl fishery has the highest catch weight of all three fisheries (1267 tonnes, or 67%; Republic of Kenya & KeFS, 2022). Most fish are caught in the Malindi-Ungwana Bay area (Figure

16) with 44% of the catches occurring in the oceanic continental slope ecosystem, 41% from subtidal sediments and 14% from the oceanic abyssal plain, where the average catch is approximately 3 kg/ha/y (Table 18). There are some recorded catches in the offshore waters, mostly in the southern portion of the oceanic continental slope and oceanic abyssal plane ecosystems.

Table 18. Percentage of industrial fishery catches per ecosystem.

Ecosystem	**% total catch**		
	Pot	**Longline**	**Trawl**
Oceanic abyssal plain	0.0	12.2	14.4
Oceanic continental slope	98.5	85.0	43.7
Subtidal sediment	1.5	2.7	41.5
Other	0.0	0.1	0.5
Total	**100.0**	**100.0**	**100.0**

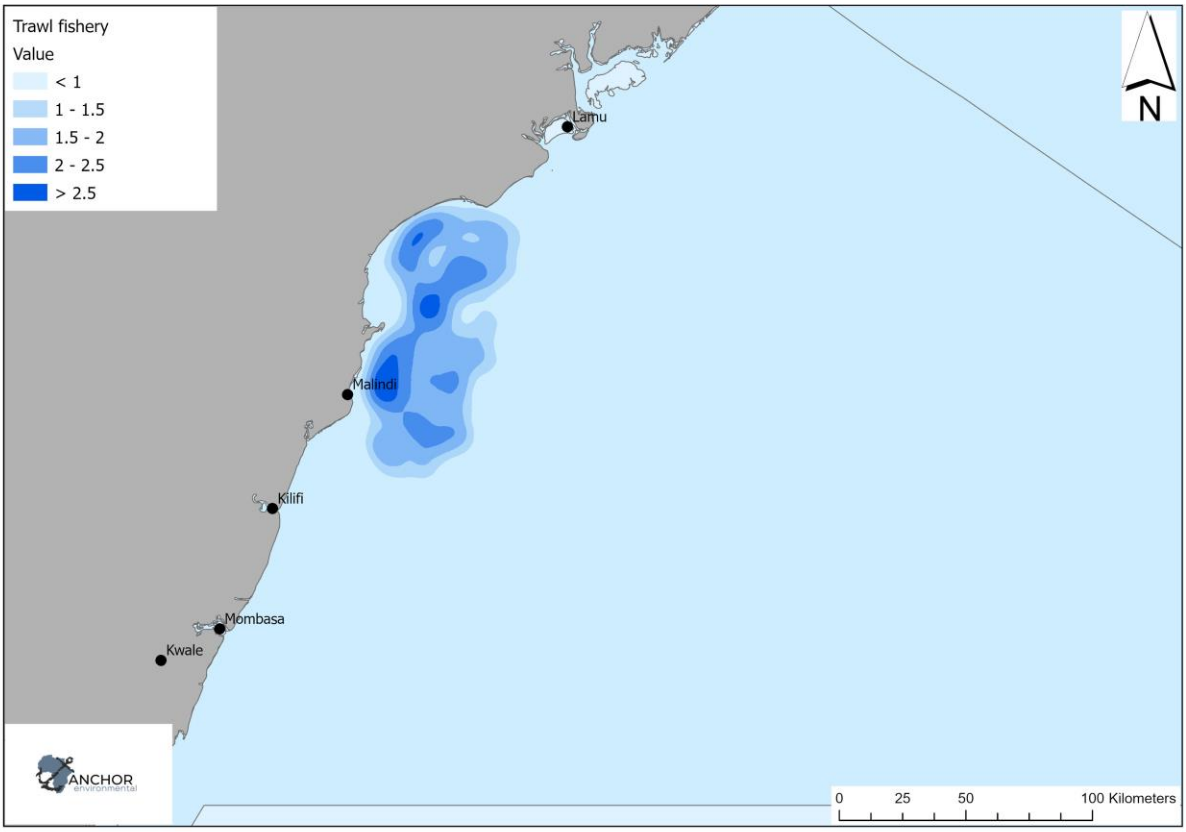

Figure 16. Estimated spatial distribution of the provisioning of fish caught in the industrial trawl fishery. Based on data in Republic of Kenya & KeFS, (2022).

5.4 Carbon storage

Coastal habitats are globally important carbon sinks, and their significance in absorbing and storing carbon has become better understood in the past decade (Githaiga et al., 2017). The most important ecosystems in this regard in the marine environment include mangroves, seagrass meadows and marine sediments (Githaiga et al., 2017; Atwood et al., 2020). Marine ecosystems differ from terrestrial ecosystems in that they store majority of their carbon in the sediment rather than in the living biomass, which makes them particularly good stores of ancient carbon (Githaiga et al., 2017). Degradation of these ecosystems poses a major threat in releasing stored carbon to the atmosphere, much of which is considered to be ancient carbon which has been stored in the sediment for decades (Githaiga et al., 2017).

Methods

In this study, carbon storage was quantified in terms of the carbon content in above- and below-ground biomass and the soil organic carbon for estuarine and coastal mangroves and seagrass meadows, and the soil organic carbon content of unvegetated marine sediments. Estimates were based on global datasets (Atwood et al., 2020; Sanderman et al., 2018; Simard et al., 2019) as well as previous studies from Kenya (Githaiga et al., 2017; Omollo et al., 2022).

Previous estimates of **mangrove forest carbon** for Kenya have been in the range of 500 - 1000 tC/ha (GOK., 2017; Hamza et al., 2020; Kairo et al., 2021), although only the latter is based on field measurements, in Lamu (Table 19). For this study, estimates of mangrove ecosystem carbon were based on a global dataset of mangrove above-ground biomass (Simard et al., 2019),[7] which was created from a combination of remote sensing data and field measurements, and a global dataset on sediment organic carbon dataset of mangroves at 30 m resolution (Sanderman et al., 2018),[8] which was based on reported measurements. The below-ground biomass was estimated using a root: shoot ratio of 0.4 (Githaiga, 2013). The carbon content is approximately half of the biomass. This was added to the soil carbon to estimate total carbon per unit area. It was assumed that the global estimates adequately incorporate condition, as they are based on variation in aboveground biomass. However, the mapped mangrove area of the above-ground biomass dataset was smaller than our determined area, thus within each county, the mean values per unit area were extrapolated to the full mapped area of mangroves.

Estimates of the carbon content of **seagrass meadows** were based on the literature from Kenya. Several studies have been carried out on carbon storage in the seagrass meadows of Gazi Bay (Table 19); the most accepted results are from Githaiga et al., (2017), who found an average of 5.9 ± 0.9 tC/ha for biomass carbon and 236 ± 24 tC/ha for sediment organic carbon (Githaiga et al., 2017; Omollo et al., 2022). Juma et al., (2020) and Omollo et al., (2022) found similar results for carbon stocks in Gazi Bay. Juma et al., (2020) compared the two tributaries flowing into the bay and found that the eastern tributary had significantly higher biomass and sediment organic carbon (268 tC/ha) than the western tributary (110.99 tC/ha) due to greater

[7] https://daac.ornl.gov/CMS/guides/CMS_Global_Map_Mangrove_Canopy.html

[8] https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/OCYUIT

human impacts on the latter habitats. Omollo et al., (2022) found that carbon storage of subtidal seagrass meadows was lower than that of intertidal seagrass meadows assessed by Githaiga et al., (2017). For this study, the estimates of Juma et al., (2020) were used to map the carbon storage of estuarine seagrass meadows in good and poor condition, and an intermediate value was applied to the meadows in fair condition. The estimate from Omollo et al., (2022) was applied to marine seagrass meadows.

Estimates of carbon in **marine sediments** were obtained from Atwood et al., (2020). This dataset was created by interpolating measured data from several global studies. However, the dataset had a course resolution of 1 km and did not follow the coastline precisely. Thus, the dataset was extended to match the coastline, with values assigned following the nearest neighbour principle, and was then resampled and smoothed to match the resolution of the mangrove and seagrass carbon datasets. The three carbon datasets were then merged to create a single raster layer of total ecosystem carbon.

Table 19. Carbon estimates for mangroves and seagrass meadows from Kenya.

Ecosystem	Source	Location	Total Biomass Carbon (tC/ha	Sediment Organic Carbon (tC/ha)	Combined Carbon (tC/ha)
Mangroves	Kairo et al., (2021)	Lamu	162.7	394±79	556.4
Seagrass	Githaiga et al., (2017)	Gazi Bay	5.9±0.9	236±24	241.9
	Juma et al., (2020)	Gazi Bay – East	10.2±0.6	258±90	268.4
		Gazi Bay – West	4.3±0.3	107±21	111.3
	Omollo et al., (2022)	Gazi Bay - subtidal	5.6	113±8	118.6

Results

The resulting map of carbon storage (see illustration of a portion thereof in Figure 17) was used to calculate the total amount of carbon stored in key habitats in the nearshore zone up the edge of the shelf at a county level, and for the remaining oceanic area at a national level (Table 20).

Overall, it was estimated that coastal and marine habitats store at least 1.7 billion tonnes of carbon. The bulk of this is stored in the vast areas of oceanic habitat that cover most of the EEZ. Within the continental shelf, most carbon is also stored in bare subtidal sediments, because of their being by far the dominant ecosystem type. However, inshore ecosystems have much high storage of carbon per unit area. It is worth noting that the inshore mangrove and seagrass ecosystems are also much more likely to be the source of carbon emissions through habitat degradation or loss, though trawling and mining activities in deeper ocen areas can also lead to significant carbon losses. At county level, Lamu has the highest carbon storage in inshore habitats, followed by Kwale county (Table 20).

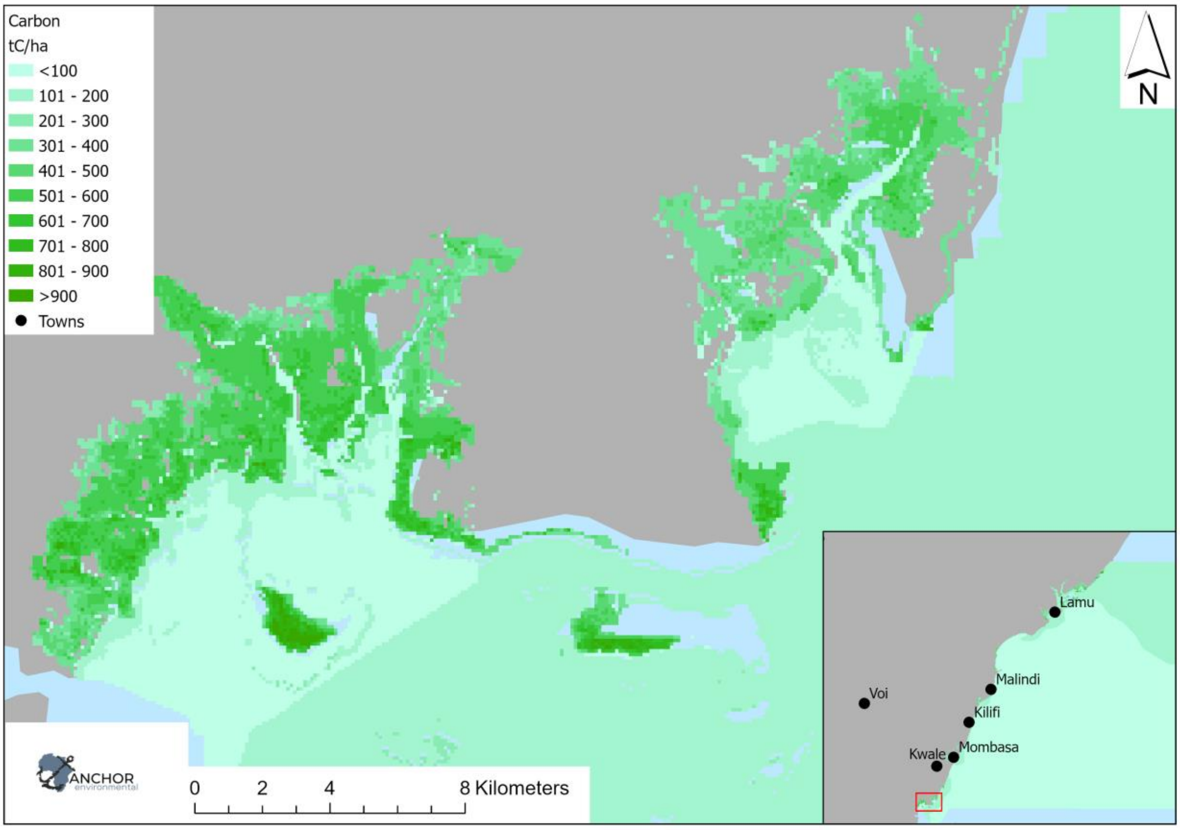

Figure 17. Mapped average total carbon storage on the Kenyan south coast.

Table 20. Carbon storage in millions of tonnes by county and by three major habitat groupings

County	Mangroves	Seagrass Meadows	Subtidal sediment	Oceanic continental slope	Oceanic abyssal plain	**Total**
Lamu	17.61	1.18	28.0			
Tana River	1.50	0.01	32.4			
Kilifi	2.50	0.24	23.1	n/a	n/a	
Mombasa	0.57	0.06	2.7			
Kwale	4.90	0.33	8.5			
Total	**27.07**	**1.82**	**94.7**	**635.1**	**980.4**	**1739.1**
Ave tC/ha	**494.4**	**138.0**	**108.5**	**106.7**	**164.8**	**0.0**

The marine sediment carbon ranges from 65 – 100 tC/ha across most of the Kenyan EEZ. In the northern waters extending from the coast to halfway into the EEZ, an area known as the Northern Banks (Figure 17, inset map), the carbon storage increases to 100 - 150 tC/ha. This is likely because of the coastal upwelling cell off the Somali coast which brings productive cooler water down into the Kenya EEZ to this area.

5.5 COASTAL PROTECTION

Marine ecosystems play an important role in protecting coastal communities from sea-level rise and storms through dissipating wave energy and reducing flood risk (Ballesteros & Esteves, 2021; Hamza et al., 2022). The open source InVEST Coastal Vulnerability model was used to assess the role individual ecosystems play to providing coastal protection. This approach has been used by Ballesteros & Esteves, (2021) and Ballesteros & Esteves, (2021) in assessing the contribution of marine ecosystems to the protection of the coastline.

Methods

The InVEST model allows for the integration of up to seven variables assessing the physical, ecological, and socioeconomic conditions (Ballesteros & Esteves, 2021; Hamza et al., 2022). The following variables were included in our model: wave exposure, wind exposure, surge potential, relief, and ecosystem. Each variable is then assigned a value of 1 (very low exposure) to 5 (very high exposure) by the model. The model then calculates the index of exposure as the geometric mean of all the variables values. The equation below was used by the model in assessing relative vulnerability, where R is the associated value of each variable and n is the number of variables included in the model (Ballesteros & Esteves, 2021; Hamza et al., 2022).

$$IE = \left(R_{relief} * R_{waves} * R_{wind} * R_{surge} * R_{habitats}\right)^{\frac{1}{n}}$$

We followed the approach outlined in Ballesteros & Esteves, (2021), where a series of model scenarios were run to access the contribution of each ecosystem to coastal protection. The first scenario included the presence of the mangrove, coral reefs, seagrass meadows, and sandy shores/dunefield ecosystems, the next four scenarios looked at the effect of losing a specific ecosystems and the final scenario excluded all ecosystems.

- ***Scenario 1****:* all ecosystems: reflects the current level of exposure.
- ***Scenario 2****:* no mangroves; reflects the exposure if mangroves were lost.
- ***Scenario 3:*** no coral reefs; reflects the exposure if coral reefs were lost.
- ***Scenario 4:*** no seagrass meadows; reflects the exposure if seagrass meadows were lost.
- ***Scenario 5:*** no sandy shores/dunefields; reflects the exposure if sandy shores/dunefields were lost.
- ***Scenario 6:*** no ecosystems; reflects the exposure in the absence of all ecosystems.

Results

The provision of natural coastal protection was determined through assessing the differences in the relative levels of exposure between each scenario (Ballesteros & Esteves, 2021; Hamza et al., 2022). The scenarios used are not representative of future conditions and is by no means suggesting the possibility of complete loss of these ecosystems (Ballesteros & Esteves, 2021; Hamza et al., 2022). Through the exclusion of each ecosystem the overall contribution can be assessed by comparing the current level of exposure with the exposure if the ecosystem was lost (Ballesteros & Esteves, 2021; Hamza et al., 2022).

