



Decadal Changes in Mangrove Extent, Structure, and Anthropogenic Pressures at a Southern Range Limit

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Abstract

Understanding how mangroves respond to natural and anthropogenic pressures at global distributional range limits informs protection and restoration strategies. Mangroves along the South African coastline are at one of the most southerly global distribution limits. These endangered ecosystems have been studied for more than 25 years to determine their vulnerability and responses to global climate change. This study assessed the drivers of change in mangrove area cover, species composition and population structure between 2011 and 2021 in 17 estuaries. There was a net increase in mangrove cover over this 10-year period of 3 ha and this was attributed to natural regeneration along tidal sand banks and into areas previously covered by salt marsh. *Bruguiera gymnorhiza* was the only mangrove tree species found in all the estuaries, *Avicennia marina* occurred in 71% and *Rhizophora mucronata* in 47% of all estuaries. Major anthropogenic pressures that reduced mangrove cover and caused shifts in population structure were wood harvesting, livestock browsing and trampling. Anthropogenic pressures have persisted since 2011 resulting in structural mangrove degradation indicated by a decrease in seedling and sapling density and increase in canopy gaps. These results provide input to the National Biodiversity Assessment and are relevant to the implementation of the Global Biodiversity Framework informing site specific restoration strategies. The research also informs global studies on climate-driven range shifts; mangrove expansion is occurring, but this is slow and influenced by local pressures. The study recommended that adaptive management and monitoring frameworks are used to track mangrove changes.

Keywords Coastal wetlands · Mapping change detection · Estuary · Wood harvesting

Introduction

Globally, mangroves have a restricted geographical distribution where they occur naturally, set by specific environmental factors such as temperature, salinity and tidal inundation. They occur where the seawater surface temperature isotherm is above 20 °C and the thermal amplitude is less than 5 °C (Giri et al. 2011; Saintilan et al. 2014; Sippo et al. 2018). Mangroves can be found in different geomorphic and sedimentary settings such as deltas, estuaries, lagoons and along open coastlines in tropical and subtropical regions between

25° N and 25° S (Huxham et al. 2010; Giri et al. 2011; Saintilan et al. 2014; Worthington et al. 2020; Adame et al. 2021). The exception to this is the occurrence of mangroves on the eastern coasts of South America (28–29 °S), southern Africa (28 °S), New Zealand and Australia (38 °S) where they are beyond this range (Bunting et al. 2022). Understanding how mangroves respond to natural and anthropogenic pressures at these distributional range limits has important implications as changes in species distribution and population structure can impact ecosystem services such as fisheries, coastal livelihoods, coastal resilience and carbon storage (Osland et al. 2022). The latitudinal distribution limits of mangrove distribution are determined by cold temperatures and droughts condition, because of this, mangroves at the range limit are generally shorter, wider and more shrub-like compared to tropical mangrove (Osland et al. 2014, 2017). Monitoring mangrove range shifts informs climate-related impacts, and associated management responses to ensure their protection and sustainable use.

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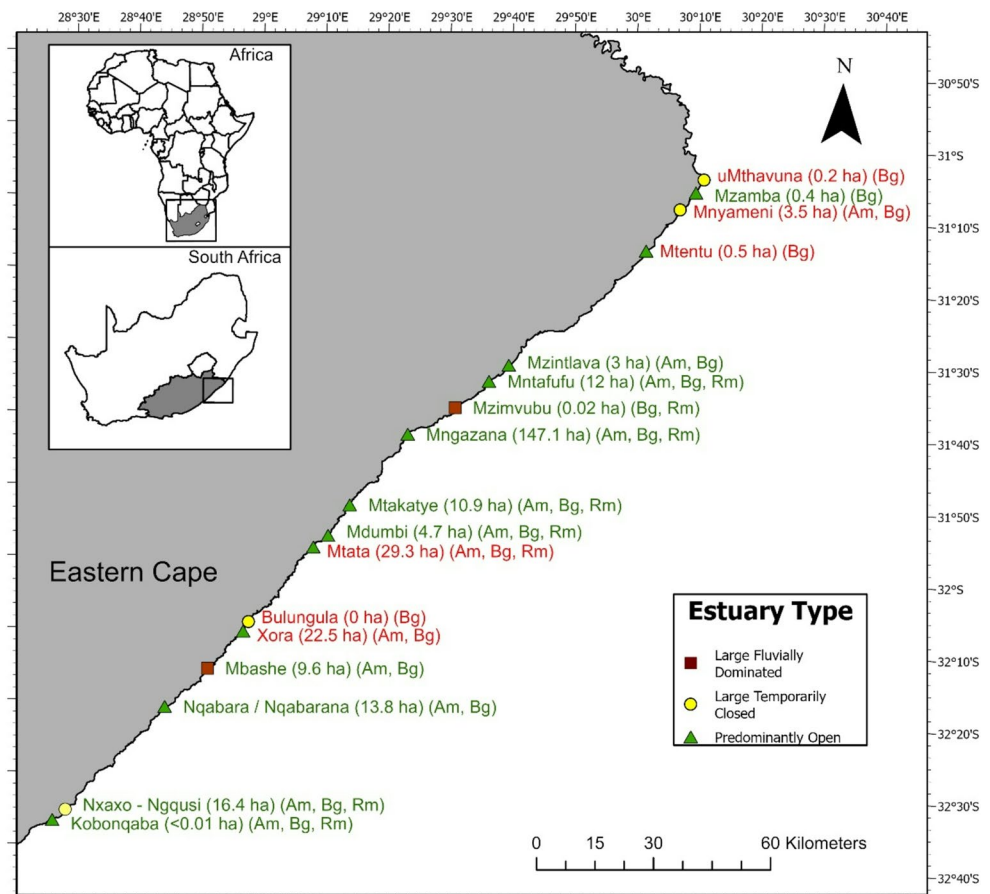
Mangroves in South Africa occur along the eastern coastline in the tropical, subtropical, and temperate bioregions from Kosi Bay in the north 26°53' S; 32°52' E to Tyolomnqa Estuary (which is a planted site) in the south (32°59' S; 27°57' E), with a total cover of ~2 300 ha (Riddin et al. 2024). The southernmost natural limit of mangroves is at the Kobonqaba Estuary (32°36' S, 28°29' E) however, planting of mangroves took place in 1969 at the Nahoon Estuary (32°59' S, 27°57' E) located 60 km south of Kobonqaba Estuary and has since been expanding at a rate of 0.06 ha y^{-1} from just 0.075 ha in 1969 to 1.62 ha in 2015, indicating that temperature is not the primary limiting factor for mangrove distribution and future expansion (Hoppe-Speer et al. 2014). Instead, future changes in mangrove distribution will be driven by propagule dispersal, near-shore currents, and intermittent connectivity between mangrove estuaries (Raw et al. 2023a). The five mangrove species found in South Africa include *Avicennia marina* (Forsk.) Vierh, *Bruguiera gymnorhiza* (L.) Lam, *Rhizophora mucronata* Lam., *Ceriops tagal* (Perr.) CB Robb and *Lumnitzera racemosa* Willd. Only *C. tagal* and *L. racemosa* are found in Kosi Bay where the transitional zone into the tropical bioregion occurs (Peer et al. 2018). *Avicennia marina* is the pioneer species in South Africa as its distribution occurs from the Eastern Cape (32°36' S, 28°29' E) to KwaZulu-Natal

(26°53' S, 32°52' E). The focus of our study was the Eastern Cape Province where mangroves occur from warm temperate to subtropical regions as narrow fringing estuarine habitats (Fig. 1).

Mangroves in South Africa occur mostly in estuaries that are predominantly open where there is freshwater input from river inflow and protection from the high-energy coastline. The smallest mangrove areas are found in large temporarily closed (formed by sandbars across their mouths) and large fluvially dominated (small tidal prisms from strong river flows) estuaries because of their small intertidal area (Adams and Rajkaran 2020). Small temporarily closed estuaries typically have only one mangrove species, mainly *B. gymnorhiza* which has a higher tolerance to prolonged inundation in estuaries that frequently close to the sea (Hoppe-Speer et al. 2011).

There has been a net decline in the global mangrove extent as a result of natural and anthropogenic pressures between 1996 and 2020 from 152 604 km² to 147 359 km²; an annual loss of 390 km² (Bunting et al. 2022). Anthropogenic activities have been the dominant cause of mangrove loss together with threats from climate change and rising sea levels (Bunting et al. 2022). In South Africa mangroves face various pressures such as footpaths and trampling from humans and livestock, livestock browsing and disturbance

Fig. 1 Distribution and extent (ha) of mangroves in 17 estuaries of the Eastern Cape province, South Africa in 2021. Estuary type is shown. Red indicates a decrease in mangrove area and green indicates an increase in mangrove area between 2011 and 2021. Species present at each estuary are shown (Av=*Avicennia marina*, Bg=*Bruguiera gymnorhiza* and Rm=*Rhizophora mucronata*)



from adjacent agricultural land (Hoppe-Speer et al. 2014; Adams et al. 2020). Harvesting of wood material also changes the population structure and extent of the mangrove forest (Rajkaran and Adams 2010). Mangrove wood material is mainly used for making houses and animal shelters. Pollution and agricultural activities have been associated with areas that are highly populated and negatively influence mangrove health (Naidoo 2023). The assessment of mangrove degradation can use a framework to evaluate the current state of a particular system, relate this to a reference system, identify the key drivers that lead to this degradation and provide insight into areas where restoration efforts can take place (Yando et al. 2021). Site specific data such as that measured in this study are needed to inform this. For example, the adult-to-seedling ratio provides an indication of forest recruitment and health (Rajkaran et al. 2009).

