

## SUPPLEMENTARY FIGURES AND TABLES



Supratidal salt marsh  
(*Salicornia pillansii*) at Kariega Estuary



Intertidal salt marsh (foreground) and  
mangrove - salt marsh ecotone (background) at  
the Nahoon Estuary



Loss of salt marsh at semi-arid Groot Berg  
Estuary due to stock farming



Invasive *Spartina alterniflora* in the Groot Brak  
Estuary in 2012, it has subsequently been  
removed.



Mosaic of salt marsh and seagrass at the warm  
temperate Kromme Estuary



First record of mangrove at southerly range  
limit Keiskamma Estuary in *Spartina maritima*  
intertidal salt marsh.

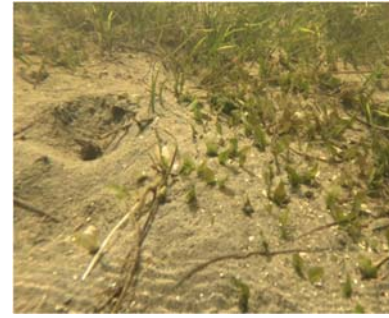
**Supplementary Figure 1 Photographs of salt marsh in South Africa.**



*Zostera capensis* with macroalga  
*Codium tenue*



*Zostera capensis* in the  
intertidal zone of the  
Kariega Estuary



Seagrasses (*Halophila ovalis* and  
*Zostera capensis*) at Knysna  
Estuary



*Z. capensis* at Nqabara Estuary  
adjacent to pneumatophores of  
mangrove (*Avicennia marina*)



Effect of bait digging on  
seagrass *Zostera capensis*  
at Knysna Estuary



Filamentous macroalgae at the  
eutrophic Groot Brak Estuary

**Supplementary Figure 2 Examples of seagrass and macroalgae in South African estuaries.**



Reeds and salt marsh at a  
stormwater input site at the  
Knysna Estuary



Reeds and sedges line the  
narrow intertidal area in the  
Kei Estuary



Bulrush (*Typha capensis*) with  
succulent salt marsh *Salicornia*  
spp.

**Supplementary Figure 3 Examples of reeds and sedges in South African estuaries.**



*Rhizophora mucronata* (Red mangrove) at Mgeni Estuary



*Bruguiera gymnorhiza* (Black mangrove) at Mlalazi Estuary



*Barringtonia racemosa* (Powderpuff tree - forested wetland) at Mdlotane Estuary



*Bruguiera gymnorhiza* with reeds (*Phragmites australis*) at the freshwater dominated Mzimvubu River Estuary