The model outputs the relative level of exposure at points along the coast, as a score of 1 to 5 (1 = very low and 5 = very high). The relative exposure levels were grouped into three categories: low (scores 1 and 2), medium (score 3) and high (scores 4 and 5) following the methods used by Ballesteros & Esteves, (2021) and Hamza et al., (2022). The approximate length of coastline in each category was calculated to quantify the relative vulnerability as a measure of distance. The length of coastline per category was calculated for each scenario at a national, county and subcounty level. As an indicator of the physical service, we determined the difference between the proportion of coastline at a high exposure with all ecosystems to the proportion of coastline at a high exposure without the ecosystems. To value coastal protection these high exposure zones need to be further assessed to determine the areas where this service is benefiting coastal communities.

The results indicated that mangroves and corals contribute the most to coastal protection along the Kenyan coastline. Seagrass meadows and sandy shores/dunefields did not measurably influence the proportion of coast at a high level of exposure. This accords with the conclusions of Ballesteros & Esteves, (2021) and Hamza et al., (2022).

Mangrove forests and coral reefs provide protection along approximately 167 km and 66 km of the coastline, respectively (Table 21). In total all the ecosystems provided approximately 276 km of coastal protection. Our estimates differ to that of Ballesteros & Esteves, (2021) and Hamza et al., (2022) in that they found corals to provide the most coastal protection, whereas our findings suggest that mangroves provide more protection. This difference can be attributed to the improved resolution and quality of ecosystems inputs into this model. Higher resolution bathymetry, ecosystem extent, country coastline and continental shelf datasets were used to generate 8573 exposure points in comparison to their 1589 exposure points. The increased resolution of data inputs and higher proportion of coastal exposure points generated in this model would indicate more reliable results which assess the intricacies of the coastline.

Table 21: length of coastline per coastal exposure category.

Scenario	Length of coast (km) per vulnerability score			Protection by ecosystem (km)
	low	medium	high	
All ecosystems	325	663	345	-
No Mangroves	190	632	512	167
No Corals	309	614	411	66
No Ecosystems	165	548	621	276

Coastal exposure was summarized per county for each scenario, summary tables can be seen in Appendix 6. Tana River, Lamu and Kwale receive the largest amount of protection from mangrove forests (Figure 18). In Tana River 42% (33 km) of the coast was considered at a high level of exposure with all ecosystems, this increased to 64% (50 km) of the coast at a high level of exposure in the scenario without mangroves. Overall mangrove forests provide protection for approximately 17 km of the Tana River coastline. In Lamu, 41% (256 km) of the coast was considered to have a high level of exposure with all ecosystems (Figure 18). This increased to 58% (343 km) after the removal of the mangrove forests (Figure 18), indicating that the mangrove forests provide protection to 87 km of the Lamu coastline. Kwale saw the same trend with the proportion of coastline at high exposure increasing from 17% (36 km) to 29% (63 km) following the removal of mangrove forests. Mangrove forests in Kwale protect approximately 27 km of the coast. The county comparisons are comparable with what was determined by Ballesteros & Esteves, (2021) and Hamza et al., (2022), Tana River being the most exposed county and without the ecosystems would remain the most exposed.

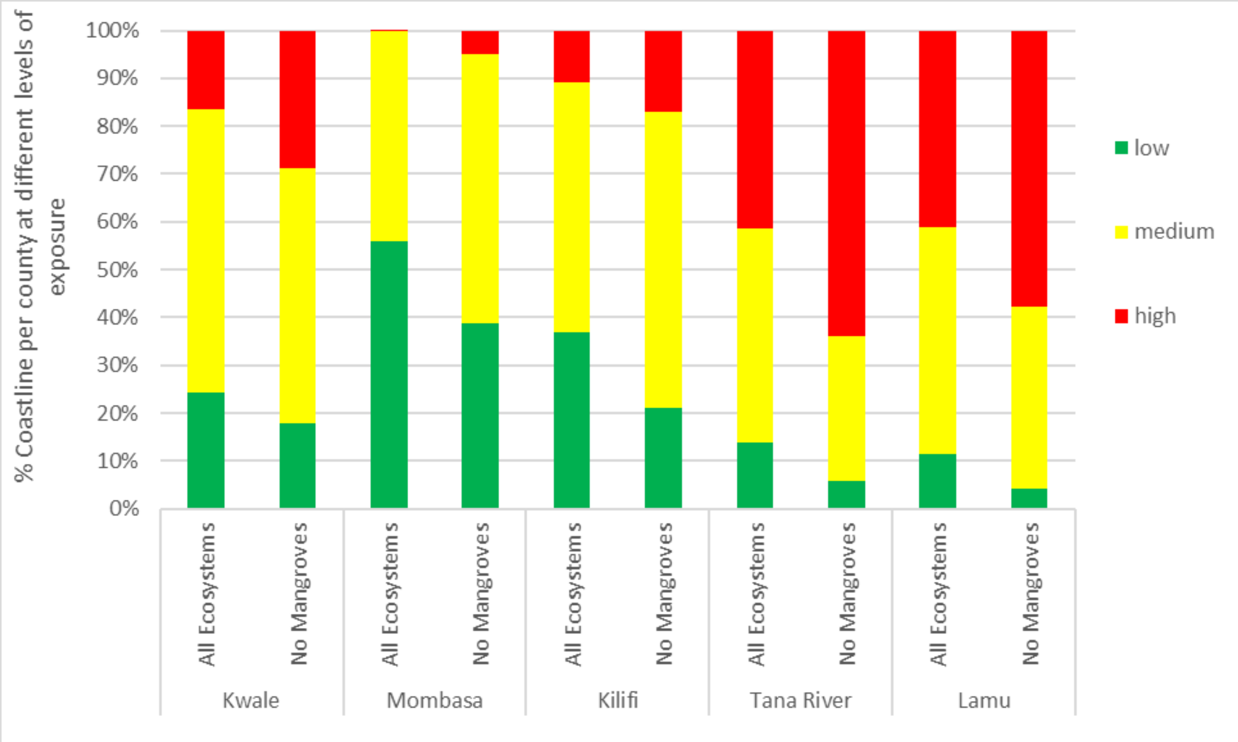

Figure 18: Proportion of each county coastline length at different relative levels of exposure with all ecosystems and without mangroves.

Coral Reefs provided most protection along Kilifi's coastline. The proportion of the coast with a high level of exposure increased from 11% (31 km) with all the ecosystems to 23% (65 km) following the removal of the coral reefs (Figure 19). In total, the coral reefs protect approximately 34 km of the Kilifi coastline. Coral reefs protect 4% (23 km) of Lamu's coastline, with the proportion of coastline at high exposure increasing from 41% (246 km) to 45% (269 km) following the removal of the coral reefs (Figure 19).

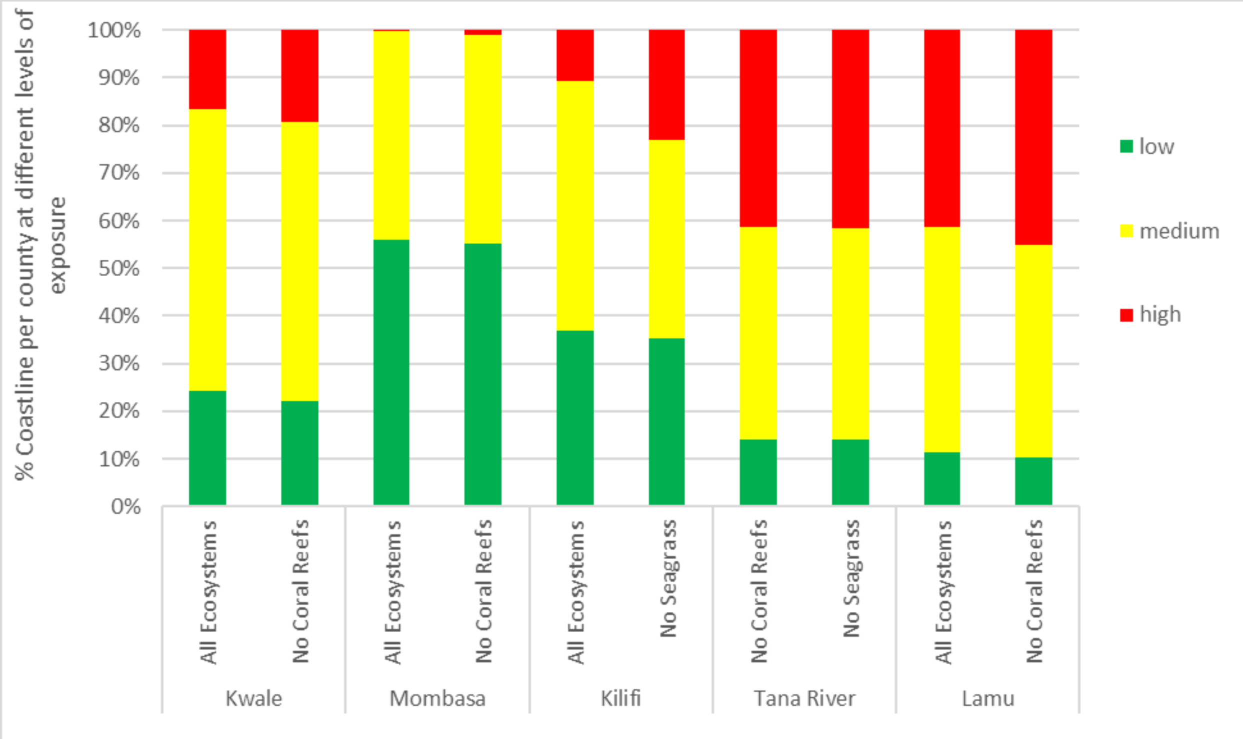

Figure 19: Proportion of each county coastline length at different relative levels of exposure with all ecosystems and without coral reefs.

The relative protection provided by the ecosystems was summarized for each sub-county (Appendix 6). Lamu West, Lamu East and Lunga Lunga are three sub-counties where mangrove forests provide the most protection (Ballesteros & Esteves, 2021; Hamza et al., 2022). Some 56 km of the coastline is protected by mangroves in Lamu West, 42 km in Lamu East and 23 km in Lunga Lunga. Coral reefs provide a large amount of protection for the coast in Lamu West (19 km), Kilifi North (18 km), and Magarini (6 km). The sub-counties receiving the most protection from ecosystems is Lamu West (78 km), Lamu East (68 km), Lunga Lunga and Kilifi North (30 km each), and Magarini (23 km). Several sub-county's receive little to no protection from ecosystems (Ballesteros & Esteves, 2021; Hamza et al., 2022), most of these sub-county's coastlines are considered to have a low to medium level of exposure. These coastlines are at a lower level of exposure due to the presence of islands and waterways or the surrounding topography dissipating coastal storm surges protecting the coastlines.

5.6 NATURE BASED TOURISM

Tourism is a major economic sector in Kenya, with a total contribution of 10.4% to the country's GDP (Ministry of Tourism Wildlife & Heritage, 2023). According to the Kenya Tourism Board (KTB), 65% of all tourists visit the coast during their stay, signifying the importance of the coastal tourism as a contribution to the overall GDP of the country. The latest annual tourism sector performance report indicates that tourism is on the rise following the major decline during the Covid-19 pandemic. With tourism statistics almost returning to pre-covid levels in 2022 and the projected trends indicating further increases for 2023 (Ministry of Tourism Wildlife & Heritage, 2023). In 2022, nearly 1.5 million tourists arrived in Kenya for various purposes - 36.6% for vacation, 27.9% to visit family or relatives and 27.2%

for business or MICE (Ministry of Tourism Wildlife & Heritage, 2023). These statistics indicate the importance of tourism in Kenya's economy, and the significance coastal tourism plays. National Parks see a significant number of visitors throughout the year, in 2022 over two million visitors entered national parks, of whom about 1.66 million were Kenyan citizens or residents and 0.45 million were non-residents (Ministry of Tourism Wildlife & Heritage, 2023). These numbers are still in recovery relative to the pre-Covid 19 trends. Although the natural features of Kenya's coastal areas feature in the marketing of Kenya as a destination (Kenya Tourism Board, 2021), there has been little research on exactly what these natural assets contribute to overall tourism activity or value.

Methods

Although the SEEA EA recommends measures such as visitor numbers for quantifying the physical flows associated with ecosystem-based tourism, this is only viable for specific destinations that have an entry point, and it is not actually possible when mapping across a land or seascape. Rather, one can use a measure of relative attraction that can then be related in monetary terms as contribution to tourism expenditure (e.g. see Turpie et al., 2022). For this study, we used the measure of photo user days (PUDs), based on the distribution of geotagged photographs (Wood *et al.*, 2013).

The spatial distribution of photo-user-days (PUDs) was calculated from geo-tagged photographs uploaded to the internet (www.flickr.com) and accessed using the InVEST Recreation model. A single PUD is a unique photographer who took a minimum of one photo per pixel in a single day. The average PUDs were obtained for each grid cell (1 km^2) for the period from 2005 – 2017. It was necessary to use a long time period in order to have a high enough resolution in the data. This method provides a reliable proxy for visitation rates (Wood *et al.*, 2013), and maps value to the attractions rather than to overnighting locations (Wood *et al.*, 2013).

The method has not previously been applied to marine environments, however. In this study, it was found that the results did not provide a reliable indication of the relative value of marine habitats, since most photographs were taken from the shore. Therefore, we summarise the density of PUDs per km of coastline and assume that the value pertains to all inshore habitats. This likely underestimates the relative value of habitats such as coral reef which may form a core attraction. Future studies therefore need to combine these kinds of data with field data on tourist perceptions.

Results

A map presenting the spatial distribution of PUDs can be seen in Figure 20. This shows highest levels of activities around major towns such as Mombasa, Kilifi, Malindi and Lamu. The highest densities of PUDs were in Diani-Chale Marine National Park, Mombasa City, Mombasa Marine National Park, and Mombasa Marine National Reserve (Figure 21). These suggest Mombasa is the main tourist destination and the marine national parks or reserves within proximity to the city see a high density of tourists.

Offshore activity can also be detected to some extent, with photographs presumably taken from cruise ships, fishing, diving, or boating excursions, but as discussed above, these are likely to underrepresent the relative levels of activity in those areas (Figure 20- inset map).

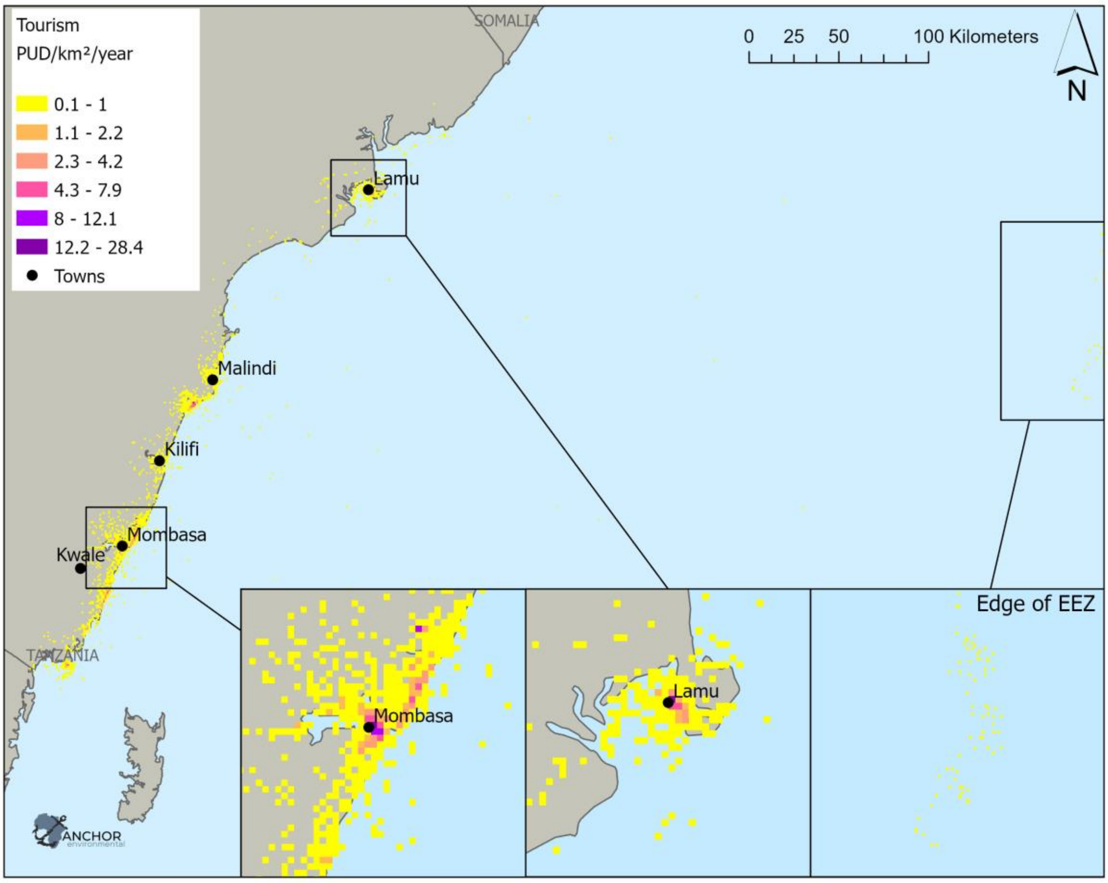

Figure 20. Average photo-user days per km² for the coastal ecosystems, derived from the spatial distribution of geotagged photographs. Inset maps showing (left to right) Mombasa, Lamu and a portion of the coastal waters along the EEZ boundary in more detail.