The loss of mangroves from mouth closure, floods and changing salinity conditions has been reported for several estuaries globally (Lovelock et al. 2017; Asbridge et al. 2019) and in South Africa (Rajkaran and Adams 2010; Hoppe-Speer et al. 2014; Adams and Human 2016; Taylor 2016). Future events related to climate change such as rising sea levels and increased precipitation will all assist with maintaining open mouth conditions allowing for tidal conditions to persist, a requirement for mangrove occurrence. However, sea storms will increase marine sediment deposition and could increase incidences of mouth closure (Adams and Rajkaran 2020). There is a high demand for freshwater for urban and agricultural uses as South Africa is a semi-arid country, and as such many of the smaller estuaries are also closing more frequently through anthropogenic freshwater abstraction (Adams and Van Niekerk 2020). During periods of inundation and flooding, death of mangroves occurs along seaward margins and shifts in species composition to those that have a higher tolerance to inundation and salinity occurs (Krauss et al. 2014). Because of these threats, the status of the Agulhas mangrove ecosystem in South Africa was assessed as Endangered (EN) (Riddin et al. 2024).

The aim of this study was to identify mangrove changes in response to natural and anthropogenic pressures in 17 estuaries along the Eastern Cape coastline of South Africa over a ten-year period. This was done by first quantifying spatial and temporal changes in mangrove area cover between 2011 and 2021 as there was a lack of structured monitoring of these mangrove forests over that time span. Secondly, species composition in mangrove forests and population structure was measured. Finally, the effects of anthropogenic and natural pressures on mangrove habitat were assessed to identify specific pressures negatively impacting mangrove habitats. This information is important as mangroves in South Africa have a limited distribution and are under constant change in response to anthropogenic and

natural pressures. This research informs site specific management, potential restoration strategies, and global mangrove responses at a range limit. Because of their patchy distribution, global studies mapping mangroves at poleward range limits need field data to accurately identify distribution (Ximenes et al. 2023). Some expansion of mangrove into salt marsh habitat was expected due to the warming climate.

Methods and Materials

Distribution and Mapping

Mangrove habitats of 17 estuaries between uMthavuna and Kobonqaba (Fig. 1) were digitized using ESRI ARCGIS Pro (2020) software, orthorectified images from the Chief Directorate: National Geo-Spatial Information (CD: NGI, 2015 images with 50 cm resolution; source: <http://www.cdnigiportal.co.za/cdnigiportal/>) and Google Earth images (30 m resolution). These are all the estuaries that have mangroves along this section of coastline and were previously studied by Hoppe-Speer et al. (2014). Therefore, historical data were available for extent (mangrove cover in 2011), population structure and anthropogenic pressures.

Mapping was completed for the Estuarine Functional Zone which considers all habitats that lie below the 5 m contour line above mean sea level (Riddin et al. 2024). For mangrove habitats, only intact canopies were mapped and bare ground was excluded. Canopy gaps defined as discrete or circular holes in the canopy caused by multiple death of individual trees whether standing or have fallen were not included in the total mangrove area (Amir and Duke 2019). Field surveys and ground-truthing was conducted between August and December 2021 using handheld GPS and Google Earth images to update and modify the 2021 area for mangrove forests. The percentage change was done by comparing the difference in mangrove extent between 2012 and 2021. Manual digitizing and aerial drone imagery were used to delineate vegetation transition zones following the ground-truthing due to the patchy and fragmented nature of mangrove forests in this region. These mapping data are then integrated with the South African National vegetation layer curated by the South African National Biodiversity Institute to be used in the National Biodiversity Assessment. All GIS data is available at <http://bgis.sanbi.org/Projects/Detail/192>.

Population Structure

To measure population structure, transects were placed in intact mangrove stands from the water edge to the upper

intertidal zone. If the total mangrove area was less than 5 ha (Fig. 1), one transect was placed through the largest stand with three quadrats 25 m² (total of 75 m²) measured. If mangrove cover was more than 5 ha (Fig. 1), three transects were placed each with three quadrats 25 m² (total of 225 m²). Transects varied in length depending on the size of the intertidal zone. To examine the population structure, the height of each mangrove tree was measured in each quadrat and categorised into three different size classes: seedlings (<50 cm), saplings (51–129 cm) and adults (>130 cm). These size classes were selected for comparative purposes with Hoppe-Speer et al. (2014). The circumference of all adult trees was measured at circumference breast height (CBH) (1.3 m) and then converted to diameter at breast height (DBH) using the following equation:

$$DBH = \frac{CBH}{\pi}$$

In estuaries with sparse mangrove distribution, all mangrove individuals were measured for height and DBH. The adult-to-seedling ratio was determined to provide an indication of forest recruitment and health (Rajkaran et al. 2009). Population structure for mangroves in each estuary is shown in Supplementary Tables 1 and 2.

Anthropogenic Pressures

The percentage occurrence of pressures in all 17 estuaries was used to identify which impacts were dominant (Table 1). In each estuary, an impact score was assigned according to the extent of mangroves that were influenced by that pressure (Table 2). Natural pressures included records of changes in rainfall and weather patterns, flood events, droughts, mouth

Table 1 Description of human pressures that were used to determine the state of the mangroves (adapted from Hoppe-Speer et al., 2014)

Anthropogenic Impacts	Descriptions
Agriculture	Freshly ploughed, cultivated fields behind mangrove forests or along the banks.
Footpaths & trampling	Paths and breaks in vegetation created by harvesters and cattle moving through the mangroves leaving it bare and unvegetated. Recreational paths and paths to fishing spots.
Livestock browsing	Recorded where animals were seen in the mangroves namely cattle, goats and sheep. Evidence of animal tracks, distinct browsing lines and browsed stunted mangroves present.
Wood harvesting	Visible tree stumps in the mangrove forest with clear saw cuts. Presence of harvested trees in heaps or bundles. The number of stumps were counted if they were present in quadrats.
Pollution	Litter and plastic pollution in or around the mangrove stands

Table 2 Impact score for human pressures based on the percentage of the mangrove forest affected by the pressure

Impact score	Percentage of estuary area influenced
1	<5%
2	5–20%
3	21–40%
4	41–60%
5	61–80%
6	>81%

state and evidence of sediment deposition. The results from this survey were then compared to findings from 2011 (Hoppe-Speer et al. 2014). Where mangrove harvesting was evident, the harvesting intensity was determined by setting out three replicate quadrats (25 m²) in areas that showed signs of harvesting. These sites were identified by the presence of tree stumps, saw marks on trees and already harvested stockpiles. In each quadrat the number of adults and stumps were counted to determine the harvesting intensity and the regeneration potential of the site. Low harvesting intensity had a ratio of adults to stumps of 2:1 indicative of a higher number of adults and low harvesting, medium intensity of 1:1 was indicative of an equal ratio. Lastly a ratio of 1:2 was high harvesting intensity indicative of a fewer number of adult trees to tree stumps, significant disturbance and a low regeneration potential (Rajkaran et al. 2004; Rajkaran and Adams 2010).

Results

Distribution and Mapping

In 2021, mangroves were present in 16 of the 17 estuaries sampled (Fig. 1). Total mangrove area cover increased in 59% (10 estuaries) of the estuaries and decreased in 41% (7 estuaries) of the estuaries between 2011 and 2021 (Table 3). The mangrove area cover in 2021 was ~274 ha, a net increase of 3 ha since 2011. Natural regeneration of mangroves took place at Mzamba, Mntafufu, Mzimvubu, Mdumbi, Mbashe and Kobonqaba estuaries. New mangrove individuals and stands developed in areas previously covered by salt marsh vegetation such as at Mbashe Estuary (supplementary Fig. 1). At Mdumbi Estuary an increase in mangrove cover occurred along the margins of the intertidal island from sedimentation, shallowing and mangrove colonization (Fig. 1).