**Supplementary Figure 4 Photographs of mangroves and swamp forest habitats in South Africa.**



Die back of mangroves and replacement by reeds & sedges at St Lucia Estuary



Replacement of mangroves by freshwater herbs at St Lucia Estuary

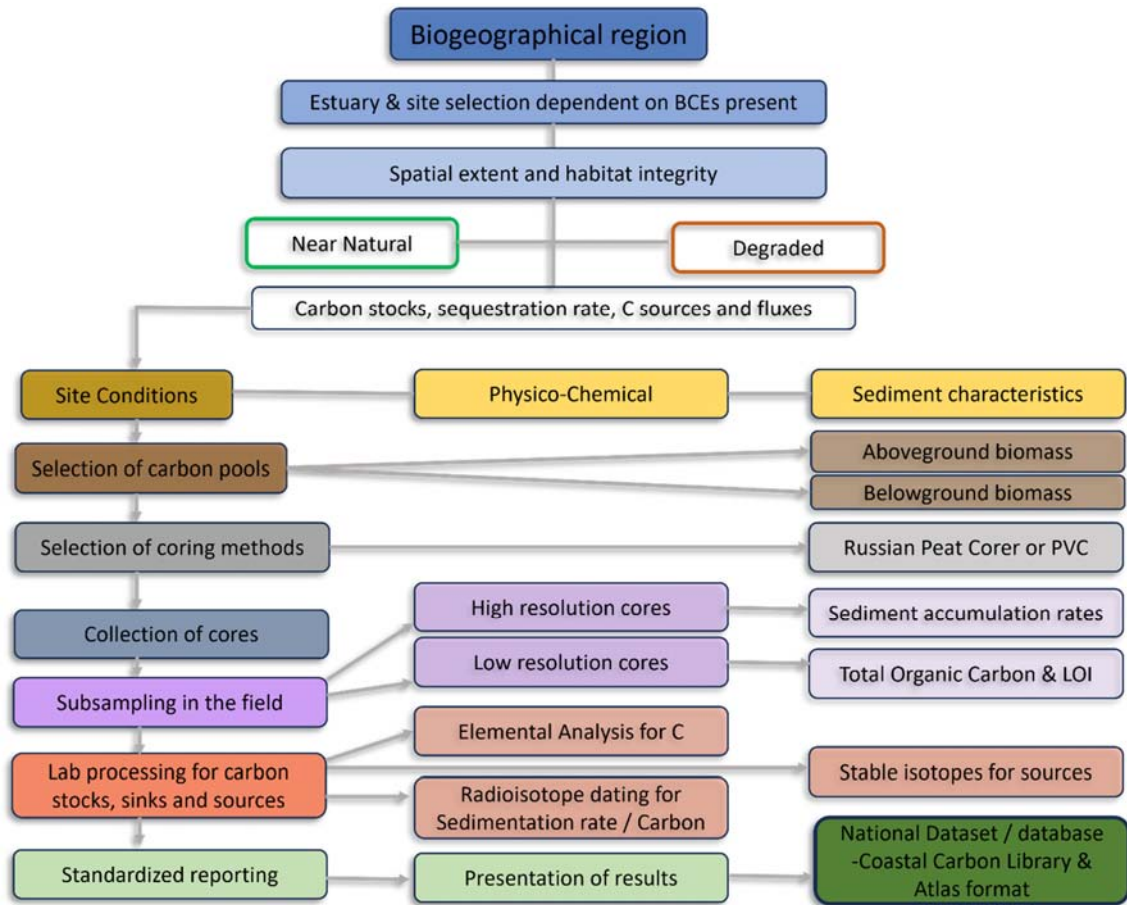


Die back of mangroves and salt marsh growth at Bulungula Estuary



Die back of *Avicennia marina* at Kobonqaba Estuary

**Supplementary Figure 5 Examples of dynamic estuary habitat changes .**



**Supplementary Figure 6** Steps to consider when planning, sampling, measuring and reporting blue carbon studies (BCE = Blue Carbon Ecosystems; LOI = loss on ignition).

**Supplementary Table 1** Research questions for Blue Carbon Ecosystems [categorised](#) in seven themes.

## **THEME 1. Carbon Storage, Sequestration and Fluxes**

1. What are the allochthonous versus autochthonous contributions to carbon stocks? (including the influence of wastewater and eutrophication)?
2. What is the turnover rate and permanence of carbon within different BCEs?
3. How to efficiently sample the different estuary types and biogeographic regions for national coverage of carbon stocks and sequestration?
4. How do we deal with /measure spatio-temporal variability in BCEs?
5. Does bioturbation hinder or enhance blue carbon storage in sediment? (i.e. for example, crabs on carbon storage and sequestration?)
6. How important is the microbiome of BCEs to resilience of these systems?
7. What is the influence of animal diversity on carbon storage and sequestration?
8. How to quantify fluxes of GHGs?
9. To what extent do environmental factors, such as temperature and rainfall, explain the variability in blue carbon stocks?
10. What is the relationship between the microbiome, BCE health, carbon sequestration and storage?
11. How do we determine what specific factors affect carbon storage and fluxes at a site and regional scale?
12. Is carbon stored at a particular depth 'safe' from remineralisation if there is a change to a freshwater-dominated system?
13. How to quantify lateral and vertical carbon exchanges?
14. Can fragmentation indices be used to identify the status of BCEs?
15. To what extent are seagrasses contributing to GHG removal when accounting for GHG fluxes of methane and nitrous oxide?

## **THEME 2. Drivers and Responses**

1. Are there any clear drivers / environmental settings that can be used to infer when a BCE may no longer be a net carbon sink?
2. Due to the fragmented nature of our BCEs, is connectivity of carbon between our estuaries important to consider?
3. How can an understanding of sediment availability (catchment to coast) inform coastal carbon sequestration?
4. What role do bioturbators play in restoring habitats for the provision of blue carbon storage?
5. How significant is within-estuary variability on sedimentation rates?
6. What is the relationship between microbes, microplastics and blue carbon? (blue carbon storage versus microplastic sinks)?
7. What is the global significance of BCEs as alkalinity buffers and value as exporters of dissolved inorganic carbon?

## **THEME 3. Climate Change Prediction**

1. How to identify and implement buffer areas for the expansion of mangroves and salt marsh in response to climate change and sea level rise?
2. How do BCEs and estuaries respond to climate change stressors like storm surges, floods, droughts and reduced freshwater inflow?
3. How to determine the impact of climate change scenarios on BCEs to ensure persistence and focus restoration for resilience?
4. How best to model climate change parameters and influence on BCEs?