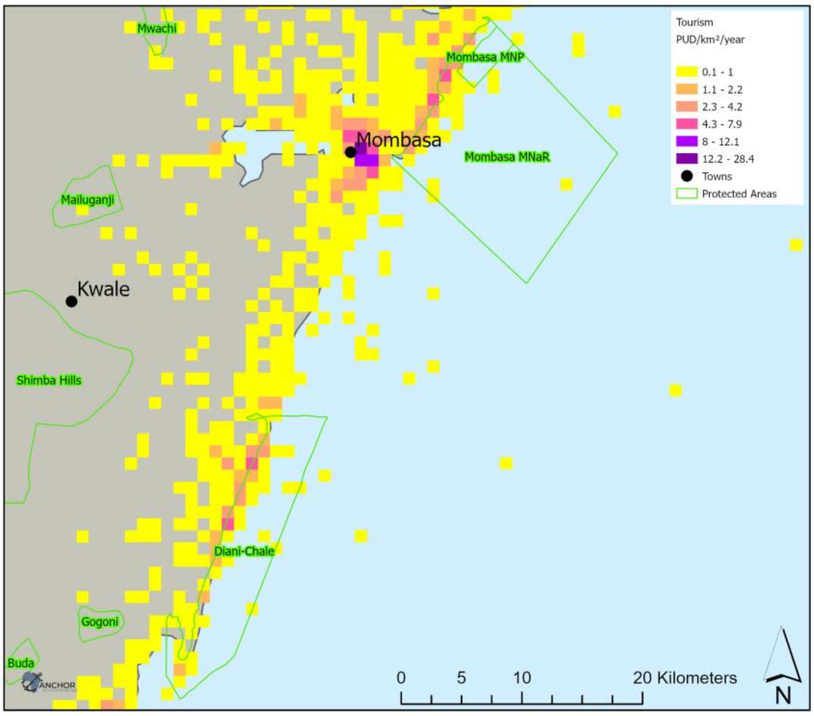

Figure 21. Variation in nature-based tourism activity for the coastal ecosystems of the Mombasa-Kwale coast and nearby protected areas, as indicated by the spatial distribution of geotagged photographs.

In addition, there are high densities of PUDs associated with marine national parks, in particular Watamu Marine Reserve (25 PUDs/y), Mombasa Marine National Reserve (22 PUDs/y), Diani-Chale Marine Reserve (25 PUDs/y), and Watamu Marine National Park (8 PUDs/y; Table 22).

Table 22: Summary of total tourism value (PUDs/year) for Marine Protected Areas occurring along the Kenyan Coast.

Marine Protected Area	Area (ha)	Ave PUDs/km²/y	Ave PUDs/y
Diani-Chale	10 500	0.24	25.1
Dodori	42 500	0.00	0.1
Kisite MNP	3 500	0.06	1.7
Kiunga MNaR	24 300	0.00	0.9
Malindi MNP	600	0.08	0.5
Mombasa MNaR	19 400	0.11	21.9
Mombasa MNP	1 000	0.00	0.0
Mpunguti MNaR	1 300	0.05	0.7
Watamu	19 300	0.13	25.2
Watamu MNP	1 100	0.73	7.6
Overall	**123 500**	**0.07**	**83.8**

Table 23: Summary of tourism activity per subcounty, in total, per unit area of coastal and marine habitat and per km of coastline. summarises the variation in tourism activity along the coastline, by subcounty, in total, and expressed in terms of the average value per unit area of habitats inshore of the continental shelf, and in terms of the coastline length. However, it should be noted that the marine area is dominated by subtidal sediment (essentially bare habitat), whereas interest would not be evenly weighted across this and other habitats. The coastline gives a better indication of relative value, but is still complicated by its being much more convoluted in some subcounties than in others. Nevertheless, a comparison of these measures helps to convey the relative value of this service in the different areas. The top five sub counties in terms of overall activity, and activity per unit area or per km of coastline are shown in bold in Table 23: Summary of tourism activity per subcounty, in total, per unit area of coastal and marine habitat and per km of coastline.. Overall, the highest levels of activity are in Mombasa County. Other important areas are Malindi-Kilifi North, Lamu West, and the Matuga- Msambweni area of Kwale County. More detailed information is required to map tourism value more accurately to individual habitat types.

Table 23: Summary of tourism activity per subcounty, in total, per unit area of coastal and marine habitat and per km of coastline.

County	Subcounty	Marine area (ha) up to shelf	Coastline length (km)	Average PUDs/y	Average PUDs/km²	Average PUDs/km/y
Lamu	Ijara	8 103	3	0	0.00	0.00
	Lamu East	170 346	299.4	4	0.00	0.01
	Lamu West	167 374	296.3	**79**	0.05	0.27
Tana River	Garsen	337 037	78.7	3	0.00	0.03
Kilifi	Magarini	127 743	74.0	28	0.02	0.38
	Malindi	15 397	9.2	**48**	0.31	**5.20**
	Kilifi North	99 082	154.7	**111**	0.11	0.72
	Ganza	3	0.0	1		
	Kilifi South	14 259	45.3	29	0.20	0.63
Mombasa	Rabai	4	0.0	4		
	Kisauni	7 395	60.9	41	**0.56**	0.68
	Nyali	6 476	11.1	35	**0.54**	**3.14**
	Mvita	3 340	19.1	**93**	**2.78**	**4.85**
	Jomvu	982	18.1	9	**0.92**	0.50
	Changamwe	1 464	14.5	5	**0.35**	0.35
	Likoni	9 022	34.0	18	0.20	0.52
Kwale	Kinango	1 726	8.5	5	0.28	0.57
	Matuga	11 217	16.6	22	0.20	**1.33**
	Msambweni	23 387	52.9	**80**	0.34	**1.52**
	Lunga Lunga	54 070	140.1	24	0.04	0.17

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1 APPENDIX 1: IUCN GLOBAL ECOSYSTEM TYPOLOGY (GET)

Table 24 Marine and coastal realms, biomes and ecosystem functional groups in the IUCN Global Ecosystem Typology (Keith *et al.* 2020), and those that occur within Kenya.

Realm	Biome	Ecosystem Functional Group (EFG)	Recorded in Kenya
Freshwater-marine	FM1. Semi-confined transitional waters	FM1.1 Deepwater coastal inlets	
		FM1.2 Permanently open riverine estuaries and bays	X
		FM1.3 Intermittently closed and open lakes and lagoons	X
Marine	M. Marine shelfs	M1.1 Seagrass meadows	
		M1.2 Kelp forests	
		M1.3 Photic coral reefs	X
		M1.4 Shellfish beds and reefs	X
		M1.5 Photo-limited marine animal forests	
		M1.6 Subtidal rocky reefs	X
		M1.7 Subtidal sand beds	X
		M1.8 Subtidal mud plains	X
		M1.9 Upwelling zones	
	M2. Pelagic ocean waters	M2.1 Epipelagic ocean waters (~0-200m)	X
		M2.2 Mesopelagic ocean waters (~200-1000m)	X
		M2.3 Bathypelagic ocean waters (~1000-3000m)	X
		M2.4 Abyssopelagic ocean waters (~3000-6000m)	X
		M2.5 Sea ice	
	M3. Deep sea floors	M3.1 Continental and island slopes	X
		M3.2 Marine canyons	
		M3.3 Abyssal plains	X
		M3.4 Seamounts, ridges and plateaus	
		M3.5 Deepwater biogenic beds	
		M3.6 hadal trenches and troughs	
		M3.7 Chemosynthetically-based ecosystems	
	M4. Anthropogenic marine systems	M4.1 Submerged artificial structures	
		M4.2 Marine aquafarms	
Marine-terrestrial	MT1. Shoreline systems	MT1.1 Rocky shores	X
		MT1.2 Muddy shores	X
		MT1.3 Sandy shores	X
		MT1.4 Boulder and cobble shores	
	MT2. Supralittoral coastal systems	MT2.1 Coastal shrublands and grasslands	X
	MT3. Anthropogenic shorelines	MT3.1 Artificial shores	
Marine-freshwater-terrestrial	MFT1. Brackish tidal systems	MFT1.1 Coastal river deltas	X
		MFT1.2 Intertidal forests and shrublands	X
		MFT1.3 Coastal saltmarshes and reedbeds	X

2 APPENDIX 2: FULL REFERENCE LIST OF ECOYSTEM SERVICES

Table 25. The ecosystem services in the SEEA-EA reference list, with a summary of each service based on the descriptions in the SEEA-EA, based on Turpie *et al.*, (2022). Key marine, estuarine and coastal ecosystem services included in the study area marked with an asterisk. The remainder are either not applicable to the coast/estuary/marine realms, relatively minor, and/or not possible to estimate within the constraints of this study. A brief explanation is provided of how the service flow can be measured in physical terms.

Broad category	Ecosystem service	Description	Physical measure (all per ha and per year) and notes
Provisioning services	Crop provisioning services	In situ ecosystem inputs to crop production.	Not applicable
	Aquaculture provisioning services	In situ ecosystem inputs to aquaculture production	Total harvested production (kg) as a proxy measure for the various ecosystem inputs which are difficult to quantify
	Grazed biomass/Livestock provisioning services	Ecosystem contributions to the growth of grazed biomass that is an input to the growth of cultivated livestock.	Not applicable to coast/estuary/marine realms
	Wood provisioning services*	Ecosystem contributions to the growth of trees and other woody biomass in both cultivated (plantation) and uncultivated production contexts.	Total output in terms of m^3 per ha per year of wood for fuelwood, charcoal, poles and timber. For coastal-marine context this comprises mangrove wood only.
	Wild fish and other natural aquatic biomass provisioning services*	Ecosystem contributions to the growth of fish and other aquatic biomass harvested in uncultivated production contexts	Total output in terms of m^3 per ha per year of fish, grouped by major fishery type. Note that the contribution of nursery areas in different ecosystem types is subtracted and allocated under regulating services.
	Wild animals, plants, and other biomass provisioning services	Contributions to growth of wild animals, plants and other biomass harvested in uncultivated production context (other than wood and aquatic resources).	Not applicable
	Genetic material services	Genes and varieties obtained and their influence on pharmaceutical sales and crop and livestock production.	Not included due to lack of information. Largely intermediate to cultivated outputs.
	Water supply	Combined ecosystem contributions of water flow regulation, water purification, and other ecosystem services to the supply of water of appropriate quality to users for various uses including household consumption	Not included (but noting that future studies might want to include supply through desalination).

Regulating services	**Global climate regulation services***	**Ecosystem contributions to reducing concentrations of GHG in the atmosphere**	**Stocks of carbon in each period, expressed as tonnes of carbon per ha**
	Rainfall pattern regulation (at sub-continental scale) services	Ecosystem contributions of vegetation, in particular forests, in maintaining rainfall patterns through evapotranspiration at the sub-continental scale.	Not applicable
	Local climate regulation services *	Regulation of ambient atmospheric conditions (including micro and mesoscale climates) through the presence of vegetation that improves the living conditions for people and supports economic production	Not applicable
	Air filtration services	Ecosystem contributions to the filtering of air-borne pollutants through the deposition, uptake, fixing and storage of pollutants by ecosystem components, particularly plants, which mitigates the harmful effects of the pollutants.	Not applicable
	Soil quality regulation services	Ecosystem contributions to the decomposition of organic and inorganic materials and to the fertility and characteristics of soils, an intermediate service.	Not applicable
	Soil and sediment retention services	Reducing soil loss and sediment transportation to downstream environments (including mudslides) through holding soils in situ (by vegetative cover) or through trapping eroded sediments (by slowing down movement of water through the landscape, e.g. in a wetland).	Not applicable
	Solid waste remediation services	Ecosystem contributions to transformation of organic or inorganic substances, through the action of micro-organisms, algae, plants, and animals that mitigates their harmful effects. Final or intermediate service.	Not applicable
	Water purification services: retention and breakdown of nutrients and other pollutants	Ecosystem contributions to the restoration and maintenance of the chemical condition of surface water and groundwater bodies through the breakdown or removal of nutrients and other pollutants by ecosystem components that mitigate the harmful effects of the pollutants on human use or health.	Not included. Coastal and marine ecosystems can be pollution sinks, but this is not without negative impact. A proper accounting for this service needs to be holistic in this regard to avoid distorted policy outcomes.
	Water flow regulation services: base flow maintenance and peak flow mitigation	Smoothing of flow over the longer duration through infiltration and storage, reducing need for storage to achieve a given yield.	Not applicable

Regulating services (cont'd)	**Flood control: coastal protection services**	**Contributions of linear elements in the seascape, for instance coral reefs, sand banks, dunes or mangrove ecosystems along the shore, in protecting the shore and thus mitigating the impacts of tidal surges or storms on local communities. Final ecosystem service.**	**To be added.**
	Flood control: river flood mitigation services	Smoothing of fluvial flows during storm events through interception, infiltration, storage, and landscape roughness, reducing the flood peak volume, velocity and flood height in the receiving area.	Not applicable
	Storm mitigation	Ecosystem contributions of vegetation including linear elements, in mitigating the impacts of wind, sand and other storms (other than water related events) on local communities. A final ecosystem service.	Not applicable
	Noise attenuation	Ecosystem contributions to the reduction in the impact of noise on people that mitigates its harmful or stressful effects. Usually a final ecosystem service.	Not applicable
	Pollination services	Pollination of crops by animals living in surrounding environments, thus contributing to productivity.	Not applicable
	Biological control services: pest control and disease control*	Control of crop pests by animals living in surrounding environments, thus contributing to productivity.	Not applicable
	Nursery population and habitat maintenance services*	Provision of critical habitat for populations that are utilised in other locations, such as fish nursery areas, wildlife breeding areas or migratory staging areas. As for the above service, this requires attributing some of the ecosystem inputs to these activities to the critical habitat areas rather than the areas in which the activities take place.	Very preliminary estimate of proportion of marine catches originating in estuaries (data are lacking)

Cultural services	**Experiential-related services*[9]**	**Experiential fulfilment associated with active or passive use, through any type of or purpose including recreation, education, scientific research, spiritual, artistic, or other cultural activities (typically some combination of these).**	**This manifests as contributions to tourism value, recreation/experiential activities, and to property value. Since user days cannot be mapped on a continuous grid the relative use is expressed as an index that relates directly to monetary value.**
Flows related to non-use values	Ecosystem and species appreciation *	Ecosystem and species appreciation concerns the wellbeing that people derive from the existence and preservation of the environment for current and future generations, irrespective of any direct or indirect use. e.g. donations	Not included

[9] Note that the SEEA EA reference list separates these into (i) recreation related services, (ii) visual amenity services, (iii) education, scientific and research services and (iii) spiritual, artistic and symbolic services. The authors feel that this separation is artificial as experiences and motivations for use often comprise a mixture of these, and that the breakdown should be based on user types which involve different valuation methods (Turpie et al. 2022, Turpie et al. in prep.). Therefore, we use the term "Experiential-related services" to encompass the full suite. This is only partially valued in these accounts, and the aspect valued could be classified as "recreation-related services" if the reference list is strictly followed.