Mangrove cover decreased in seven estuaries between 2011 and 2021: uMthavuna (79%), Mnyameni (26%), Mtentu (7%), Mzimvubu (33%), Mtata (5%), Bulungula (100%) and Xora (12%). At Mzamba Estuary, a small stand of approximately 50 dead *B. gymnorrhiza* individuals were found along the landward edge adjacent to *Juncus*

Table 3 Mangrove extent and the percentage change in area between 2011 (Hoppe-Speer et al. 2014) and 2021. Shaded rows indicate those estuaries where there was a decrease in mangrove area. Mangrove tree species present are shown; Av=*Avicennia marina*, Bg=*Bruguiera gymnorhiza* and Rm=*Rhizophora mucronata*. * Kobonqaba Estuary had an increase in the number of individuals following dieback in 2008

uMthavuna	2011 Extent (ha)	2021 Extent (ha)	Percent- age change (%)	Tree Species
	1	0.21	-79.2	Bg
Mzamba	0.27	0.36	34.9	Bg
Mnyanemi	4.72	3.5	-25.8	Am, Bg
Mtentu	0.57	0.53	-6.8	Bg
Mzintlava	1.7	3.01	76.9	Am, Bg
Mntafufu	11.9	12	0.6	Am, Bg, Rm
Mzimvubu	0.03	0.02	-33.3	Bg, Rm
Mngazana	145	147	1.4	Am, Bg, Rm
Mtakatye	9.94	10.9	9.3	Am, Bg, Rm
Mdumbi	4.66	4.7	0.9	Am, Bg, Rm
Mtata	30.94	29.3	-5.4	Am, Bg, Rm
Bulungula	0.014	0	-100	-
Xora	25.5	22.5	-11.8	Am, Bg
Mbashe	9	9.6	4.5	Am, Bg
Nqabara/Nqabarana	11.8	13.84	17.3	Am, Bg
Nxaxo/Ngqusi	9.5	16.4	72.1	Am, Bg, Rm
Kobonqaba	0	<0.01	*	Am, Bg, Rm
TOTAL	270.04	273.8		

kraussii; there was a net increase in total mangrove area between 2011 and 2021. Areas of dieback of (*A*) *marina* and (*B*) *gymnorhiza* at Mnyanemi Estuary covered an area of 0.6 ha (17% of the total area) and complete dieback of *A. marina* occurred at Bulungula Estuary.

Estuaries that had notable canopy gaps because of anthropogenic pressures were Mngazana, Mzintlava, Mtata and Nxaxo/Ngqusi (Supplementary Fig. 2). At Mdumbi Estuary, canopy gaps were a result of the wider dispersal of individual trees. Footpaths were present in these areas and through the salt marsh vegetation (Supplementary Fig. 2).

Mangrove Species Composition and Population Structure

Bruguiera gymnorhiza was found at all the sampled estuaries and the only species present in four small temporarily closed estuaries (uMthavuna, Mtentu, Mzamba and Mzintlava estuaries) (Fig. 1). *Avicennia marina* was not present in the northern estuaries of the Eastern Cape at uMthavuna, Mzamba and Mtentu. Large *R. mucronata* stands were only found at Mngazana Estuary and sparsely distributed individual in seven other estuaries. *Avicennia marina* has not been present at Mzimvubu and Bulungula estuaries since 2011.

Anthropogenic pressures were different for each mangrove species (Table 4). Wood harvesting occurred more

frequently for *B. gymnorhiza* than for (*A*) *marina*. High intensity wood harvesting resulted in the loss of canopy cover, density, and a secondary effect was the visible compaction of sediment within the vicinity of the mangroves. Estuaries that were dominated by (*B*) *gymnorhiza* had a higher harvesting intensity and this was evident by the lack of certain DBH size classes. Livestock browsing on adults of *A. marina* resulted in stunted growth (Fig. 3) and the formation of canopy gaps while browsing on *A. marina* caused the loss of mangrove propagules (Table 4, Supplementary Fig. 2). Large estuaries such as Mtata, Mngazana, Nqabara and Xora had a high number of pressures impacting the mangrove forests (Tables 4 and 5), resulting in the formation of canopy gaps and a low density of seedlings and saplings (Supplementary Tables 1 and 2, Supplementary Fig. 2).

Changes in Anthropogenic Pressures Between 2011 and 2021

There has been an increase in the occurrence of footpaths and trampling, livestock browsing and plastic pollution since 2011 (Fig. 2; Table 5). The pressure of wood harvesting remained the same (70%) between 2011 and 2021 while agricultural pressures decreased by 5% from 2011 to 2021 (Fig. 2). Field surveys at Mngazana, Mtata and Xora estuaries showed a loss of mangrove cover and density in areas where wood harvesting, and livestock browsing took place (Figs. 3 and 4). The presence of saw marks on trees stumps and wood bundles were used as indicators for harvesting intensity and varied between species. *Bruguiera gymnorhiza* and *R. mucronata* were the favoured species for wood harvesting in multiple estuaries.

Bruguiera gymnorhiza was harvested at eight out of the 17 estuaries and high intensity harvesting took place at five large estuaries: Mngazana, Mtata, Mzintlava, Mntafufu and Xora. Intensive harvesting of *R. mucronata* took place at Mngazana Estuary and along the creeks at Mtata Estuary (Fig. 4). Harvesting of *A. marina* was moderate to low, with the trees at Bulungula and Kobonqaba estuaries only harvested after they had died from stress due to prolonged inundation and flooding. Footpaths and trampling from livestock and human activities were evident in most estuaries and had the highest occurrence (94%) in all estuaries sampled followed by livestock browsing (82%). These pathways through mangrove stands were present in areas where livestock browsing, and wood harvesting took place. *Avicennia marina* was the preferred species browsed by livestock and showed signs of stunted growth (Fig. 3). The five mangrove stands most affected by livestock browsing (cattle, sheep and goats) were at Mtata, Mntafufu, Nxaxo/Ngqusi, Nqabara/Nqabarana and Xora estuaries (Table 5). Large areas of agricultural or cultivated land were found

Table 4 Summary of the pressures, mangrove extent and population structure in 2021. Ratios in the pressure's column are indicative of the adult trees to harvested stumps as a measure of harvesting intensity. The ratios in the population structure column indicate adult trees to seedlings. Additional detail on the population structure can be found in the Supplementary Material

Estuary	Pressures & mangrove extent	Population structure of <i>Avicennia marina</i> Adults: seedlings	Population structure of <i>Bruguiera gymnorhiza</i> Adults: seedlings
Mnyameni	Harvesting and mouth closure. Dieback from sediment deposition.	Scattered individuals with low seedling density. 1:1	No seedlings
Mzintlava	Harvesting of <i>B. gymnorhiza</i> (1:1). Canopy gaps, loss of density.	Scattered adult individuals. No seedlings or saplings.	Low density of adults, seedlings and saplings 1:3
Mntafufu	Livestock browsing, harvesting and trampling.	Low sapling density 1:6	High adult density but low seedlings & sapling density. 1:2
Mngazana	Livestock browsing, mangrove harvesting (1:1 for <i>A. marina</i>). Canopy gaps, loss of cover & density.	Low adult density 1:6	Pressure from wood harvesting 2:1
Mtakatye	Loss of mangrove cover and density. Harvesting of <i>B. gymnorhiza</i> , livestock browsing.	Low sapling and adult density 1:7	Low sapling and adult density 1:4
Mdumbi	Canopy gaps and dry sandy sediment. Increase in mangrove cover on isolated island.	No saplings present 1:4	Three adults present, with seedlings, no saplings.
Mtata	Livestock browsing, footpaths and trampling. Harvesting ratio of 3:1 for (<i>A. marina</i> and 1:2 for (<i>B. gymnorhiza</i> and <i>R. mucronata</i> combined. Canopy gaps, loss of cover & density.	Low sapling density 1:3	
Bulungula	Loss due to mouth closure & flooding.	No adults or juveniles present	One adult in the middle reaches of estuary
Xora	Livestock browsing. Harvesting & canopy gaps. Loss of mangrove cover & density.	Stands are in different states. Seedlings and saplings absent on Eastern Bank. On Island, low density of adults and saplings. 1:14	Low adult density. 1:2
Mbashe	Livestock browsing. Increase in <i>A. marina</i> area on the western bank following dieback in 2012.	Low sapling density 2:1	
Nqabara	Livestock browsing, wood harvesting, footpaths and trampling.	Low sapling density 2:1	
Nxaxo/Ngqusi	Livestock browsing. Canopy gaps from harvesting and footpaths. Increase in area on protected island.	Low density of saplings and adults. 1:6	Low density of seedlings and saplings. 9:1

adjacent to mangrove stands at Mngazana, Mtata, Xora and Nqabara/Nqabarana estuaries.