## **THEME 4. Emerging Ecosystems**

1. What is the role of estuarine reeds and sedges as BCE sinks?

2. How does estuarine reed, sedge and forested wetland carbon storage and sequestration differ from mangrove, salt marsh and seagrass ecosystems?
3. For "emerging" BCEs - i.e. kelp what data are available to indicate carbon sequestration potential in the form of biomass accumulation?
4. Will we lose estuarine blue carbon stocks if there is a shift to freshwater or 'teal' carbon ecosystems under climate change?

#### **THEME 5. Management, Conservation and Restoration**

1. How can we design and implement restoration and a national estuary protection plan for BCEs?
2. What must be done regarding conservation/management/restoration of BCEs in the face of climate change?
3. How does restoration using hydrological connectivity restore carbon stocks in salt marsh and other degraded areas in estuaries?
4. How do we integrate traditional and local community knowledge when monitoring and restoring BCEs?
5. How to link restoration of BCEs to other estuary management processes such as Environmental Flows, implementation of Estuary Management Plans, Critical Biodiversity Areas?

#### **THEME 6. Monitoring and Reporting**

1. How can we improve the quantification and monitoring of BCE carbon stocks particularly in ecosystems and regions that are data-deficient?
2. Where can we establish long-term estuary monitoring sites to track changes in BCEs in response to climate change and human pressures?
3. How to develop a monitoring system to determine current and future threats to blue carbon ecosystems and monitoring programmes to track changes (to facilitate early response and intervention)?
4. How can earth observation be used to quantify BCE extent, condition and trends over time?
5. How can earth observation be used to distinguish anthropogenic and climate change impacts on BCEs?

#### **THEME 7. Carbon Finance and Policy**

1. How to develop a BCEs Account for South Africa collaborating with the South African National Department of Forestry, Fisheries and the Environment (DFFE), Statistics South Africa and the South African National Biodiversity Institute (SANBI) following international guidelines & standards?
2. Nature credits are based on stewardship; which estuaries can be identified where there is secured biodiversity/ecological integrity through this?
3. What is the socio-ecological impact of blue carbon markets ? (e.g. land grab in Africa for carbon market).

*(Acronyms: BCEs = Blue Carbon Ecosystems, DFFE = Department of Fisheries, Forestry & Environment, GHGs = greenhouse gases, Stats South Africa, SANBI = South African National Biodiversity Institute).*

**Supplementary Table 2** Standardised metadata to use for reporting on collection and analysis of Blue Carbon study sediment samples. This was informed by the Smithsonian Coastal Carbon library database (Holmquist et al. 2024).

		Description
<b>Study Site Data</b>	Data collectors	Names of the data collectors and affiliations
	Site ID (estuary name)	Unique ID codes for each estuary
	Site Description	Estuary type, lower, middle, upper reaches, north, south bank
	Core ID	Unique core ID for each of the study, sites and replicate number
	Year, Date and Time	Date of the sediment collection (e.g. 20240415, 10H25)
	GPS co-ordinates	Location of core (GPS)
	Habitat	Where core collected e.g. mangroves, salt marsh, seagrass
	Sampling season	Summer, Autumn, Winter or Spring
	Weather	Air temperature, conditions (rain, sunshine, cloudy)
	Estuary Mouth status	Open, Closed, Perched
	Sampling activity	What was collected? Intended analysis, sectioning resolution, number of cores and replicates
	Disturbances present	Natural or anthropogenic within sampling site and adjacent
<b>Core ID</b>	Depth min	Top layer of core (cm)
	Depth Max	Bottom layer of core (i.e. 50 cm, 1 m or greater)
	Dry bulk density	Sample volume (cm <sup>3</sup> )
	Organic matter	Organic matter percentage and the LOI method (incl. temperature and period of combustion)
	Sediment Redox potential	Oxidation and Reduction potential of sediment in the field (Millivolts : mV)
	Sediment Moisture content	Sediment moisture (percentage)
	Particle size	Percentage of sand, silt and clay content. Use of Hydrometer method or Laser particle size analyser
<b>Methods</b>	Coring method	<i>Soil pit</i> = Dug from the surface to the bedrock, samples collected from sides of pit. <i>Surface sample</i> = Upper 5 cm of sediment collected. <i>Russian peat corer</i> = Half cylinder with a fin that isolates sediment around a rotating pivot point. <i>PVC</i> = PVC pipe is driven to the desired depth
	Roots present	Approximate percentage and size class (fine, medium or large roots)
	Sediment sieved	Laboratory test sieve mesh size used on bulk sediment
	Compaction	Present or Absent. If present, calculated factor applied to each section
	Sample volume (DBD)	m <sup>3</sup>
	Dry bulk density	Sample volume (cm <sup>3</sup> )
	Loss on ignition (sample mass)	Grams and percentage
	Carbon measured or modelled	Elemental analysis, wet oxidation or allometric equations
	Carbonates removal method	Whether they were removed prior to calculating organic fraction (direct acidification, low carbonate content, carbonates not removed)
	Fraction Carbon type TOC, TC, TIC	Megagrams of Carbon (Mg C) or allometric equation used for estimation
<b>Species</b>	Species code	Unique code for either dominant species or species composition
	Code type	Genus and Species
	Habitat	BCE being sampled (e.g. mangroves, salt marsh, seagrass)
	Vegetation cover & height	Vegetation cover (percentage) and average height (meters)