3 APPENDIX 3: SERIES OF 1:250 000 MAPS OF THE KENYAN COAST

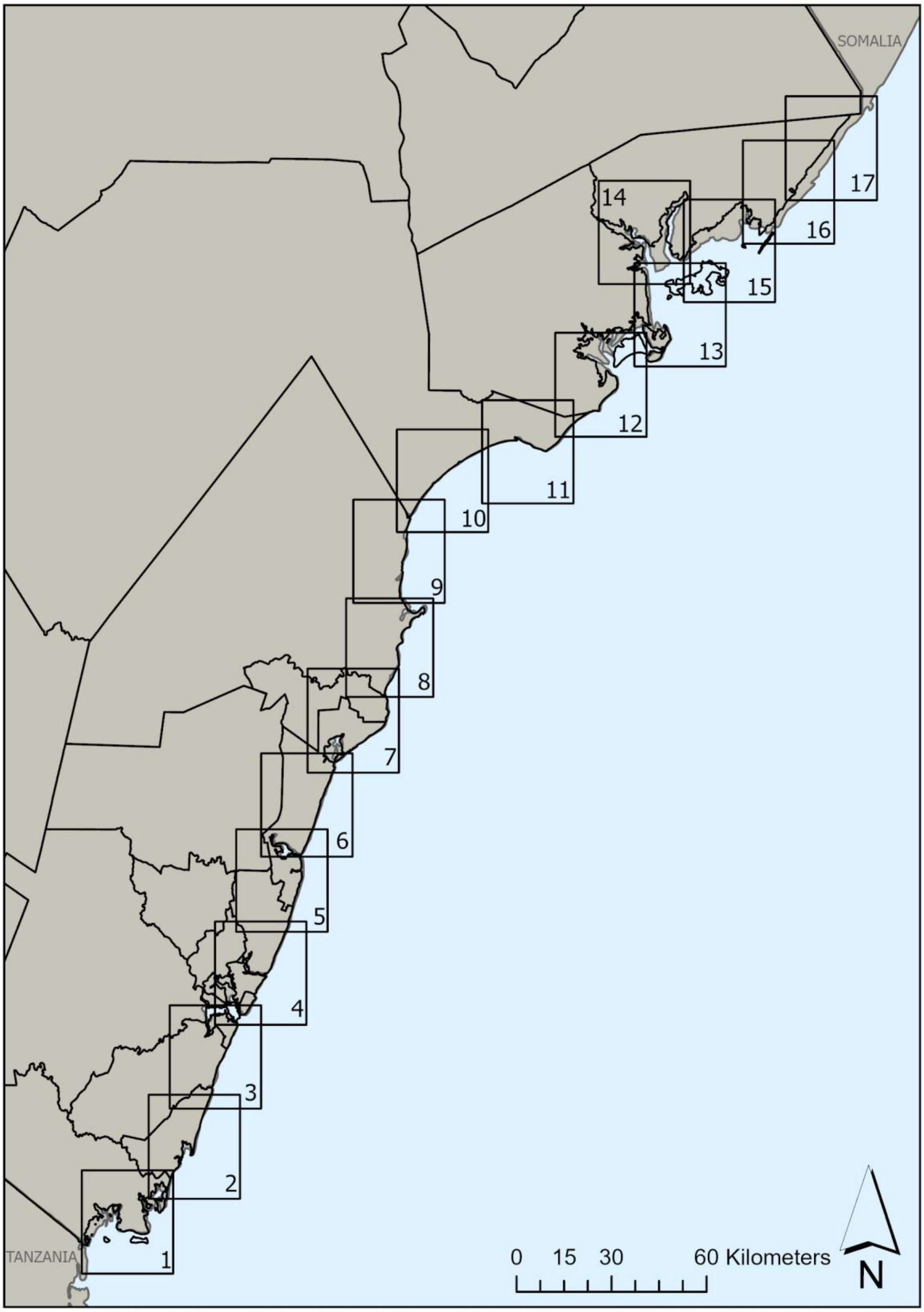

Figure 22: Map Series key, locating the map number along the coastline.