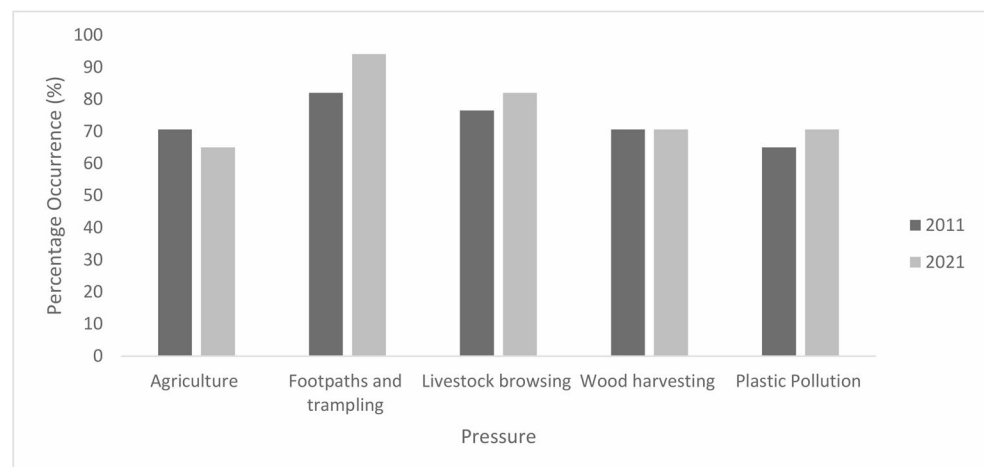
Discussion

Mangroves in South Africa occur at the south-easternmost African distribution limit providing an opportunity to study mangrove response to changes at their distributional range limits where these trees are at the edge of their climatic or ecological tolerance (Quisthoudt et al. 2013; Whitfield et al.

2016). The results from our study for 17 estuaries showed dynamic changes in mangrove forest area within a decade and the persistence of anthropogenic pressures. Whilst there has been a small increase in mangrove area overall, the percentage occurrence and severity of pressures on mangrove forests has remained high and resulted in localized degradation. The results from this study indicated functional declines in several estuaries such as the loss of regeneration capacity (lack of saplings), occurrence of canopy gaps (associated with dry, saline sediment), and changes in population structure (Rajkaran and Adams 2010; Amir and Duke

Table 5 Quantification of pressures (impact scores, see Table 2) for mangroves in each of the estuaries sampled comparing 2011 with 2021 (shaded blocks)

Estuary	Agriculture		Footpaths and trampling		Livestock browsing		Wood harvesting		Pollution	
	2011	2021	2011	2021	2011	2021	2011	2021	2011	2021
uMthavuna				1						1
Mnyameni	2	2	1	3		1	4	4	1	1
Mntafufu	3	3	3	4	1	2	4	3	1	1
Mngazana	2	2	4	4	1	5	5	6		1
Mtata	3	3	3	5	5	6	5	6		3
Xora	2	2	4	4	4	3	4	5	1	4
Nqabara	2	1	3	3	4	1	4	3		
Nxaxo		2	5	4	5	2	4	4		2
Mzamba	2	2	2	1	2		4		1	1
Mtentu	3		2	1			3		2	1
Mzintlava	3	2	2		2			3	2	
Mtakatye		1	3		3	3	3	3	2	2
Mdumbi	3	3	3	2	5	3	4	3	3	
Mbashe				1		2		1		1
Mzimvubu	3		3	1	3	1			4	1
Bulungula	5	5	3	2	5		5	5	2	
Kobonqaba				2	2	2		5		1

Fig. 2 Percentage occurrence of anthropogenic pressures in 17 estuaries with mangroves in 2021

2019). *Bruguiera gymnorrhiza* was the only mangrove tree species found in all estuaries, while *A. marina* occurred in 71% and *R. mucronata* in 47% of the estuaries. *Bruguiera gymnorrhiza* was the dominant species in smaller estuaries (<5 ha) and often occurred as individual trees. *Rhizophora mucronata* occurred as stands at three estuaries (Mngazana, Mtakatye and Mntafufu estuaries) and was present as scattered individuals at an additional six estuaries. Mtentu, Mzamba, Mnyameni and Mzintlava estuaries had the highest density of *(B) gymnorrhiza* and the density of adults was higher than the seedlings.

Population Structure

Five of the mangrove forests (Mntafufu, Mdumbi, Mtakatye, Mtata and Mdumbi) were in a degraded state as indicated by the numerous pressures and the low mangrove adult to

seedling ratios which represented a fair regenerative capacity as there were a greater number of adults than seedling thus showing declining recruitment capacity (Table 4). Density of seedlings and saplings was low with only large old *A. marina* adults but no juveniles indicating a lack of recruitment (Rajkaran and Adams, 2009, 2010). In 2011, 35% of all sampled estuaries had low seedling and sapling density (Hoppe-Speer et al. 2014). In 2021, sapling density was low for all estuaries but there was high seedling density at five large estuaries, Mntafufu, Mdumbi, Mtata, Mbashe and Nqabara for *A. marina*. Seedlings mostly occurred directly below the canopy of the adult (mother) tree as a mechanism to protect against predation, erosion, and sedimentation (Nicolau et al. 2017).

Avicennia marina mostly occurred as tall sparsely distributed individuals in impacted forests. The main pressures on *(A) marina* were from cattle browsing followed by wood

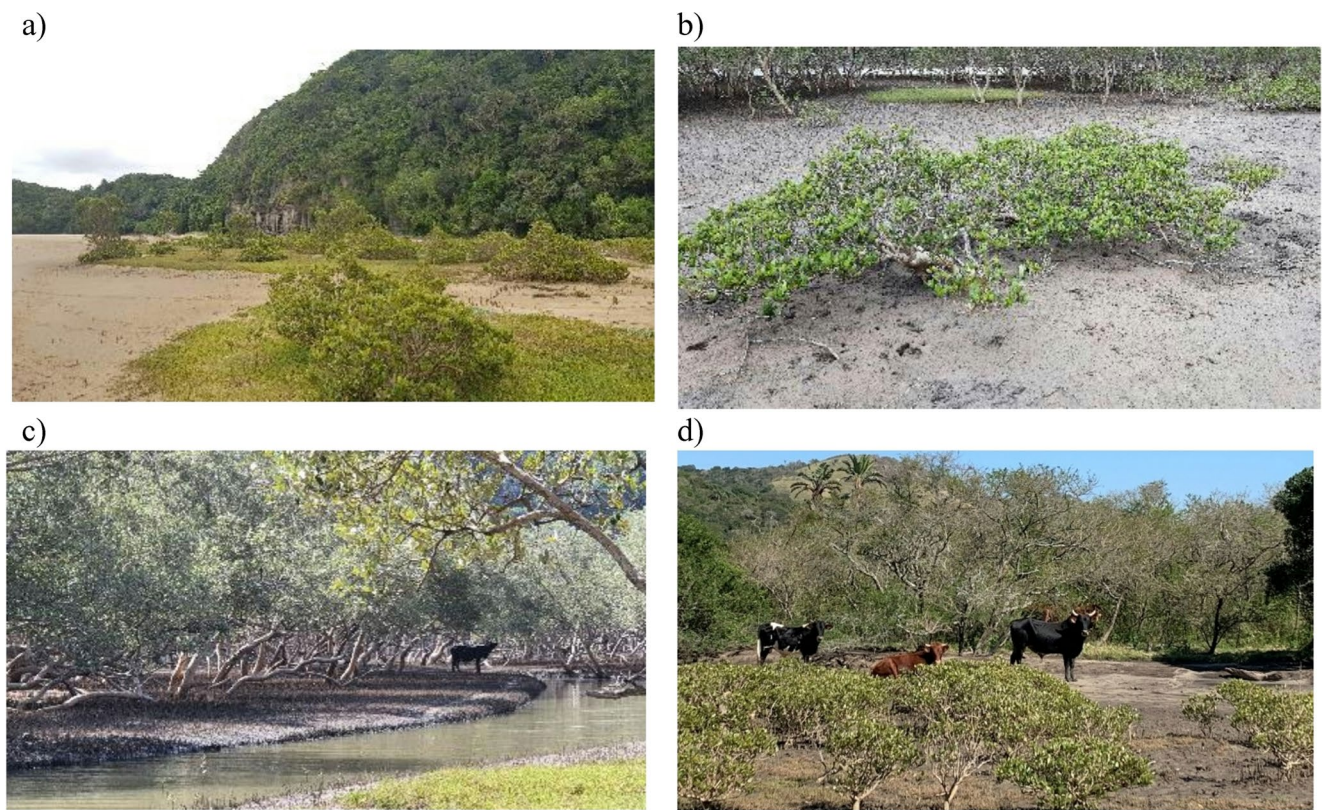


Fig. 3 Photo (a) and (b) are dwarf *Avicennia marina* trees at Nqabara Estuary, Photo (c) shows a cow browsing on an *A. marina* stand in the lower reaches of Mtata Estuary and Photo (d) cows and dwarf *A. marina* individuals in the lower reaches at Mntafufu Estuary