**Supplementary Table 3** Details on Blue Carbon Ecosystems and other potential carbon rich coastal habitats in South Africa.

ECOSYSTEM FUNCTIONING GROUP	EXTENT	ISSUES WITH DEFINITIONS	SINKS?	ANTHROPOGENIC PRESSURES AND CLIMATE CHANGE RESPONSES	REFERENCE
<b>Blue Carbon Ecosystems</b>					
MANGROVES	2 400 ha	N.A.	Biomass Sediment	May increase in extent with southward expansion but under threat in specific estuaries due to harvesting, livestock browsing & trampling changes in hydrology, estuary mouth closure, chemical and waste pollution.	Van Niekerk et al. (2019)
INTERTIDAL SALT MARSH	~ 5 000 ha	N.A.	Biomass Sediment	Possible expansion of mangroves into salt marsh habitats. Estuary mouth closure and increase in water level. Chemical and waste pollution. Erosion from boats, trampling and grazing.	Van Niekerk et al. (2019)
SUPRATIDAL SALT MARSH	~10 000 ha	Generally, not tidal but can be	N.A.	Coastal development, catchment and hydrological changes. Trampling and grazing, removal by agriculture, salinization and desiccation.	N.A.
SEAGRASS ( <i>Zostera capensis</i> )	~1 500 ha	N.A.	Biomass Sediment	Coastal development, catchment and hydrological changes, boat and bait digging activities, chemical and waste pollution. Eutrophication and competition with macroalgae.	Van Niekerk et al. (2019)
<b>Inland freshwater ecosystems occurring in estuaries</b>					
PEATLANDS	21 284 ha (most not tidal)	Generally, not tidal but can occur in the Estuarine Functional Zone	Sediment	Desiccation of peat substrate from overallocation of water from aquifers. Climate change and drying, increase susceptibility to desiccation, transformation and substrate fires that release GHGs. Pollution, and land cover/ land use transformation.	Grundling et al. (2021)
FORESTED WETLANDS (SWAMP FORESTS)	5400 - total of 12 000 ha	Ecotone habitat in estuaries, can be tidal when mouth is open	Biomass Sediment	Changes in hydrology may lead to area loss, whereas salt water intrusion may alter species composition. Overallocation of water in aquifer-dependent ecosystems result in desiccation, transformation to subsistence and commercial crops, and/or ignition and burning of peat substrate.	Grundling et al. (2021) and Van Deventer et al. (2021)
REEDS AND SEDGES	~19 000 ha	Ecotonal habitats, tidal when mouth is open	Biomass Sediment	Sedimentation, eutrophication and increased runoff leads to expansion. Important buffer acting as filter and taking up chemical and waste pollution. Coastal development, agricultural expansion and burning removes reeds and sedges.	Adams et al. (2016)
<b>Other marine ecosystems</b>					
STROMATOLITES with associated rocky shore	18 km <sup>2</sup>	Estuarine-like functionality but associated with Rocky Shores	Not known	Reduction in freshwater input, coastal squeeze and development will decrease extent, chemical and waste pollution also a threat.	Van Niekerk et al. (2019)
KELPS	27 698 km <sup>2</sup>	N.A.	Biomass	Expansion due to changes in sea surface temperature. Fisheries, harvesting, mining, wastewater pressures.	Dunga (2020)
SEAWEEEDS	?	N.A.	Biomass	Changes in species composition in response to global climate change. Increase in biomass and cover in response to nutrient inputs and estuary mouth closure.	