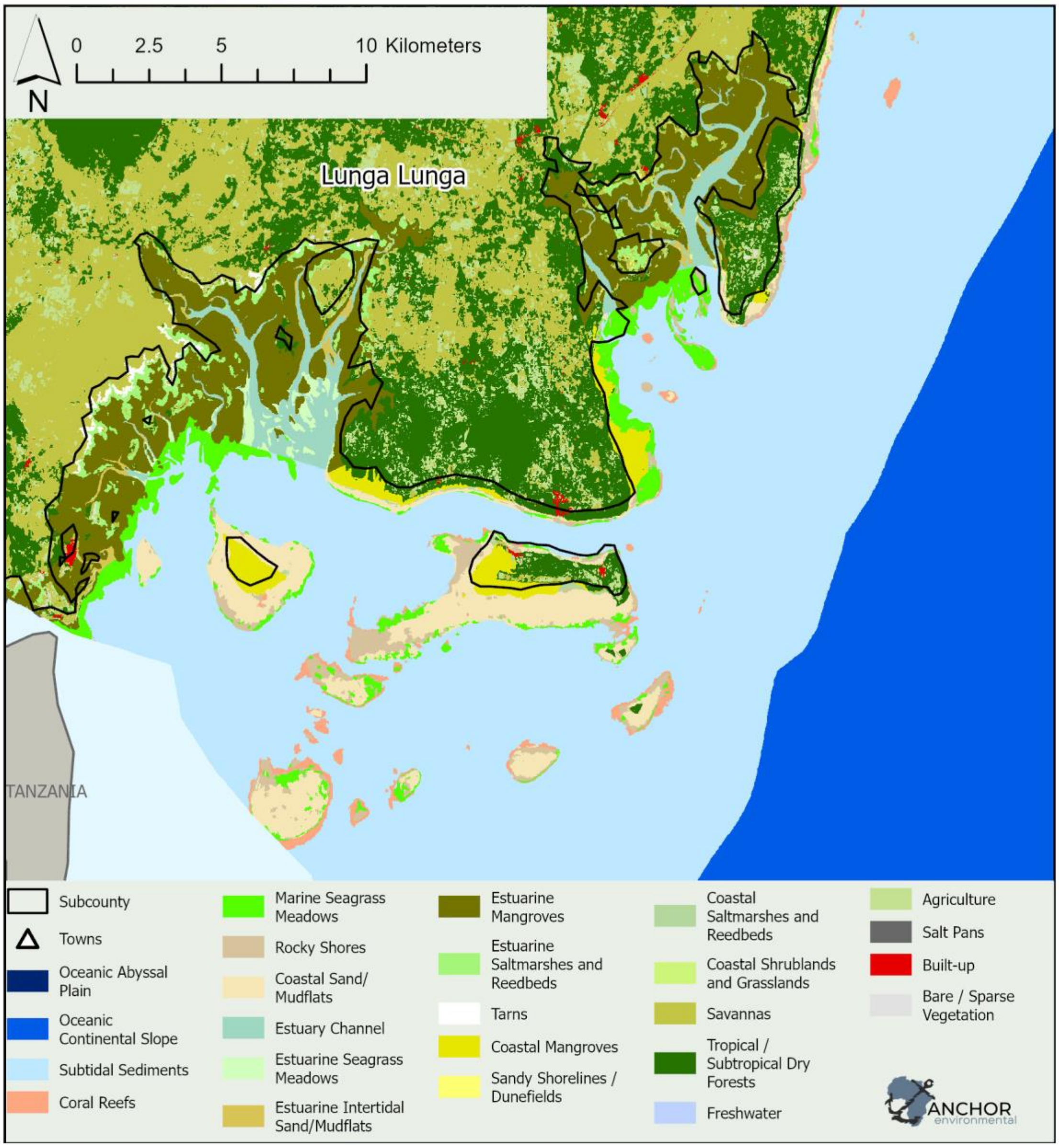

Figure 23: 1:250 000 scale map 1

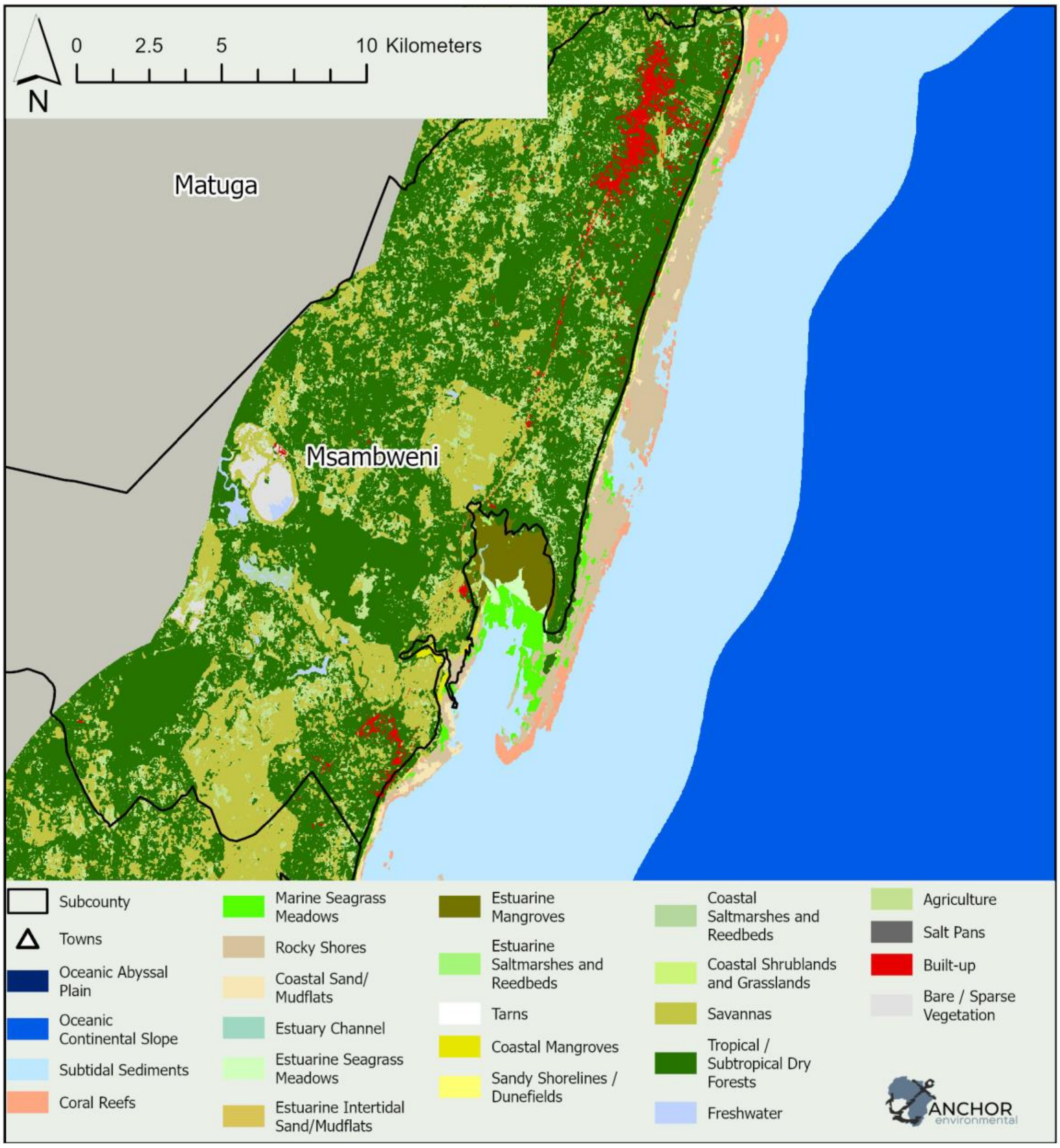

Figure 24: 1:250 000 scale map 2

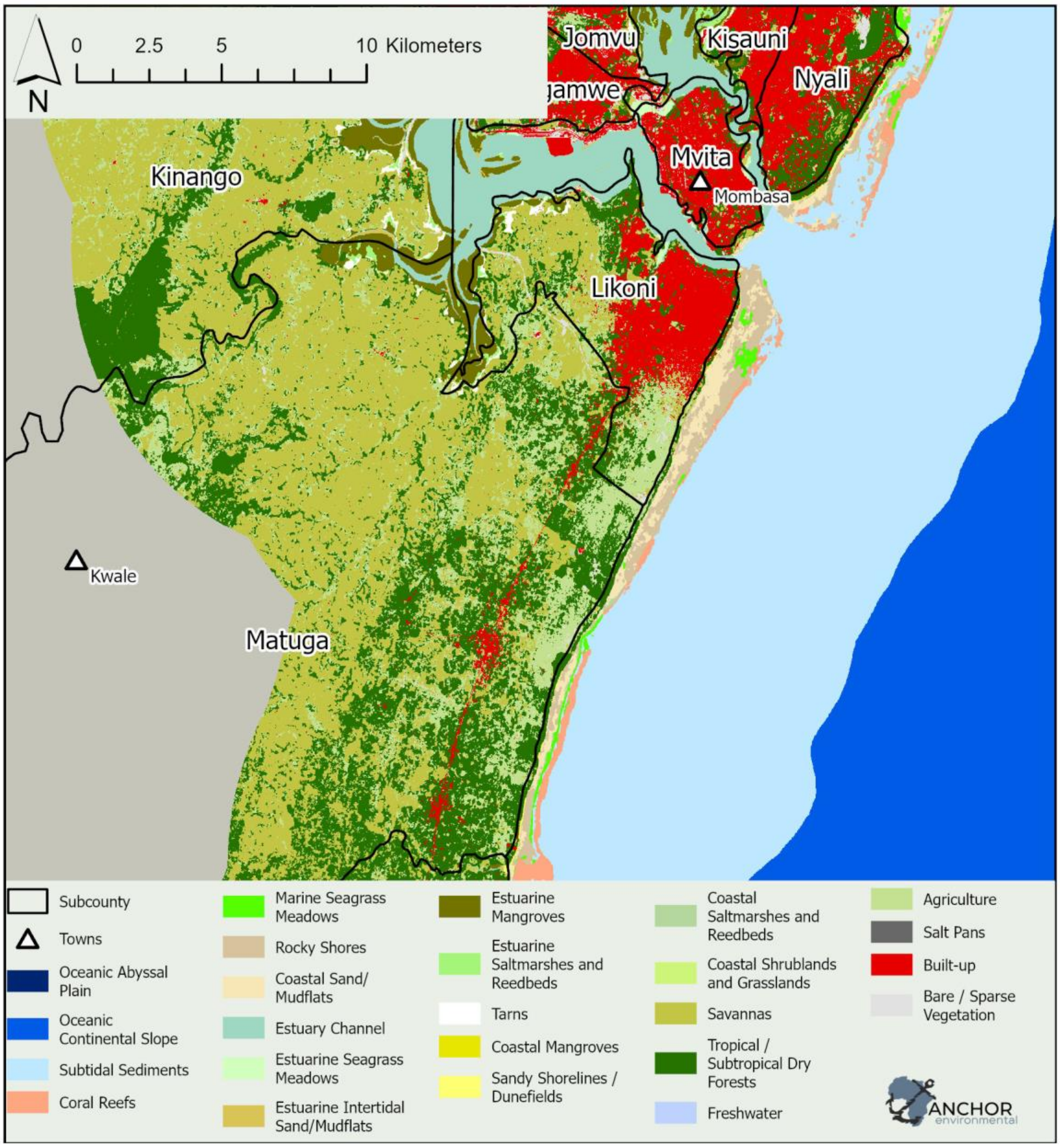

Figure 25: 1:250 000 scale map 3

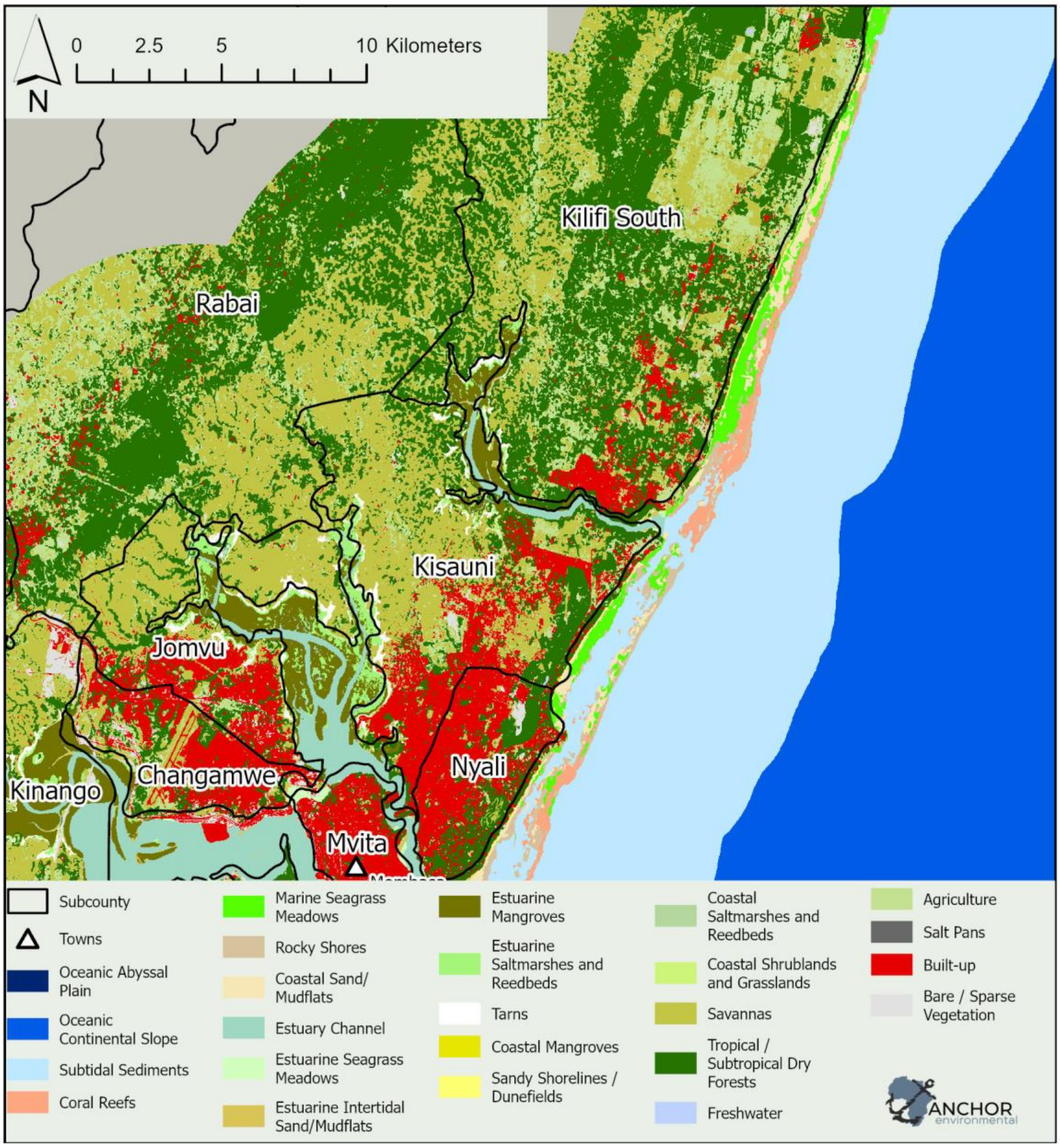

Figure 26: 1:250 000 scale map 4

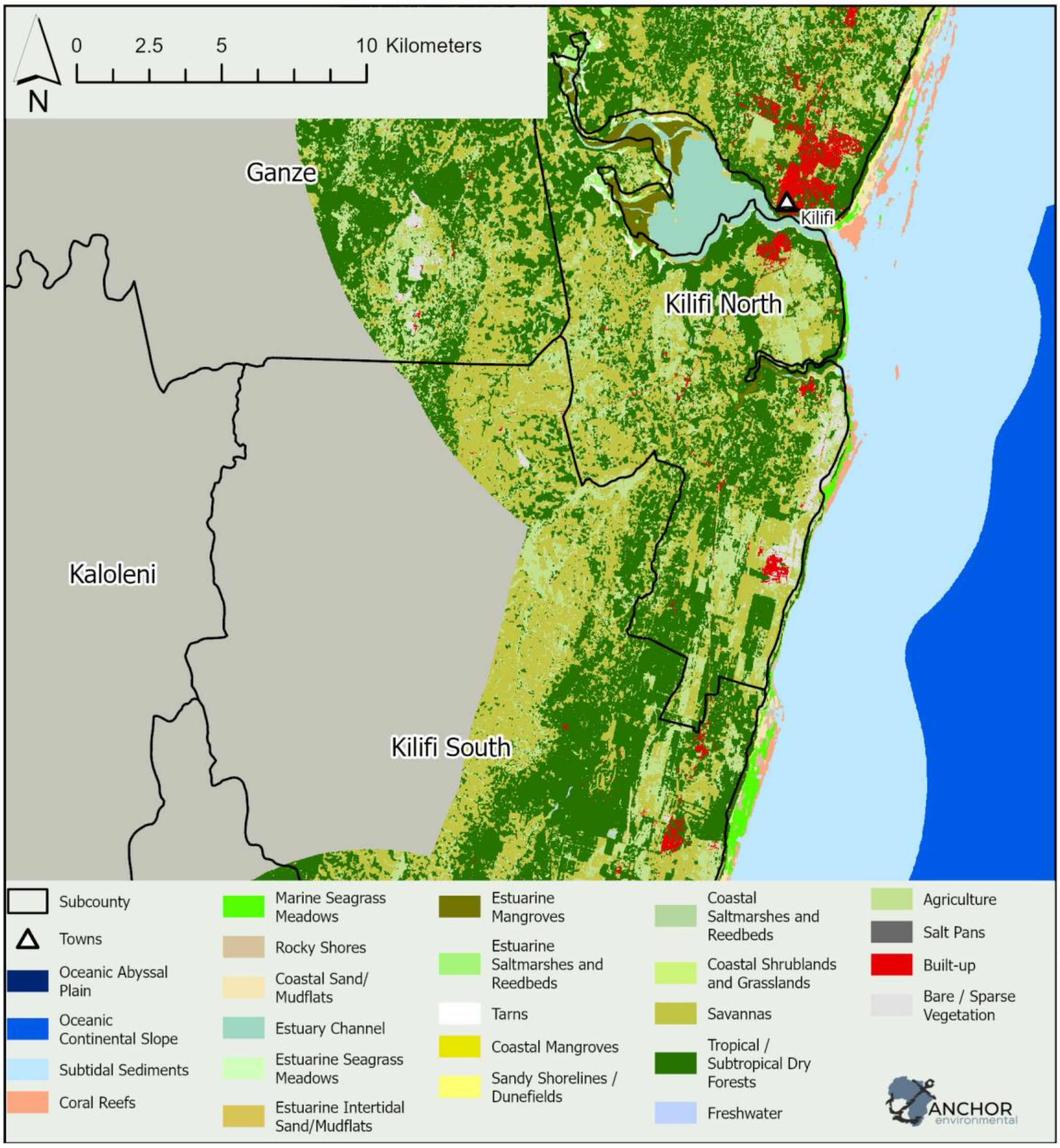

Figure 27: 1:250 000 scale map 5

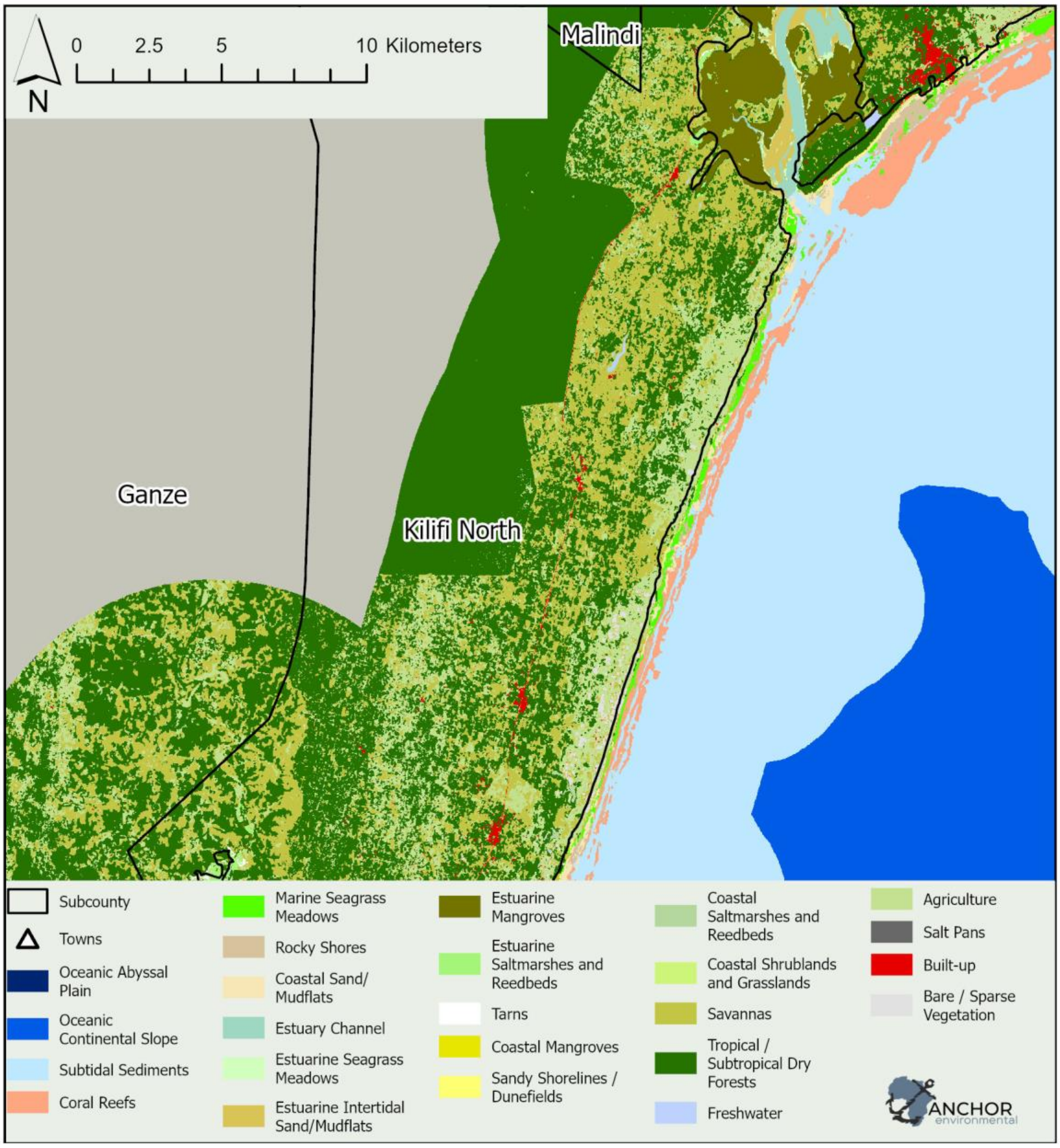

Figure 28: 1:250 000 scale map 6

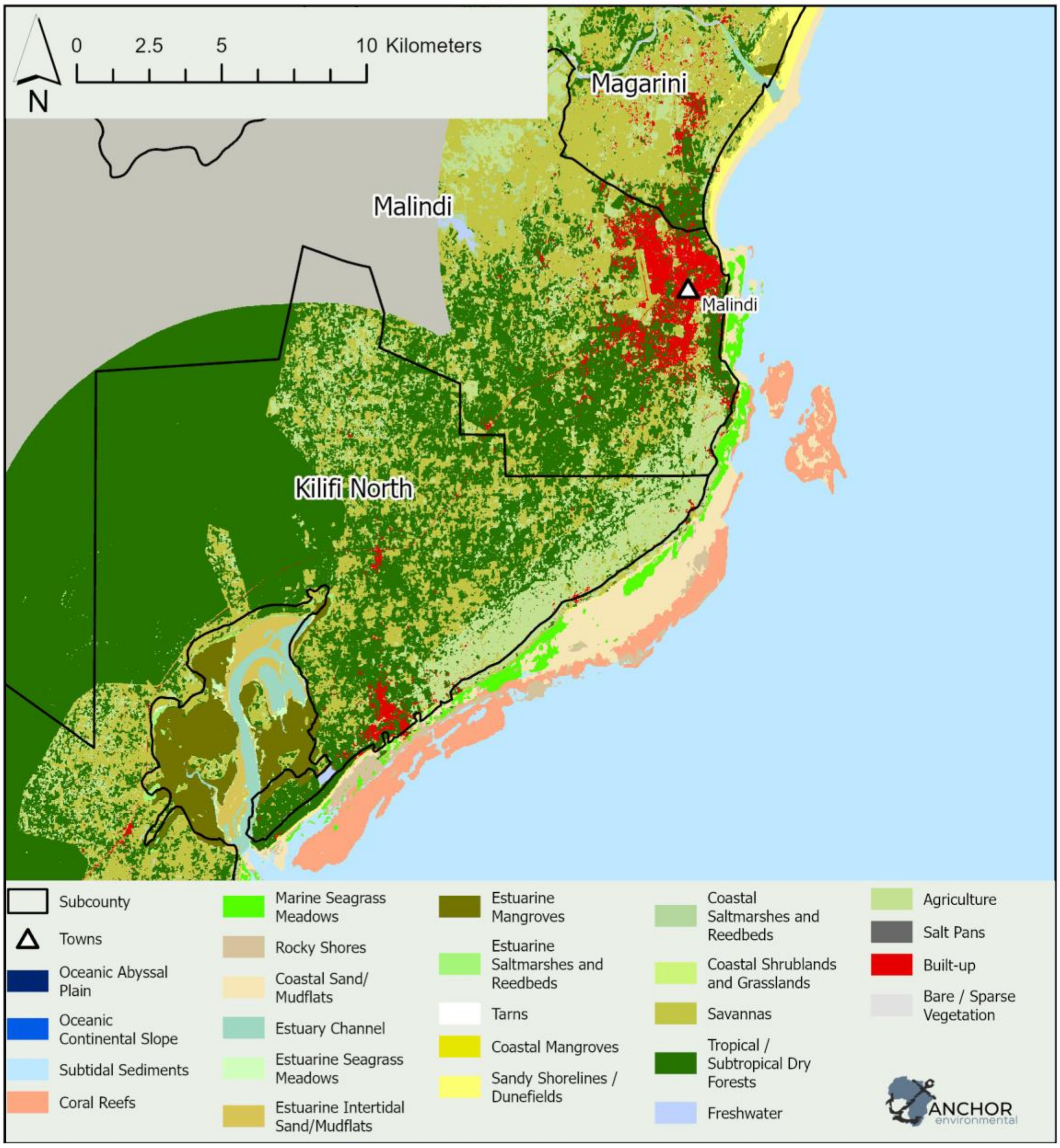

Figure 29: 1:250 000 scale map 7

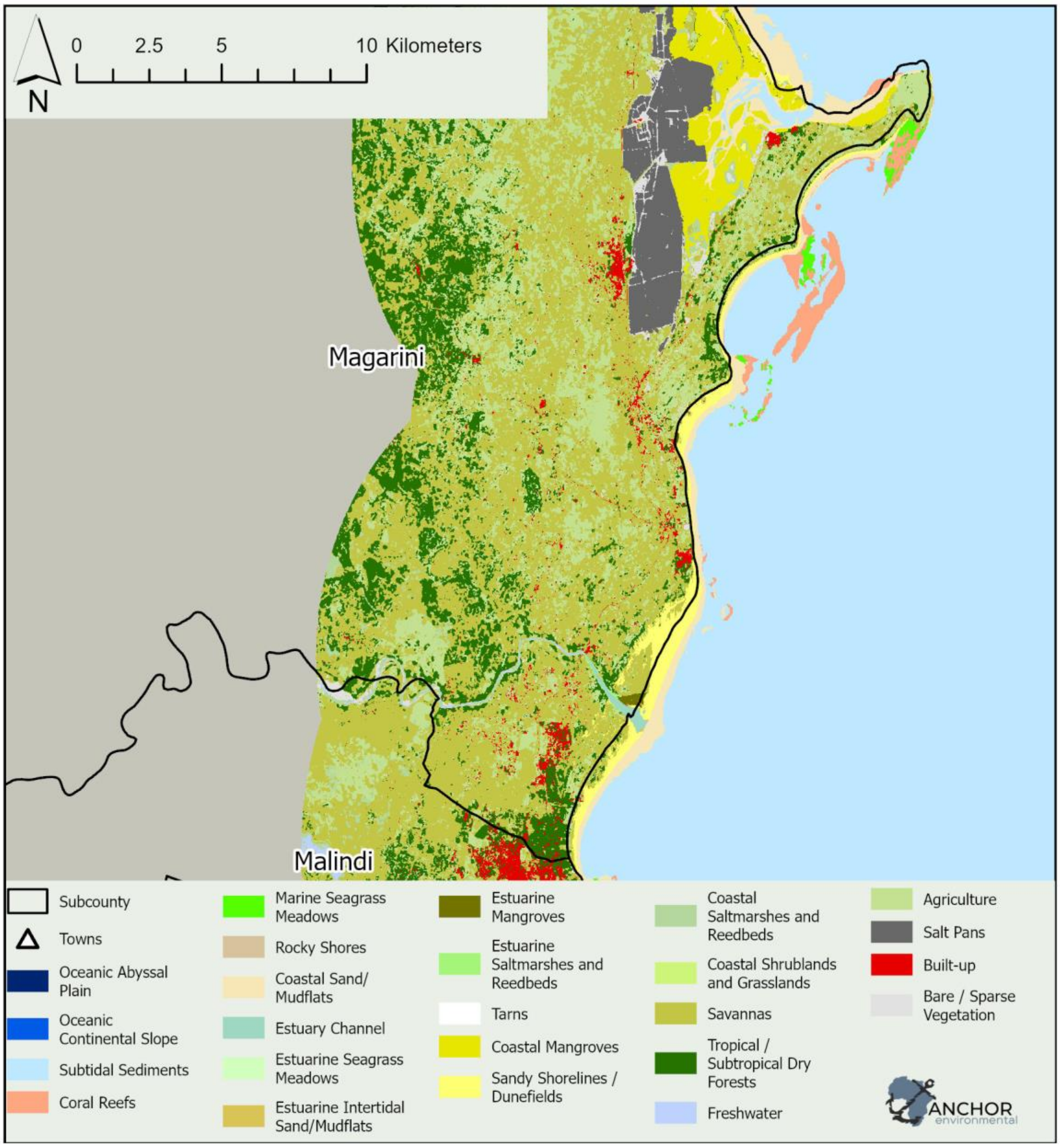

Figure 30: 1:250 000 scale map 8

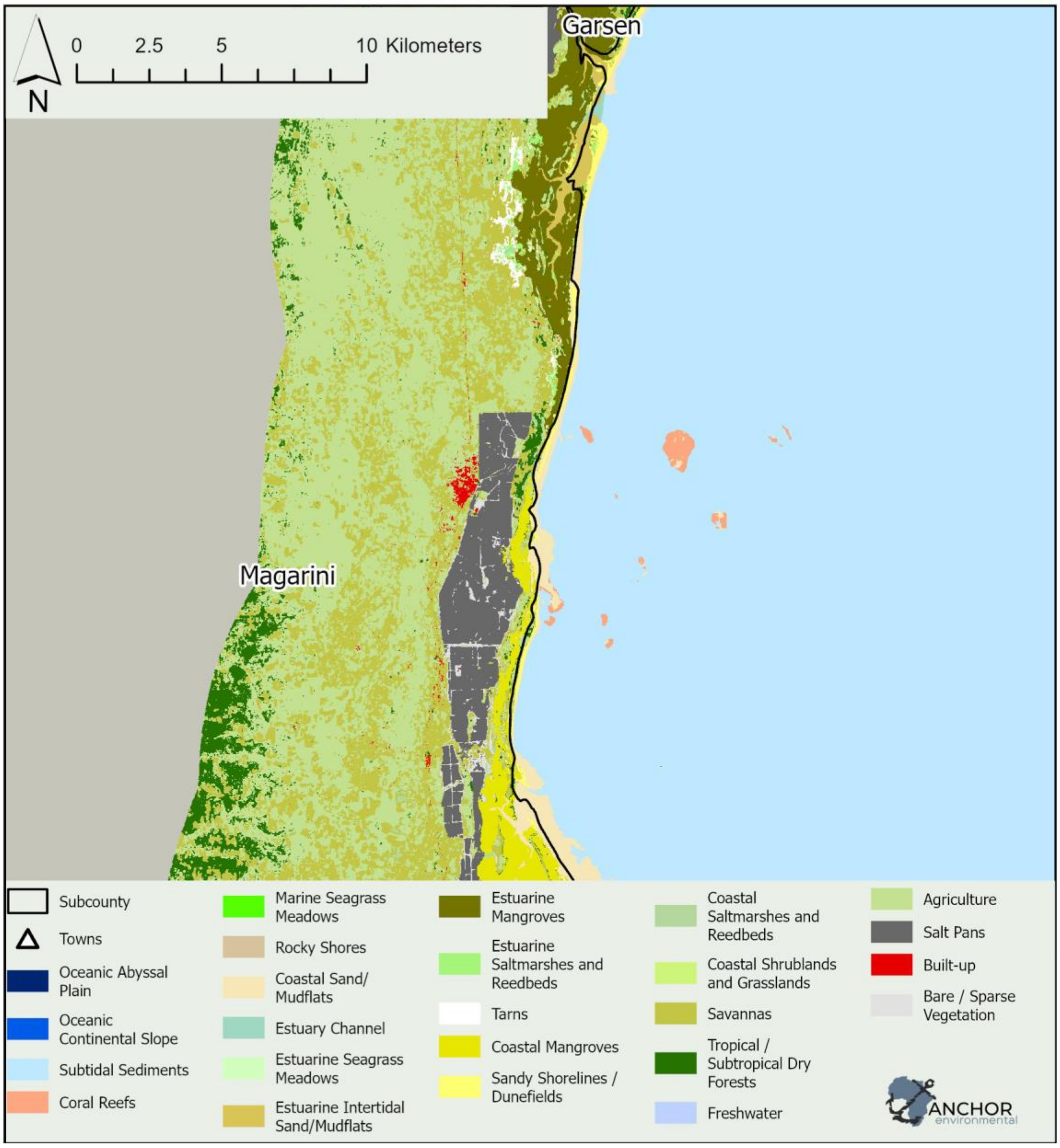

Figure 31: 1:250 000 scale map 9

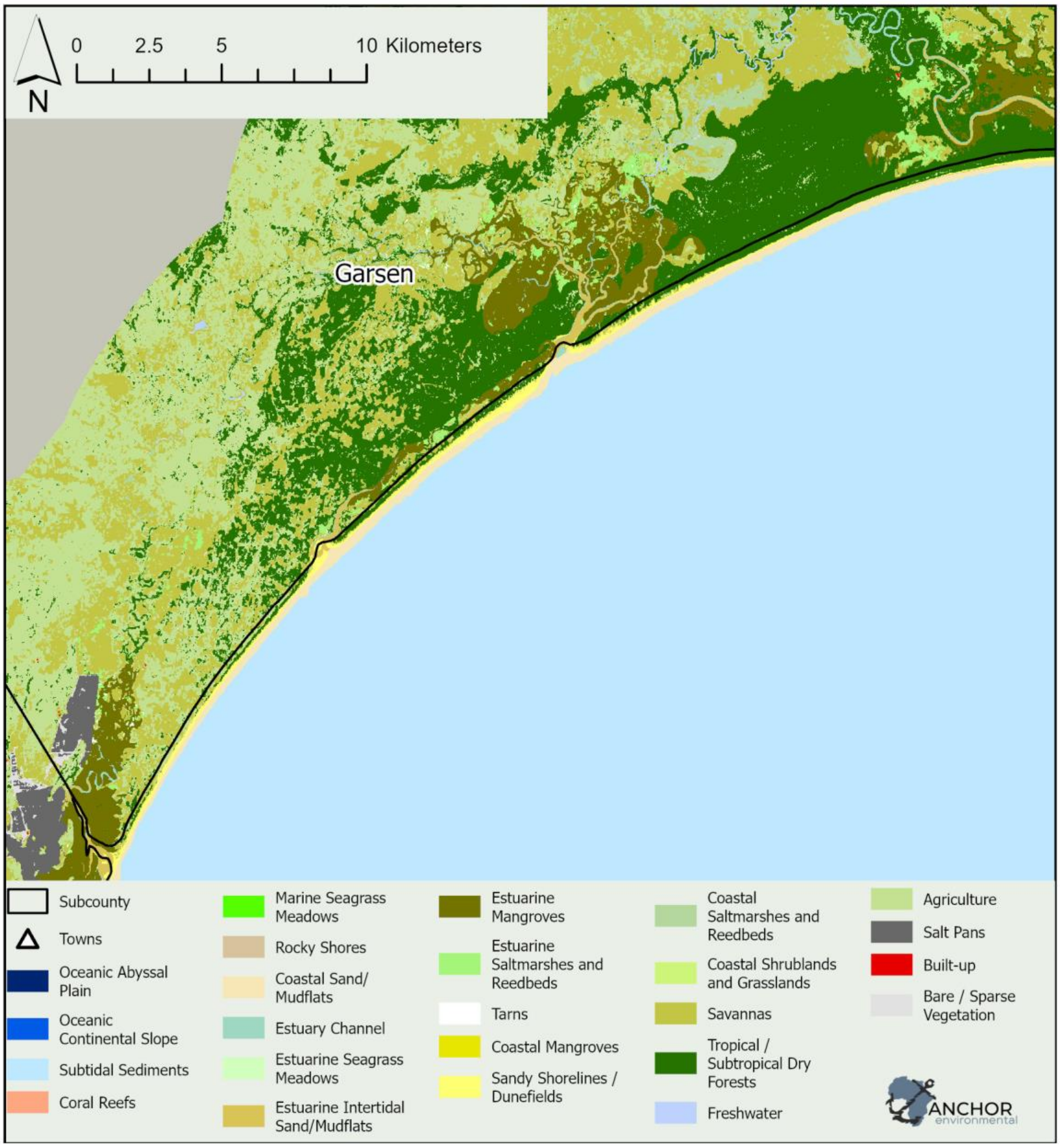

Figure 32: 1:250 000 scale map 10

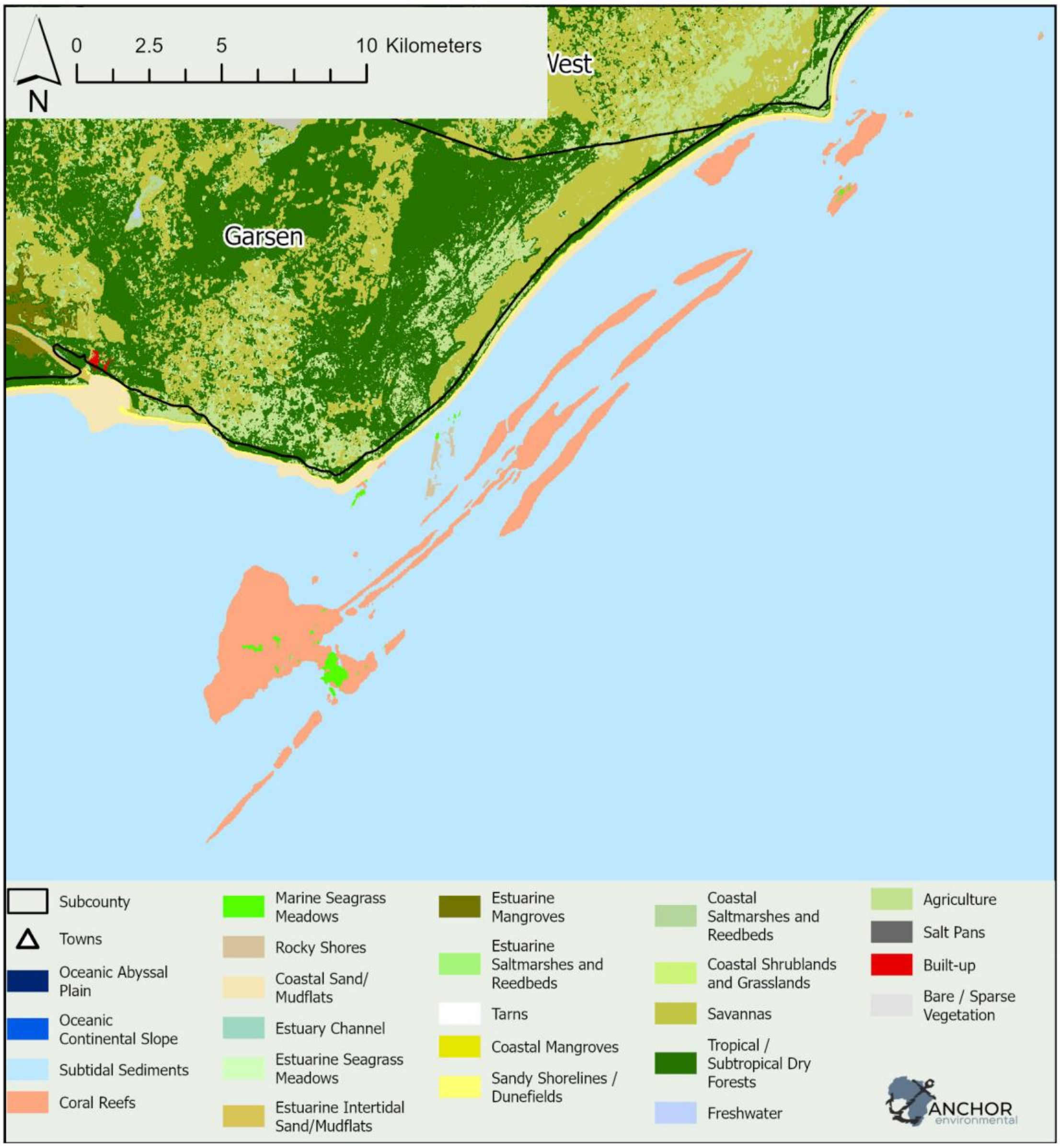

Figure 33: 1:250 000 scale map 11

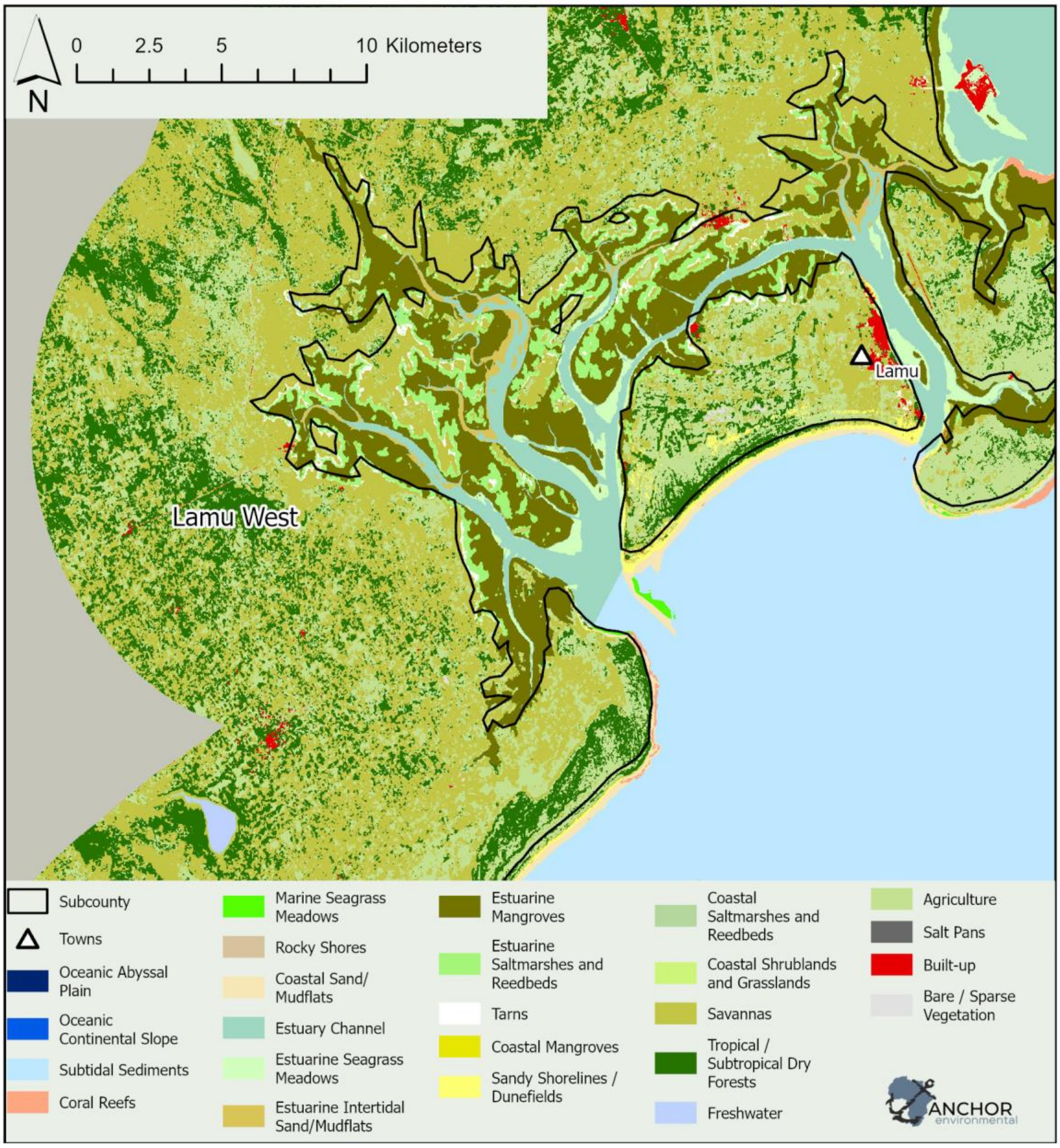

Figure 34: 1: 250 000 scale map 12

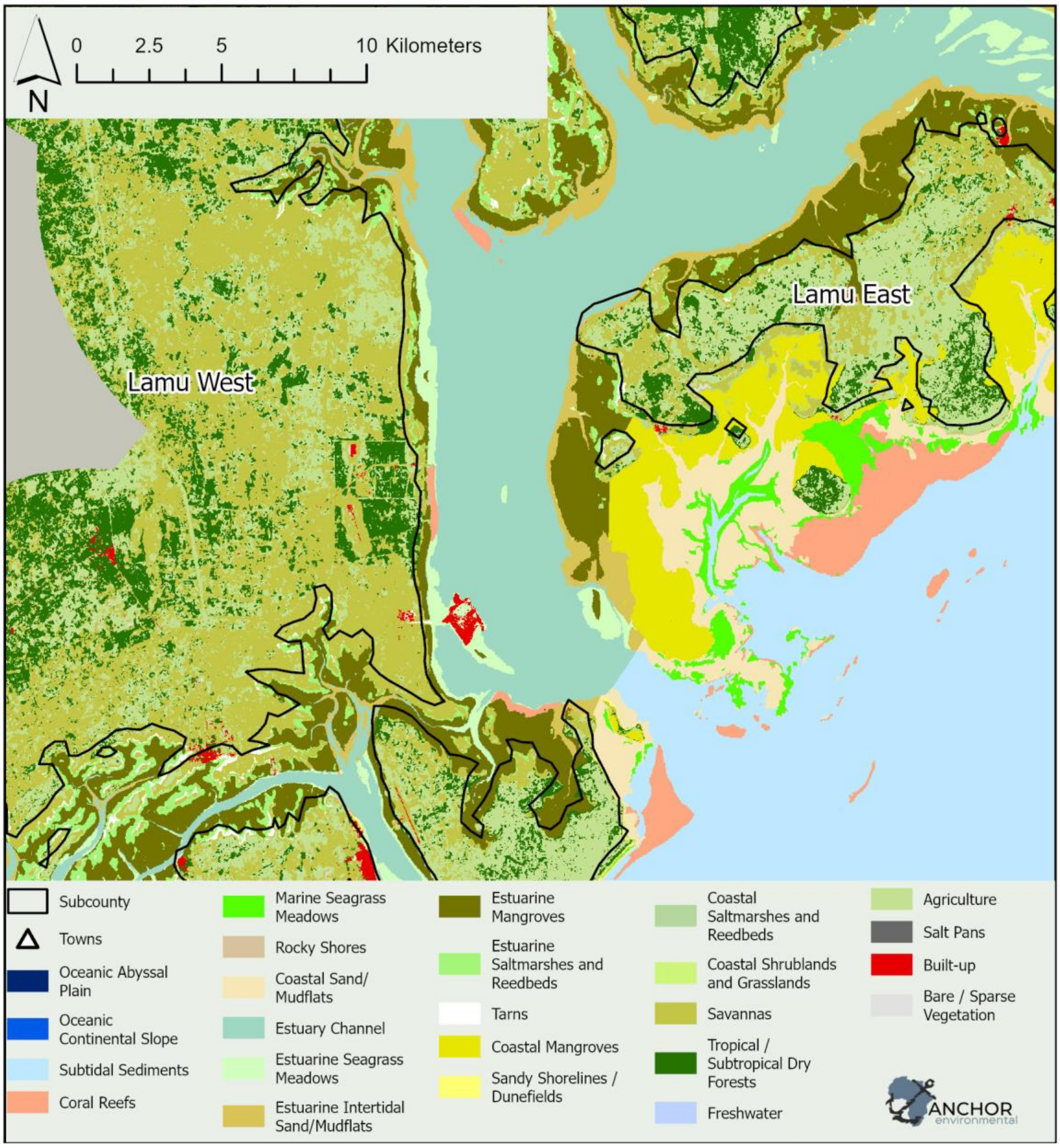

Figure 35: 1: 250 000 scale map 13

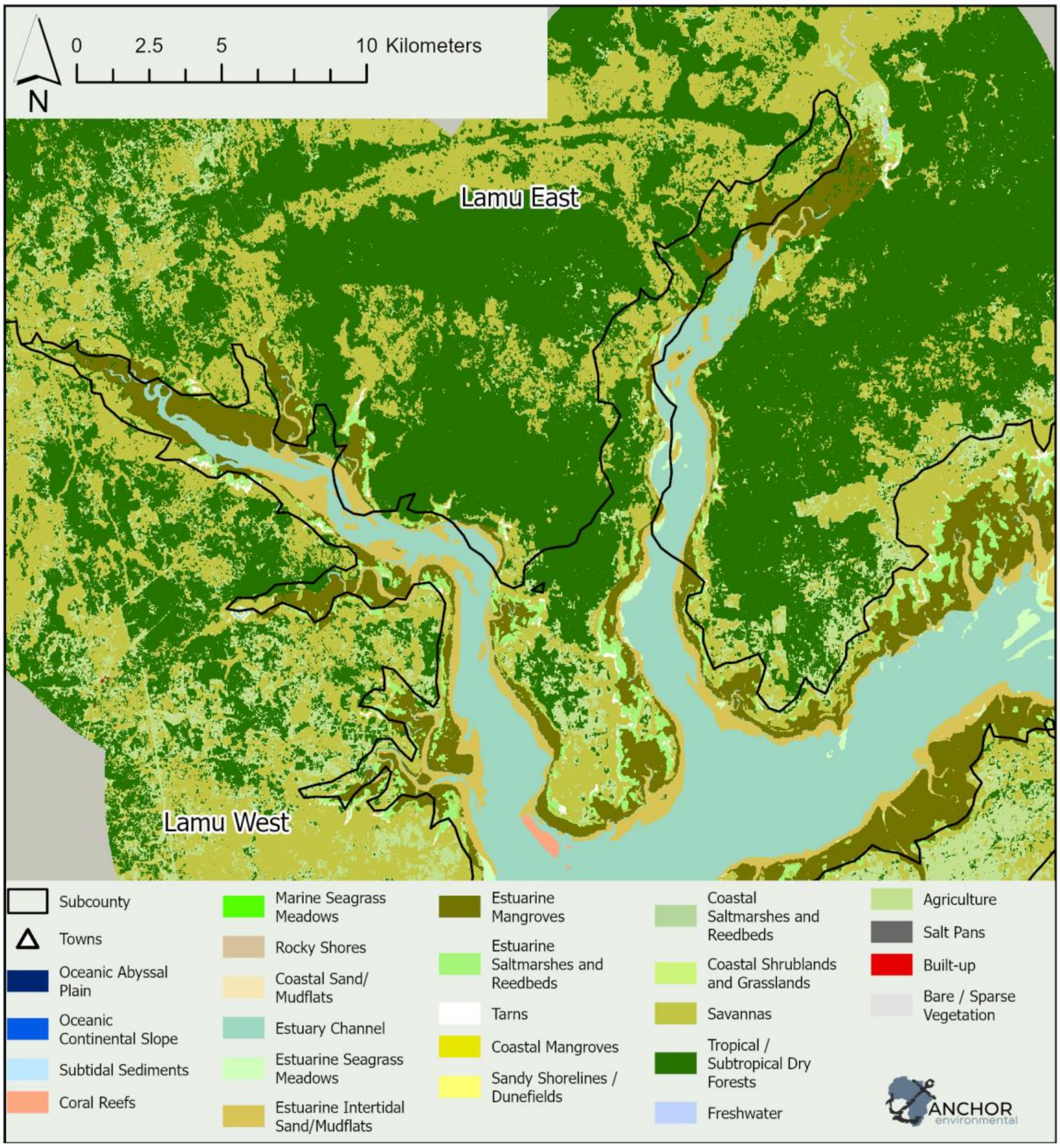

Figure 36: 1: 250 000 scale map 14

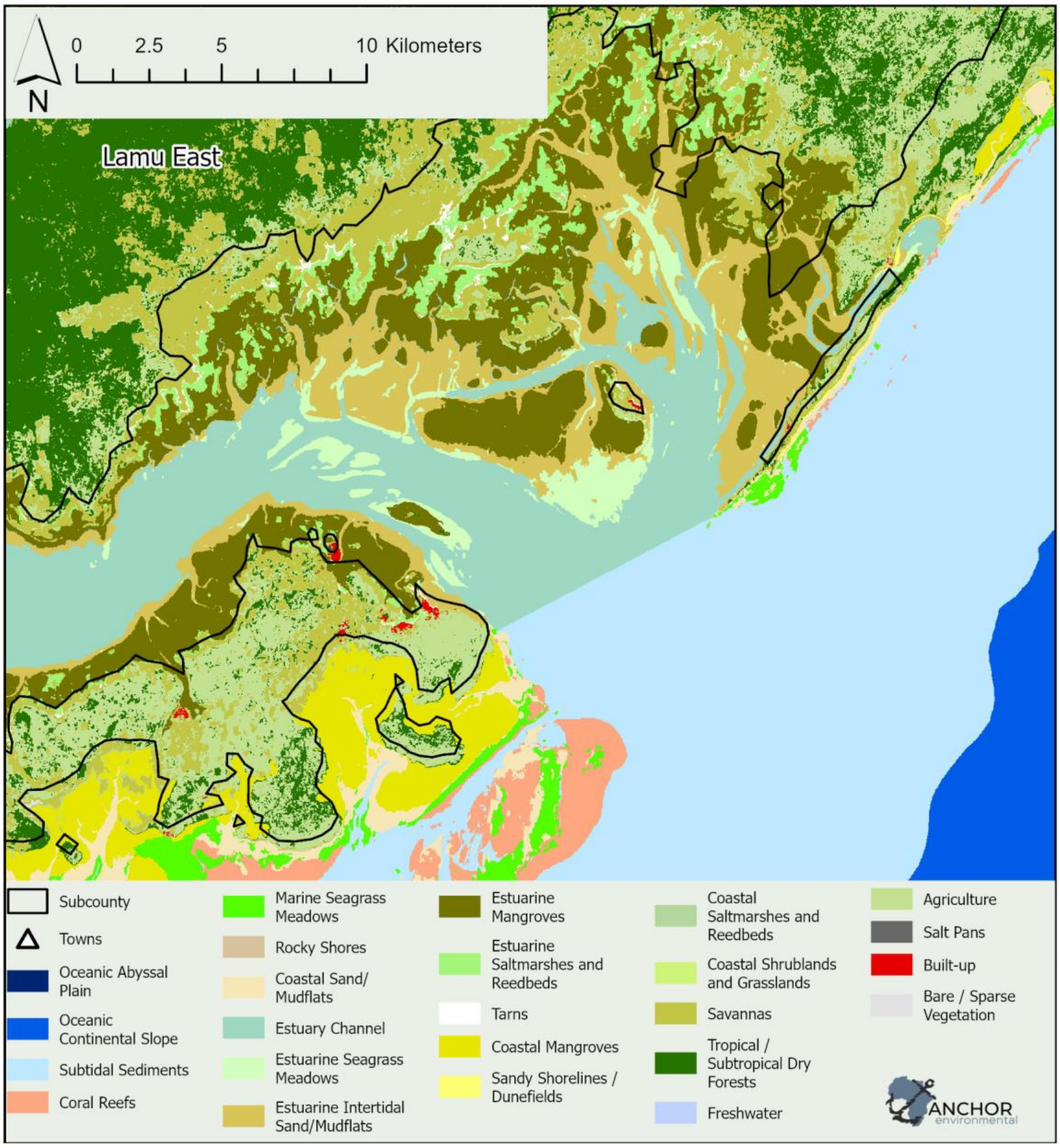

Figure 37: 1: 250 000 scale map 15

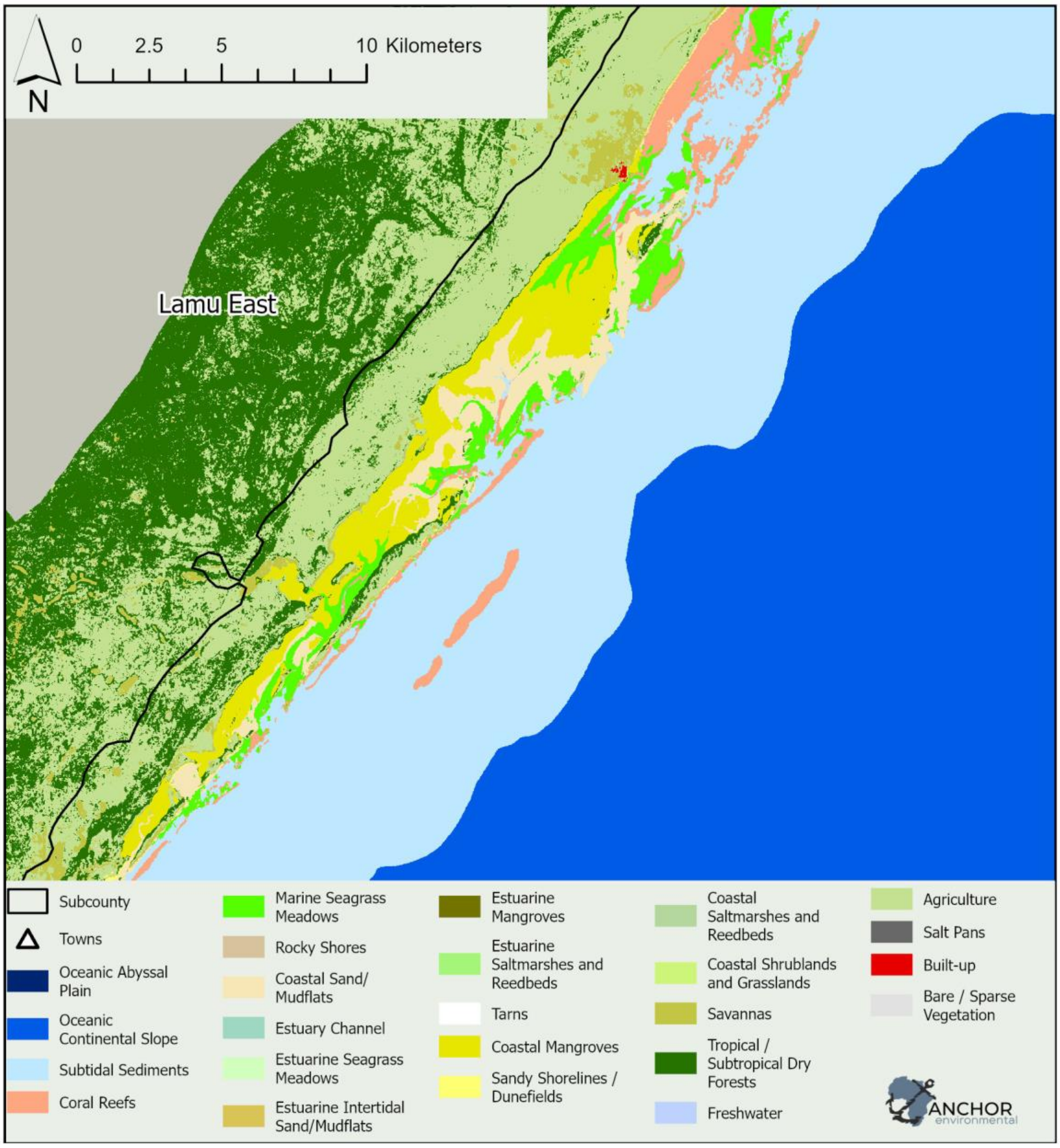

Figure 38: 1: 250 000 scale map 16

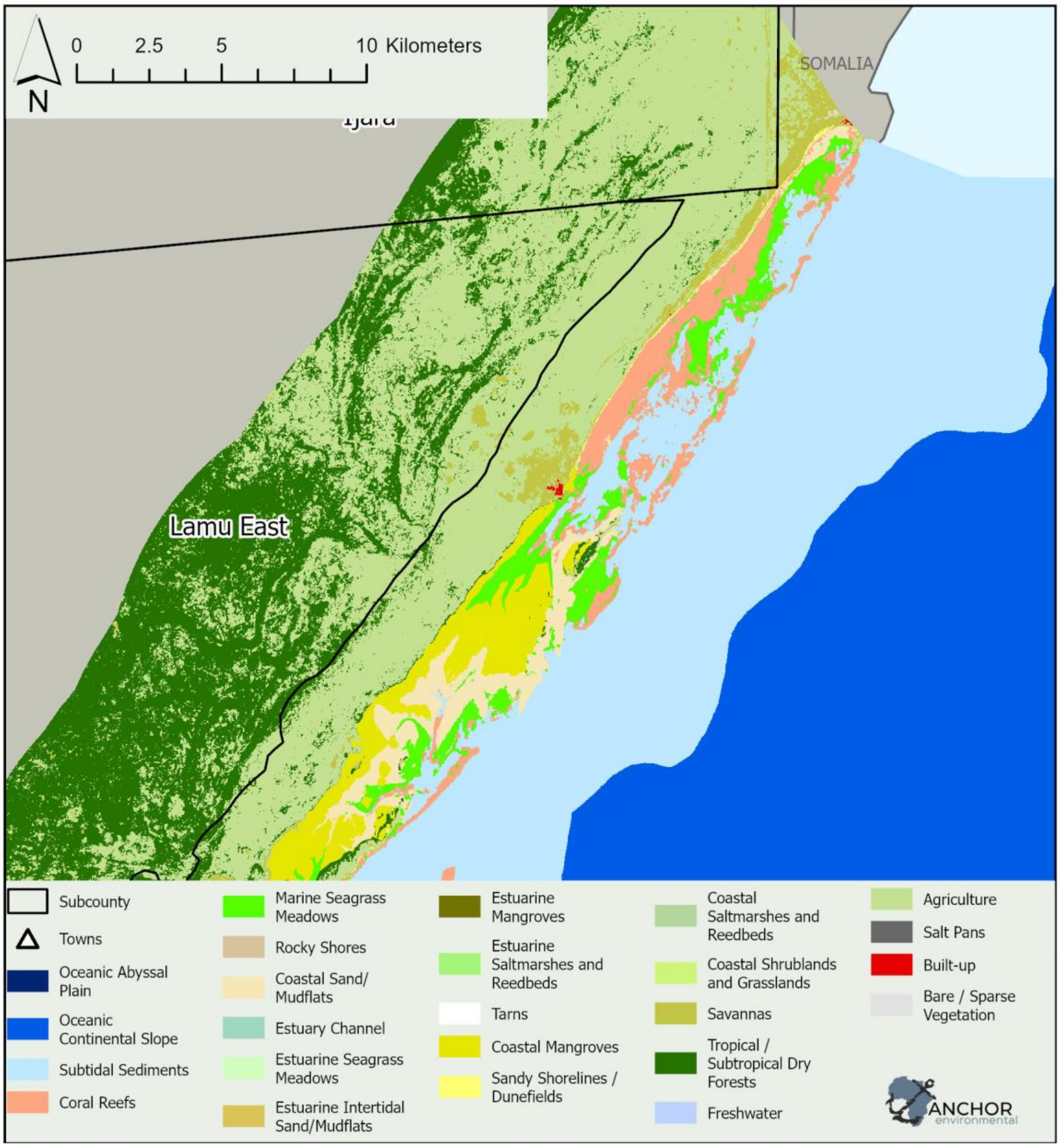

Figure 39: 1: 250 000 scale map 17

4 APPENDIX 4: COUNTY AND SUBCOUNTY MARINE EXTENTS

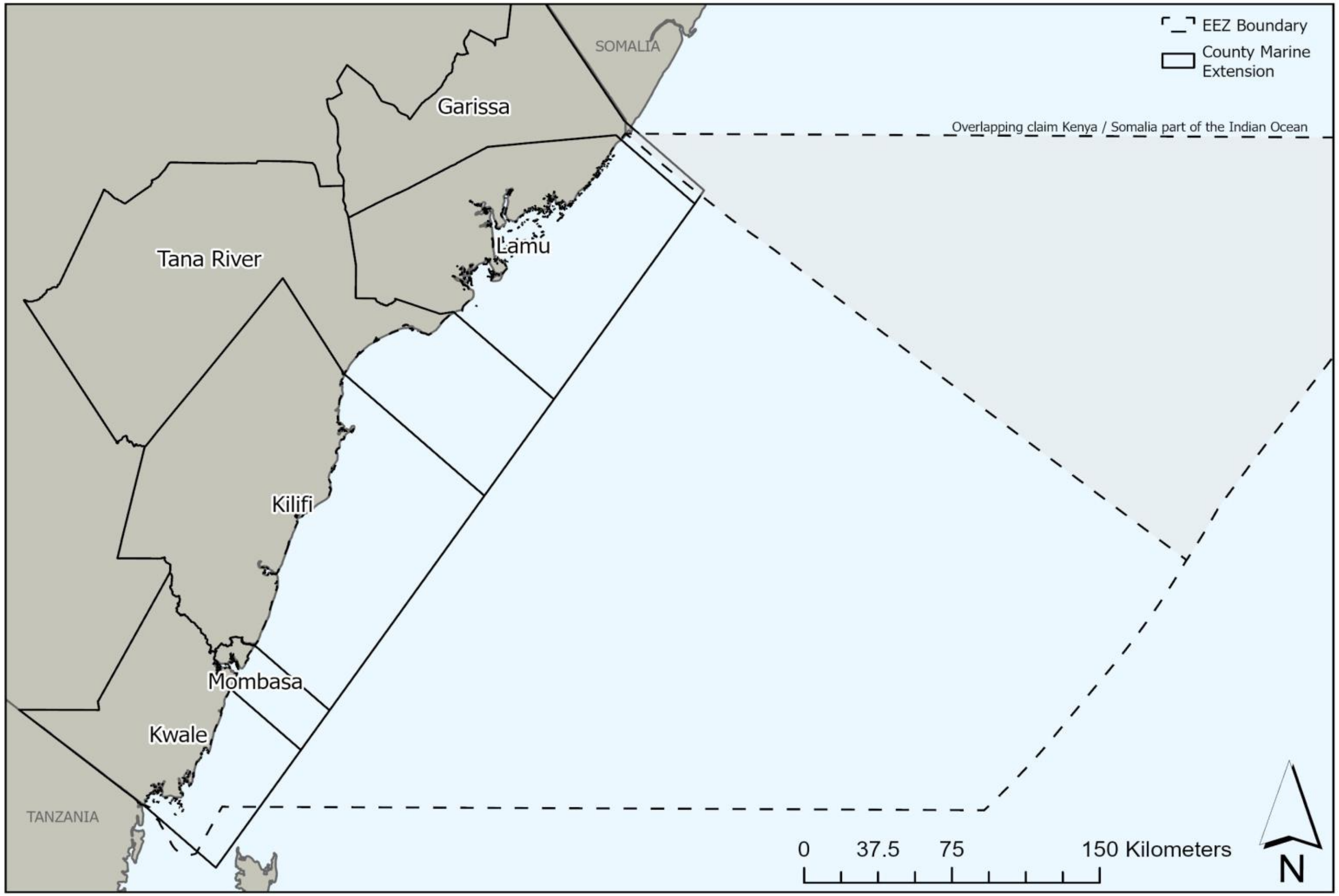

Figure 40: Kenya County Marine Extents.

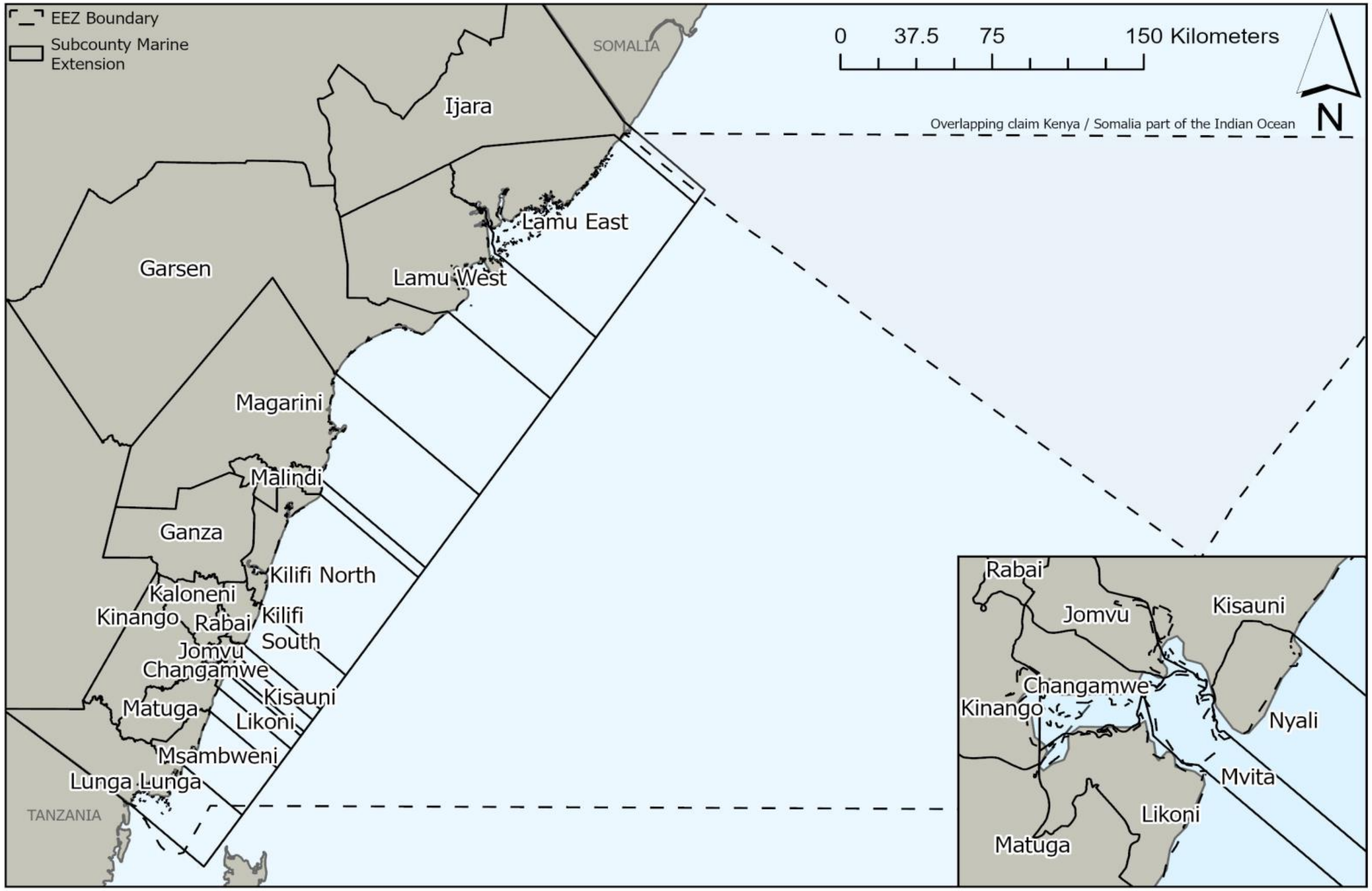

Figure 41. Kenya Subcounty Marine Extents, inset map on bottom right provides finer detail of the subcounties in the Mombasa region.(map to be updated without cutoff line)

5 APPENDIX 5: ECOSYSTEM CONDITION MODEL INPUTS

Table 26: Threats table model input. The weighting assigned to each threat and the maximum distance (km) the threat can reach.

Threat	Max_dist	Weight	Decay
ke_population	40	1	exponential