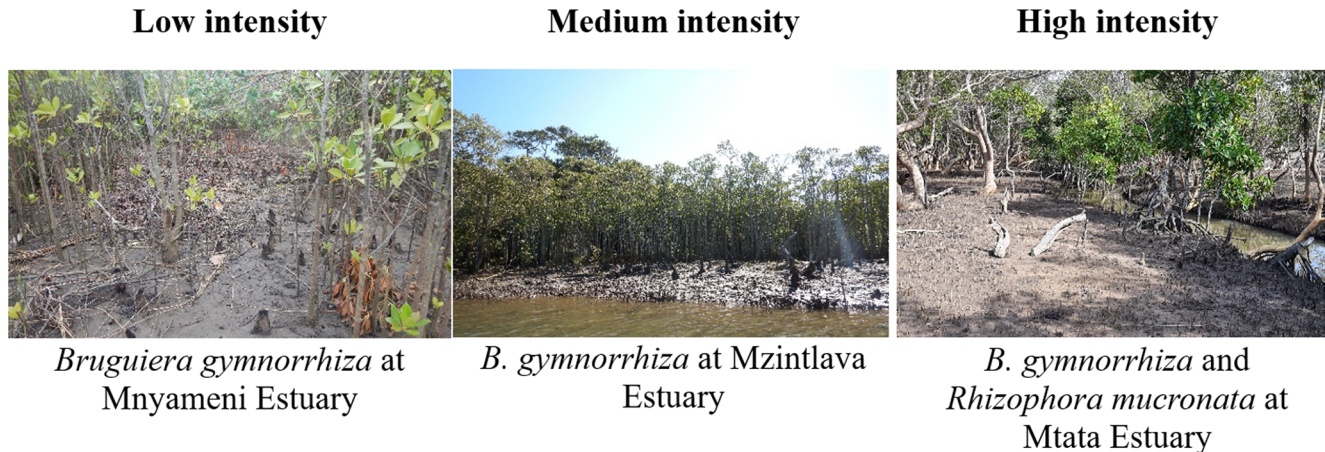


Fig. 4 Mangrove wood harvesting intensity based on the ratio of tree stumps to adult mangrove trees. Low harvesting intensity had a ratio of stumps to adults of 2:1, medium intensity 1:1 and, high intensity 1:2

harvesting. *Avicennia marina* showed signs of stunted growth because of browsing pressures as their leaves and propagules were eaten by cattle and goats (Fig. 3). Estuaries that only had (*B. gymnorhiza*) stands had low seedling to sapling density and this was also observed in the 2011 study at these estuaries. The loss of mangrove cover, and density coincided with areas where wood harvesting and livestock browsing

took place. The absence of saplings indicated that estuary environmental conditions such as dynamic mud banks, low sediment moisture and high salinity does not favour growth and persistence of seedlings and saplings (Hoppe-Speer et al. 2014). Future research needs to investigate the reasons for low survival of seedlings to saplings and the effects of predation by herbivores and crabs (Barnuevo et al. 2017).

Changes in Anthropogenic Pressures

Wood harvesting and cattle browsing have remained high and persistent in all estuaries since the last survey completed in 2011 (Hoppe-Speer et al. 2014). This has impacted the density and population structure of mangrove forests, particularly for the two main species (*A. marina* and *B. gymnorrhiza*). Our field observations indicated that selective harvesting of *B. gymnorrhiza* resulted in patches of trees with a small DBH-size class and trees of a similar height, indicative of large recruitment events following a disturbance. The harvesting of whole trees was present at 65% of the estuaries leading to the formation of canopy gaps. The most intense harvesting of *R. mucronata* and *B. gymnorrhiza* took place at Mngazana and Mtata estuaries. Harvesting of *R. mucronata* at Mngazana Estuary was concentrated in the two sheltered creeks that had a high density of this species. Stockpiles of harvested wood were measured and showed that *R. mucronata* and *B. gymnorrhiza* poles were all greater than 4 m in length with a mean DBH of 6.5 cm ($N=14$) compared with stockpiles of *B. gymnorrhiza* trees at Xora Estuary that were 2.2 m in length (Fig. 5). Piles of harvested mangrove poles were also found at Mntafufu, Mngazana, Mtata and Xhora estuaries. *Avicennia marina* was also harvested at many estuaries (Mngazana, Mtata, Nqabara, Mbashe, Bulungula

and Kobonqaba) but for firewood not for construction poles. This is a common use elsewhere where it has been shown that rural and urban communities make use of mangroves as sources of firewood and charcoal (Bandaranayake 1998; Din et al. 2008). Approximately 51 000 ha of mangroves were lost due to mixed anthropogenic activities such as wood harvesting (mainly used as a source of fuel) between 1980 and 2006 in seven West Central African countries (Feka and Ajonina 2011). The loss of mangroves was a combination of commercial and subsistence, however commercial use of these forests was the most prevalent use. Along the Eastern African region, the increase in human population has increased the demand for mangrove as a resource for coastal communities (Naidoo 2023).

Areas where livestock browsing took place showed signs of trampling of mangrove pneumatophores, lower tree density and changes in morphology as reported in the global synthesis on consumer controls in coastal wetland vegetation by He and Silliman (2016). The changes in tree morphology were indicative of the height at which livestock consumed mangrove leaves, taking place on the lower branches (Minchinton et al. 2019). Field observations from this study showed a distinctive browse line and stunted *A. marina* trees in estuaries with large mangrove areas (Nqabara, Mtata, Nxaxo and Mtakatye) particularly in the upper intertidal zones (Fig. 3) similarly reported by Adams and Rajkaran (2020).

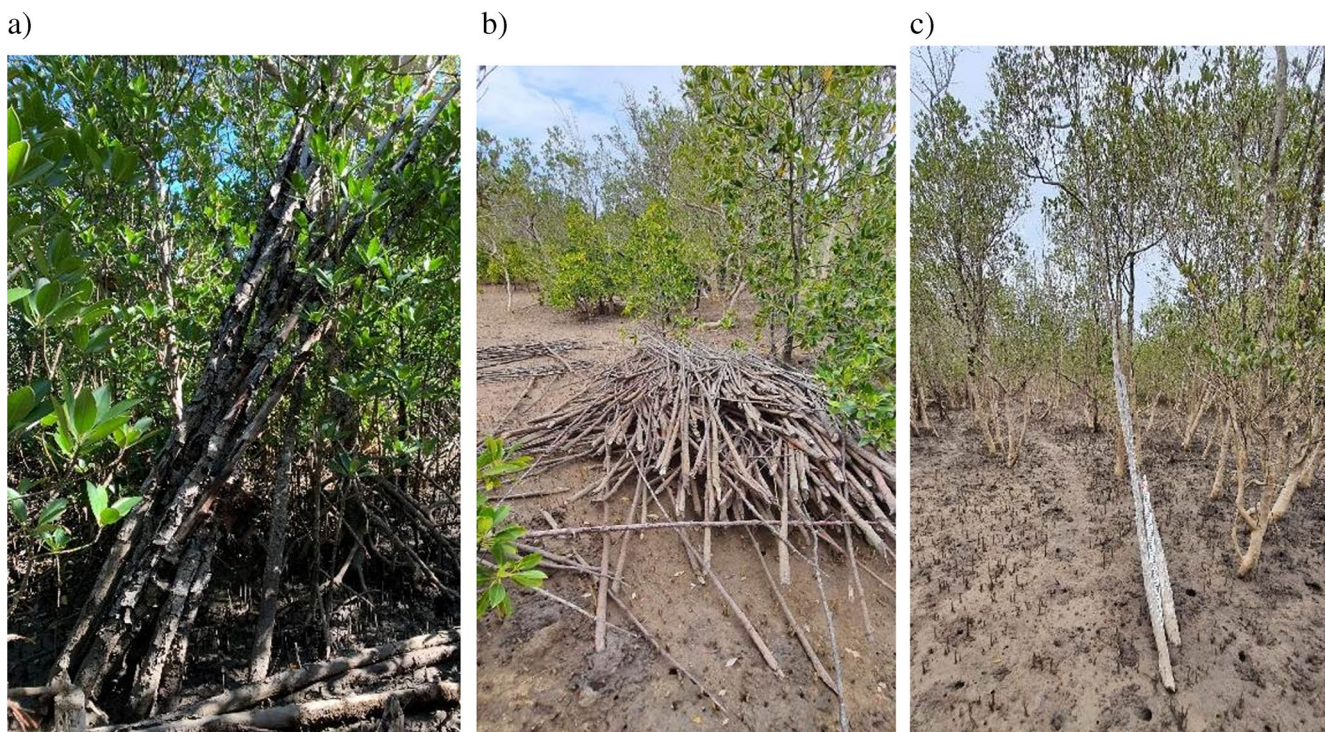


Fig. 5 (a) Harvested *Rhizophora mucronata* poles at Mngazana Estuary, (b) one of two large stockpiles of *Bruguiera gymnorrhiza* poles at Xora Estuary and (c) *Avicennia marina* poles in the lower reaches of Nqabara/Nqabarana Estuary

Geomorphological Drivers

Sedimentation has been a driver of mangrove expansion since 2011 at the Mdumbi, Mbashe, Nxaxo and Kobonqaba estuaries by increasing available habitat for mangrove growth. An increase in sediment delivery combined with increased rainfall has been shown globally to promote mangrove growth, productivity, and expansion (Friess et al. 2022). The increase in mangrove cover at Mbashe Estuary (Supplementary Fig. 1) and the slow increase in the number of individuals at Kobonqaba Estuary were a result of mangrove recovery following dieback in 2008 and 2012 (Mbense et al. 2016).

In estuaries such as Kobonqaba, salt marsh replaced mangrove habitats following dieback (Mbense et al. 2016) whilst global climate change predictions such as temperature increase show poleward migration of mangroves at the expense of salt marsh vegetation because of interspecific competition (Saintilan et al. 2014; Adams and Rajkaran 2020). Mangrove expansion into salt marsh areas has been used as an indicator of global warming (Friess et al. 2022) and continuous monitoring is needed along the South African coastline to track changes. Mangrove expansion into salt marsh poses a threat to salt marsh conservation because of coastal squeeze and the lack of intertidal habitat available for landward migration.

Complete dieback of mangroves at Bulungula Estuary occurred from high water levels within the estuary, due to the mouth of the estuary closing to the sea (Adams et al. 2004), resulting in the long-term inundation and flooding of *A. marina*. The dead *A. marina* trees had adventitious roots; a clear indication of inundation stress and anoxia (Naidoo et al. 2010). Similar processes are described for the east coast of Australia where Asbridge et al. (2024) reported dieback of mangroves at Cabbage Tree Basin following a sea storm, mouth closure and flooding of mangroves for 3 months. Dead trees at Bulungula Estuary were subsequently harvested for firewood by the surrounding communities. The loss of mangroves at Kobonqaba Estuary occurred following mouth closure, water abstraction and reduced freshwater input (Mbense et al. 2016). Mouth closure resulted in estuary water levels increasing and long-term flooding and inundation of *A. marina* pneumatophores led to the loss of 95% of the mangroves. Following dieback, a shift from mangrove vegetation to mudflats over a five-year period allowed for colonization of salt marsh vegetation (Mbense et al. 2016). These results highlight the need for species-specific physiology and tolerance studies, to validate or inform distribution models, essential for mangrove management (Vervaeke et al. 2025). This is especially true considering that under climate change conditions, it has been suggested that 30% of South African estuaries are at risk of marine sediment

deposition and back-flooding of mangrove stands (Raw et al. 2023a).

Feasibility of Manual Digitizing for Monitoring

We used heads-up/manual digitizing in this study because of the small mangrove extent; mapping of these narrow fringing mangrove forests using satellite images can underrepresent the true area (Suyadi et al. 2018; West et al. 2025). GIS and remote sensing can be used to provide details on the state of mangrove forests as a relatively low cost (Dahdouh-Guebas et al. 2020). However, coarse satellite images (such as Landsat) show an underestimation of mangrove extent in estuaries with small, narrow and fragmented mangrove stands, as observed in the Agulhas province, South Africa (Riddin et al. 2024) and are unable to capture canopy details (Kirui et al. 2013; van Deventer et al. 2025). Due to the smaller fragmented nature of mangroves in South Africa, on-site field assessments and GPS surveys, are far more accurate at describing the condition of mangroves. Reyes et al. (2024) also reported that fragmented small mangrove areas in urban environments were missed by large-scale mapping efforts. Drone aerial drone images allowed us to map mangrove areas that were difficult to access. The use of drones as a mangrove mapping and monitoring tool needs further investigation in South Africa. However, this too needs to be combined with detailed fieldwork; similar measurements to those completed in 2011 and 2021 in the 17 estuaries should be repeated in 2031. This research has provided a unique dataset of mangrove changes at a global range limit.

Remote sensing methods that integrate Hyperspectral Image (HSI) technology and Deep Learning (DL) algorithms (Ilamathi and Chidambaram 2025) may be useful for consistent and frequent monitoring followed by field surveys and ground truthing (Altamirano & Primavera, 2010; Maurya et al. 2021). HSI allows for a more detailed analysis of mangrove tree health, species types and environmental stress factors (including salinity levels, waterlogging, soil erosion, pollution, habitat fragmentation, disturbances from human activities). DL algorithms can be used to detect change in mangrove health and provide estimates of carbon sequestration (Ilamathi and Chidambaram 2025). This is particularly relevant near the range limits of mangroves where abrupt, frequent and intense changes can occur (Bardou et al. 2023) and thus relevant to the monitoring of mangroves in South Africa. A suitable long-term approach for mapping habitat changes in South African estuaries would probably be like that used for New South Wales estuaries, Australia (West et al. 2025) where a combination of aerial photography, Object-Based Image Analysis and Deep Learning is used to map changes in the patchy and narrow

fringing habitats which is typical for the distribution of salt marshes and mangroves.

Nationally and globally, it is important to continue conserving, managing, and restoring mangrove habitats as they provide ecosystem services such as carbon storage, support unique faunal assemblages and high biodiversity (Raw et al. 2023b). Disturbances must be limited and restoration prioritized as mangrove ecosystems change from carbon sinks to sources when disturbed (Sasmito et al. 2019). Livestock browsing should be discouraged through fencing of mangrove areas to prevent further degradation and allow for increased growth and establishment of seedlings and saplings (Hoppe-Speer et al. 2014). Conservation of mangrove habitats must include the monitoring of freshwater flow into estuaries so that freshwater abstraction upstream can be limited, reducing the likelihood of mouth closures and allowing for natural regeneration to take place. Future responses to El Niño-Southern Oscillation (ENSO) events also require investigation as the low rainfall and increased temperature lead to mangrove dieback in Australia (Lovelock et al. 2017; Asbridge et al. 2019). Mangroves located at a range limit are expected to be especially sensitive to climate change. Higher temperatures and an increase in CO₂ will allow for expansion of mangroves poleward, however this will depend on successful propagule dispersal between estuaries and if there are suitable intertidal habitats available for mangrove colonisation (Raw et al. 2023a). The fragmented distribution of mangroves along this coastline will hinder the natural migration and limit future resilience (Adams and Rajkaran 2020).

Almost two thirds of mangrove governance publications in Africa highlight that a multi-level mangrove governance approach is widely used, however there is a decrease in mangrove habitat due to the lack of strong regulations (Queen et al. 2024). Community-based mangrove restoration models are needed; in Mozambique successful mangrove co-management serves as a promising model for sustainable restoration and conservation (Macamo et al. 2024). Co-management is effective in protected areas and increases the capacity of mangroves to support human-livelihoods (Hagger et al. 2022). Effective mangrove restoration requires an understanding of the ecological functioning and interactions between abiotic and biotic factors such as the productivity, carbon and sediment dynamics as this leads to mangrove resilience (Ferreira et al. 2022; Lovelock et al. 2024). Estuaries with large mangrove stands that have been prioritised for restoration include Mntafufu, Mngazana, Mtata, Mbashe and Nxaxo. The passive and active restoration strategies in these estuaries should include removal of wood harvesting, preventing trampling and livestock browsing to allow for improvement of sediment conditions, allowing for natural recovery and regeneration to take place. Best practice guides

have been developed for mangrove restoration in East Africa (Kairo et al. 2020) and globally the Mangrove Restoration Tracker records and tracks outcome from restoration projects (Gatt et al. 2024). This study has identified pressures that need to be addressed to restore mangrove ecosystems. The findings from this study will inform global frameworks such as the Kunming-Montreal Global Biodiversity Framework (GBF) that aims to ensure that there is sustainable management, restoration and protection of ecosystems with at least 30% of degraded areas being under restoration by 2030. In South Africa the implementation of Estuary Management Plans a requirement of the Integrated Coastal Management Act (2008) provides an adaptive management and monitoring framework to do this (Adams, 2020).

Conclusions

At their southernmost distribution in Africa, mangroves have shown notable changes as indicated in this and previous studies (Hoppe-Speer et al. 2014; Adams and Rajkaran 2020). In this study region, although there was a net increase in mangrove area, there was a decline in the structural integrity as anthropogenic pressures have remained persistent over a 10-year period. This resulted in localized mangrove degradation indicated by a decrease in the number of seedlings and saplings and increase in canopy gaps. Therefore, there is an urgency to control the identified anthropogenic pressures to prevent further degradation with repeat monitoring campaigns (i.e. in 2031) to track further changes. Continued persistence poses a threat to the resilience of mangrove forests in the face of future climate change and prevent possible poleward expansion. Mangrove populations at range limits can serve as earlier indicators of ecosystem change and thus it is important to continue to track change and investigate the interplay between human activities and climatic factors. These results inform the prioritization of management interventions to protect these endangered mangrove ecosystems in line with the objectives of the Mangrove Breakthrough and Global Biodiversity Framework.

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Author Contributions Anesu Machite and Janine Adams both contributed to the study conception, design, data collection, analysis, write-up and approval of the final manuscript. JBA was responsible for funding acquisition and project administration.