Shipping_Fishing2	5	0.5	exponential
Shipping_Cargo2	5	0.2	exponential

Table 27: Sensitivity table model inputs. Relative sensitivity of each ecosystem to the selected threats.

Lulc	Name	Ke_population	Shipping_fishing2	Shipping_cargo2
1	Oceanic Abyssal Plain	0.8	0.8	0.8
2	Oceanic Continental Slope	0.8	0.8	0.8
3	Subtidal Sediments	0.9	0.9	0.9
4	Coral Reefs	1	0.5	0.5
5	Marine Seagrass Meadow	1	0.5	0.5
6	Rocky Shores	1	0.5	0.5
7	Coastal Sand/Mudflats	0.9	0.5	0.5
8	Estuary Channel	1	0.5	0.5
9	Estuarine Seagrass Meadow	1	0.5	0.5
10	Estuarine Intertisal Sand/Mudflats	1	0.5	0.5
11	Estuarine Mangroves	1	0.5	0.5
12	Estuarine Saltmarshes and Reedbeds	0.8	0.3	0.3
13	Tarn	0.8	0.3	0.3
14	Coastal Mangroves	1	1	1
15	Sandy Shores / Dunefields	0.8	0.5	0.5
16	Coastal Saltmarshes and Reedbeds	0.8	0.5	0.5

6 APPENDIX 6: COASTAL PROTECTION SUMMARY TABLES

Table 28: Length of coastline at each exposure level per county for scenario 1(all ecosystems).

County	Length of coast (km) per vulnerability score		
	low	medium	high
Kwale	53	129	36
Mombasa	88	69	0
Kilifi	104	148	31
Tana River	11	35	33
Lamu	68	282	246
Total	**325**	**663**	**345**

Table 29: Length of coastline at each exposure level per county for scenario 2(no mangroves).

County	Length of coast (km) per vulnerability score		
	low	medium	high
Kwale	39	116	63
Mombasa	61	89	8
Kilifi	60	176	48
Tana River	5	24	50
Lamu	25	227	343
Total	**190**	**632**	**512**

Table 30: Length of coastline at each exposure level per county for scenario 3(no coral reefs).

County	Length of coast (km) per vulnerability score		
	low	medium	high
Kwale	48	127	42
Mombasa	87	69	2
Kilifi	100	118	65
Tana River	11	35	33
Lamu	62	265	269
Total	**309**	**614**	**411**

Table 31: Length of coastline at each exposure level per county for scenario 4(no seagrass meadows).

County	Length of coast (km) per vulnerability score		
	low	medium	high
Kwale	53	129	36
Mombasa	88	69	0