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Data Availability Datasets are available on request from the authors.

Declarations

Competing interest The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

- Adame MF, Reef R, Santini NS, Najera E, Turschwell MP, Hayes MA, Masque P, Lovelock CE (2021) Mangroves in arid regions: ecology, threats, and opportunities. *Estuar Coast Shelf Sci* 248:1–9
- Adams JB (2020) Salt marsh at the tip of Africa: patterns, processes and change in response to climate change. *Est Coast Shelf Sci* 237:106650
- Adams JB, Colloty BM, Bate GC (2004) The distribution and state of mangroves along the coast of Transkei, Eastern Cape Province, South Africa. *Wetlands Ecol Manage* 12:531–541
- Adams JB, Human LRD (2016) Investigation into the mortality of mangroves at St Lucia Estuary. *S Afr J Bot* 107:121–128
- Adams JB, Rajkaran A (2020) Changes in mangroves at their southernmost African distribution limit. *Estuar Coast Shelf Sci* 247:106862
- Adams JB, Taljaard S, Van Niekerk L, Lemley DA (2020) Nutrient enrichment as a threat to the ecological resilience and health of South African microtidal estuaries. *Afr J Aquat Sci* 45:23–40
- Adams JB, Van Niekerk L (2020) Ten principles to determine environmental flow requirements for temporarily closed estuaries. *Water* 12:1944
- Altamirano JP, Primavera JH (2010) Practical techniques for mapping small patches of mangroves. *Wetlands Ecol Manage* 1995:707–715
- Amir AA, Duke NC (2019) Distinct characteristics of canopy gaps in the subtropical mangroves of Moreton Bay, Australia. *Estuar Coast Shelf Sci* 222:66–80
- Asbridge E, Clark R, Denham PE, Hughes MJ, James M, McLaughlin D, Turner C, Whitton T, Wilde T, Rogers K (2024) Tidal impoundment and mangrove dieback at Cabbage Tree Basin, NSW: drivers of change and tailored management for the future. *Estuar Coasts* 47:2190–2208
- Asbridge EF, Bartolo R, Finlayson CM, Lucas RM, Rogers K, Woodroffe CD (2019) Assessing the distribution and drivers of mangrove dieback in Kakadu National Park, northern Australia. *Estuar Coast Shelf Sci* 228:106353
- Bandaranayake WM (1998) Traditional and medicinal uses of mangroves. *Mangroves Salt Marshes* 2:133–148
- Bardou R, Osland MJ, Scyphers S, Shepard C, Aerni KE, Alemu IJB, Crimian R, Day RH, Enwright NM, Feher LC et al (2023) Rapidly changing range limits in a warming world: critical data limitations and knowledge gaps for advancing understanding of mangrove range dynamics in the southeastern USA. *Estuar Coasts* 46:1123–1140
- Barnuevo A, Asaeda T, Sanjaya K, Kanesaka Y, Fortes M (2017) Drawbacks of mangrove rehabilitation schemes: lessons learned from the large-scale mangrove plantations. *Estuar Coast Shelf Sci* 198:432–437
- Bunting P, Rosenqvist A, Hilarides L, Lucas RM, Thomas N, Tadono T, Worthington TA, Spalding M, Murray NJ, Rebelo L, Bunting P, Rosenqvist A, Hilarides L, Lucas RM, Thomas N, Tadono T, Worthington TA, Spalding M, Murray NJ, Rebelo L (2022) Global Mangrove Extent Change 1996–2020: Global Mangrove Watch Version 3.0. *Remote Sens* 14:1–32
- Dahdouh-Guebas F, Ajonina GN, Amir AA, Andradi-Brown DA, Aziz I, Balke T, Barbier EB, Cannicci S, Cragg SM, Cunha-Lignon M, Curnick DJ, Duarte CM, Duke NC, Endors C, Fratini S, Feller IC, Fromard F, Hugé J, Huxham M, Kairo JG, Kajita T, Kathiresan K, Koedam N, Lee SY, Lin HJ, Mackenzie JR, Mangora MM, Marchand C, Meziane T, Minchinton TE, Pettorelli N, Polania J, Polgar G, Poti M, Primavera J, Quarto A, Rog SM, Satyanarayana B, Schaeffer-Novelli Y, Spalding M, der Van Stocken T, Wodehouse D, Yong JWH, Zimmer M, Friess DA (2020) Public perceptions of mangrove forests matter for their conservation. *Frontiers in Marine Science* 7:1–5
- Din N, Saenger P, Jules PR, Siegfried DD (2008) Logging activities in mangrove forests: a case study of Douala Cameroon. *Afr J Environ Sci Technol* 2:22–30
- Feka NZ, Ajonina GN (2011) Drivers causing decline of mangrove in West-Central Africa: a review. *Int J Biodivers Sci Ecosyst Serv Manag* 7:217–230
- Ferreira AC, de Lacerda LD, Rodrigues JVM, Bezerra LEA (2022) New contributions to mangrove rehabilitation/restoration protocols and practices. *Wetlands Ecol Manage* 31:89–114
- Friess DA, Adame FM, Adams JB, Lovelock CE (2022) Mangrove forests under climate change in a 2°C world. *Wiley Interdiscip Rev Clim Change* 13:e792
- Gatt Y, Walton R, Andradi-Brown D, Spalding M, Acosta-Velázquez J, Adame M, Barros F, Beeston M, Bernardino A, Buelow C, Cadier C, Vela A, Canty S, Dahdouh-Guebas F, Gomes L, Duncan C, Eger A, Enright J, Frausto-Illescas T, Freiss D, Glass L, Grimsditch G, Hagger V, Hein M, Herrera-Silveira J, Hilarides L, Howard J, Hoyos-Santillan J, Kandasamy K, Kenndey B, Kincaid K, Lagat A, Lara-Dominguez A, Longley-Wood K, Mahajan S, Mangubhai S, Martin P, Medard M, Nájera-Hillman E, Nicolas T, Nicolau D, Nyaega L, Paiz Y, Quarto A, Ralifo A, Randriamanantena OD, Rasolozaka T, Ravelojaona D, Robaigau A, Rodríguez-Rodríguez A, Rog S, Rounds I, Rovai A, Saunders M, Sievers M, Song D, Sutherland W, Taylor N, Teutli-Hernández C, Thornton H, Tuiwawa S, Ulumuddin Y, Veverka L, Videira E, White T, Wodehouse D, Wosu A, Yamashita H, Zimmer M, Worthington T (2024) The mangrove restoration tracker tool: meeting local practitioner needs and tracking progress toward global targets. *One Earth* 7:2072–2085
- Giri C, Ochieng E, Tieszen LL, Zhu Z, Singh A, Loveland T, Masek J, Duke N (2011) Status and distribution of mangrove forests of the world using earth observation satellite data. *Glob Ecol Biogeogr* 20:154–159
- Hagger V, Worthington TA, Lovelock CE et al (2022) Drivers of global mangrove loss and gain in social-ecological systems. *Nat Commun* 13:6373

- He Q, Silliman BR (2016) Consumer control as a common driver of coastal vegetation worldwide. *Ecol Monogr* 8:278–294
- Hoppe-Speer SCL, Adams JB, Bailey D (2014) Present state of mangrove forests along the Eastern Cape coast, South Africa. *Wetlands Ecol Manage* 23:371–383
- Hoppe-Speer SCL, Adams JB, Rajkaran A, Bailey D (2011) The response of the red mangrove *Rhizophora mucronata* Lam. to salinity and inundation in South Africa. *Aquat Bot* 95:71–76
- Huxham M, Kumara MP, Jayatissa LP, Krauss KW, Kairo J, Langat J, Mencuccini M, Skov MW, Kirui B (2010) Intra- and inter-specific facilitation in mangroves may increase resilience to climate change threats. *Philos Trans R Soc Lond B Biol Sci* 365:2127–2135
- Ilamathi P, Chidambaram S (2025) Integration of hyperspectral imaging and deep learning for sustainable mangrove management and sustainable development goals assessment. *Wetlands* 45:9
- Kairo JG, Mangora MM, Western Indian Ocean Marine Science Association and WIO mangrove network (2020). Guidelines on mangrove ecosystem restoration for the Western Indian Ocean Region-Western Indian Ocean Ecosystem Guidelines and Toolkits. UNEP. The Guidelines on Mangrove Restoration for the Western Indian Ocean Region. | <https://www.unep.org/resource/s/report/guidelines-mangrove-restoration-western-indian-ocean-region>
- Kirui KB, Kairo JG, Bosire J, Viergever KM, Rudra S, Huxham M, Brier RA (2013) Mapping of mangrove forest land cover change along the Kenya coastline using Landsat imagery. *Ocean Coastal Manage* 83:19–24
- Krauss KW, McKee KL, Lovelock C, Cahoon DR, Saintilan N, Reef R, Chen L (2014) How mangroves adjust to rising sea level. *New Phytol* 202:19–34
- Lovelock CE, Bennion V, de Oliveira M, Hagger V, Hill JW, Kwan V, Pearse AL, Rossini RA, Twomey AJ (2024) Mangrove ecology guiding the use of mangroves as nature-based solutions. *J Ecol* 112:2510–2521
- Lovelock CE, Feller IC, Reef R, Hickey S, Ball MC (2017) Mangrove dieback during fluctuating sea levels. *Sci Rep* 7:6–13
- Macamo CDCF, da Inácio Costa F, Bandeira S, Adams JB, Balidy HJ (2024) Mangrove community-based management in Eastern Africa: experiences from rural Mozambique. *Front. Mar. Sci.* 11:1337678
- Maurya K, Mahajan S, Chaube N (2021) Remote sensing techniques: mapping and monitoring of mangrove ecosystem—a review. *Complex Intell Syst* 7:2797–2818
- Mbense S, Rajkaran A, Bolosha U, Adams JB (2016) Rapid colonization of degraded mangrove habitat by succulent salt marsh. *S Afr J Bot* 107:129–136
- Minchinton TE, Shuttleworth HT, Lathlean JA, McWilliam RA, Daly TJ (2019) Impacts of cattle on the vegetation structure of mangroves. *Wetlands* 39:1119–1127
- Naidoo G (2023) The mangroves of Africa: a review. *Mar Pollut Bull* 190:1–13
- Naidoo G, Naidoo Y, Achar P (2010) Responses of the mangroves *Avicennia marina* and *Bruguiera gymnorrhiza* to oil contamination. *Flora Morphol Distrib Funct Ecol Plants* 205:357–362
- Nicolau DK, Macamo CD, Bandeira SO, Tajú A, Mabilana HA (2017) Mangrove change detection, structure and condition in a protected area of eastern Africa: the case of Quirimbas National Park, Mozambique. *WIO J Mar Sci* 16:47–60
- Osland MJ, Day RH, Hall CT, Brumfield MD, Dugas J, James WR (2017) Mangrove expansion and contraction at a poleward range limit: climate extremes and land-ocean temperature gradients. *Ecology* 98:125–137
- Osland MJ, Day RH, Larriviere JC, Form AS (2014) Aboveground allometric models for freeze-affected black mangroves (*Avicennia germinans*): equations for a climate sensitive mangrove-marsh ecotone. *PLoS One* 9:e99604
- Osland MJ, Hughes AR, Armitage AR, Scyphers SB, Cebrian J, Swine SH, Shepard CC, Allen MS, Feher LC, Nelson JA, O'Brien CL, Sanspre CR, Smee DL, Snyder CM, Stetter AP, Stevens PW, Swanson KM, Williams LH, Brush JM, Bardou R (2022) The impacts of mangrove range expansion on wetland ecosystem services in the southeastern United States: current understanding, knowledge gaps, and emerging research needs. *Glob Change Biol* 28:3163–3187
- Peer N, Rajkaran A, Miranda NAF, Taylor RH, Newman B, Porri F, Raw JL, Mbense SP, Adams JB, Perissinotto R (2018) Latitudinal gradients and poleward expansion of mangrove ecosystems in South Africa: 50 years after Macnae's first assessment. *Afr J Mar Sci* 40:101–120
- Quenum IA, Avocèvou-Ayisso C, Idohou R, Padonou EA, Akabassi G, Akakpo BA (2024) Restoration and governance approaches of mangrove ecosystems in Africa. *Wetlands* 44:54
- Quisthoudt K, Adams J, Rajkaran A, Dahdouh-Guebas F, Koedam N, Randin CF (2013) Disentangling the effects of global climate and regional land-use change on the current and future distribution of mangroves in South Africa. *Biodivers Conserv* 22:1369–1390
- Rajkaran A, Adams JB (2010) The implications of harvesting on the population structure and sediment characteristics of the mangroves at Mngazana Estuary, Eastern Cape, South Africa. *Wetlands Ecol Manage* 18:79–89
- Rajkaran A, Adams JB, du Preez DR (2004) A method for monitoring mangrove harvesting at the Mngazana Estuary, South Africa. *Afr J Aquat Sci* 29:57–65
- Rajkaran A, Adams J, Taylor R (2009) Historic and recent (2006) state of mangroves in small estuaries from Mlalazi to Mtamvuna in KwaZulu-Natal, South Africa. *South J Sci* 71:287–296
- Raw JL, Van der Stocken T, Carroll D, Harris LR, Rajkaran A, Van Niekerk L, Adams JB (2023a) Dispersal and coastal geomorphology limit potential for mangrove range expansion under climate change. *J Ecol* 111:139–155
- Raw JL, Van Niekerk L, Chauke O, Mbatha H, Riddin T, Adams JB (2023b) Blue carbon sinks in South Africa and the need for restoration to enhance carbon sequestration. *Sci Total Environ* 859:160142
- Reyes GJ, Smyth AR, Qiu J et al (2024) Highly urbanized mangrove areas are small in size, fragmented, and missed by large-scale mapping efforts. *Wetlands* 44:103
- Riddin T, Adams JB, Rajkaran A, Machite A, Peer N, Suárez EL (2024) IUCN red list of ecosystems, Mangroves of the Agulhas. <https://doi.org/10.32942/X2H322>
- Saintilan N, Wilson NC, Rogers K, Rajkaran A, Krauss KW (2014) Mangrove expansion and salt marsh decline at mangrove poleward limits. *Glob Change Biol* 20:147–157
- Sasmith SD, Taillardat P, Clendenning JN, Cameron C, Friess DA, Murdiyarso D, Hutley LB (2019) Effect of land-use and land-cover change on mangrove blue carbon: a systematic review. *Glob Change Biol* 00:1–12
- Sippo JZ, Lovelock CE, Santos IR, Sanders CJ, Maher DT (2018) Mangrove mortality in a changing climate: an overview. *Estuar Coast Shelf Sci* 215:241–249
- Suyadi GJ, Lundquist CJ, Schwendenmann L (2018) Sources of uncertainty in mapping temperate mangroves and their minimization using innovative methods. *Int J Remote Sens* 39:17–36
- Taylor R (2016) Dynamics of the macrophyte vegetation of the Mgo-bezeleni floodplain and estuary, Northern KwaZulu-Natal. *S Afr J Bot* 107:170–178
- van Deventer H, Apleni P, Adams JB, Riddin T, Whitfield E, Machite A, Van Niekerk L, Madasa A (2025) Assessing the feasibility of mapping changes of ecosystem functional groups in South

- African estuaries using Landsat and Sentinel images of 1990, 2014, 2018 and 2020. *Wetlands Ecol Manage* 33:12
- Van Niekerk L, Adams JB, James NC, Lamberth SJ, Mackay CF, Rajkaran A, Weerts SP, Whitfield A (2020) An Estuary Ecosystem Classification that encompasses biogeography and a high diversity of types in support of protection and management. *Afr J Aquat Sci* 45:199–126
- Vervaeke WC, Feller IC, Jones SF (2025) Ongoing range shift of mangrove foundation species: *Avicennia germinans* and *Rhizophora mangle* in Georgia, United States. *Estuar Coasts* 48:78
- West GJ, Gibson PT, Glasby TM (2025) Monitoring estuarine habitats and threats at a regional scale using aerial photography, object-based image analysis and deep learning. *Wetlands* 45:44
- Whitfield AK, James NC, Lamberth SJ, Adams JB, Perissinotto R, Rajkaran A, Bornman TG (2016) The role of pioneers as indicators of biogeographic range expansion caused by global change in southern African coastal waters. *Estuar Coastal Shelf Sci* 17:138–153
- Worthington TA, zu Ermgassen PSE, Friess DA, Krauss KW, Lovelock CE, Thorley J, Tingey R, Woodroffe CD, Bunting P, Cormier N, Lagomasino D, Lucas R, Murray NJ, Sutherland WJ, Spalding M (2020) A global biophysical typology of mangroves and its relevance for ecosystem structure and deforestation. *Sci Rep* 10:14652
- Ximenes AC, Cavanaugh KC, Arvor D, Murdiyarso D, Thomas N, Arcoverde GFB, da Conceição Bispo P, Van der Stocken T (2023) A comparison of global mangrove maps: assessing spatial and bioclimatic discrepancies at poleward range limits. *Sci Total Environ* 860:160380
- Yando ES, Sloey TM, Dahdouh-Guebas F, Rogers K, Abuchahla GMO, Cannicci S, Canty SWJ, Jennerjahn TC, Ogurcak DE, Adams JB, Connolly RM, Diele K, Yip S, Rowntree JK, Sharm S, Cavanaugh KC, Cormier N, Feller IC, Fratini S, Ouyang X, Wee AKS, Friess DA (2021) Conceptualizing ecosystem degradation using mangrove forests as a model system 263. *Biol. Conserv.* 263:1–11 (109355)

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