Kilifi	104	148	31
Tana River	11	35	33
Lamu	68	282	246
Total	**325**	**663**	**345**

Table 32: Length of coastline at each exposure level per county for scenario 5(no beaches and sand dunes).

County	Length of coast (km) per vulnerability score		
	low	medium	high
Kwale	53	129	36
Mombasa	88	69	0
Kilifi	104	148	31
Tana River	11	35	33
Lamu	68	282	246
Total	**325**	**663**	**345**

Table 33: Length of coastline at each exposure level per county for scenario 6(no ecosystems).

County	Length of coast (km) per vulnerability score		
	low	medium	high
Kwale	34	109	75
Mombasa	60	89	9
Kilifi	53	136	94
Tana River	5	24	50
Lamu	14	190	392
Total	**165**	**547**	**621**

Table 34: Length of coastline at each exposure level per subcounty for scenario 1(all ecosystems).

Subcounty	Length of coast (km) per vulnerability score		
	low	medium	high
Lunga Lunga	29	76	35
Msanbweni	10	43	0
Matuga	11	6	0
Kinango	3	4	1
Likoni	21	13	0
Changamwe	1	13	0
Jomvu	12	6	0
Mvita	10	9	0
Nyali	2	9	0
Kisauni	42	19	0
Kilifi South	15	30	0
Kilifi North	78	73	3
Malindi	1	8	1
Magarini	10	37	27
Garsen	11	35	33
Lamu West	24	128	145
Lamu East	45	154	101

Table 35: Length of coastline at each exposure level per subcounty for scenario 2(no mangroves).

Subcounty	Length of coast (km) per vulnerability score			Protection by ecosystem
	low	medium	high	
Lunga Lunga	22	60	58	23
Msanbweni	7	44	2	2
Matuga	8	8	0	0
Kinango	2	5	2	1
Likoni	13	21	0	0
Changamwe	1	12	1	1
Jomvu	9	8	2	2
Mvita	7	12	0	0
Nyali	2	9	0	0
Kisauni	28	27	5	5
Kilifi South	10	35	0	0
Kilifi North	43	105	7	4
Malindi	1	8	1	0
Magarini	5	29	40	13
Garsen	5	24	50	18
Lamu West	11	85	201	56
Lamu East	14	142	143	42

Table 36: Length of coastline at each exposure level per subcounty for scenario 3(no coral reefs).

Subcounty	Length of coast (km) per vulnerability score			Protection by ecosystem
	low	medium	high	
Lunga Lunga	28	73	40	5
Msanbweni	8	43	1	1
Matuga	9	7	0	0
Kinango	3	4	1	0
Likoni	21	13	0	0
Changamwe	1	13	0	0
Jomvu	12	6	0	0
Mvita	10	9	0	0
Nyali	1	9	2	2
Kisauni	42	19	0	0
Kilifi South	14	26	5	5
Kilifi North	77	56	21	18
Malindi	1	2	6	5
Magarini	7	33	34	6
Garsen	11	35	33	0
Lamu West	19	114	163	19
Lamu East	43	151	105	5

Table 37: Length of coastline at each exposure level per subcounty for scenario 4(no seagrass meadows).

Subcounty	Length of coast (km) per vulnerability score			Protection by ecosystem
	low	medium	high	
Lunga Lunga	29	76	35	0
Msanbweni	10	43	0	0
Matuga	11	6	0	0
Kinango	3	4	1	0
Likoni	21	13	0	0
Changamwe	1	13	0	0
Jomvu	12	6	0	0
Mvita	10	9	0	0
Nyali	2	9	0	0
Kisauni	42	19	0	0
Kilifi South	15	30	0	0
Kilifi North	78	73	3	0
Malindi	1	8	1	0
Magarini	10	37	27	0
Garsen	11	35	33	0
Lamu West	24	128	145	0
Lamu East	45	154	101	0

Table 38: Length of coastline at each exposure level per subcounty for scenario 5(no beaches or sand dunes).

Subcounty	Length of coast (km) per vulnerability score			Protection by ecosystem
	low	medium	high	
Lunga Lunga	29	76	35	0
Msanbweni	10	43	0	0
Matuga	11	6	0	0
Kinango	3	4	1	0
Likoni	21	13	0	0
Changamwe	1	13	0	0
Jomvu	12	6	0	0
Mvita	10	9	0	0
Nyali	2	9	0	0
Kisauni	42	19	0	0
Kilifi South	15	30	0	0
Kilifi North	78	73	3	0
Malindi	1	8	1	0
Magarini	10	37	27	0
Garsen	11	35	33	0
Lamu West	24	128	145	0
Lamu East	45	154	101	0

Table 39: Length of coastline at each exposure level per subcounty for scenario 6(no ecosystems).

Subcounty	Length of coast (km) per vulnerability score			Protection by ecosystem
	low	medium	high	
Lunga Lunga	20	55	65	30
Msanbweni	5	40	8	8
Matuga	7	10	0	0
Kinango	2	5	2	1
Likoni	13	21	0	0
Changamwe	1	12	1	1
Jomvu	9	8	2	2
Mvita	7	12	0	0
Nyali	1	9	2	2
Kisauni	28	28	5	5
Kilifi South	10	31	5	5
Kilifi North	40	81	33	30
Malindi	1	2	6	5
Magarini	2	21	50	23
Garsen	5	24	50	18
Lamu West	3	70	223	78
Lamu East	11	120	169	68

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