

# Historical changes in anthropogenic pressures, distribution and population structure of mangrove forests at a distributional range limit

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## Research Article

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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 and the impacts of natural and anthropogenic pressures. This study assessed the drivers of change in mangrove area cover, species composition and population structure between 2011 and 2021 from field surveys and manual GIS digitizing of 17 estuaries. There was a small increase in mangrove cover over this 10-year period by 3 ha to a total of 274 ha 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. Anthropogenic pressures have persisted since 2011 resulting in localized mangrove degradation indicated by a decrease in the number of seedlings and saplings and increase in canopy gaps. Major anthropogenic pressures included trampling, livestock browsing, and wood harvesting that reduced mangrove cover and caused shifts in population structure. 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 such as the exclusion of livestock browsing to ensure healthy mangrove populations. The research also informs global studies on range limit populations and their resilience. The study recommended that adaptive management and monitoring frameworks are used to track mangrove changes.

## 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. 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). Monitoring mangrove range shifts informs climate-related impacts, and associated management responses to ensure their protection and sustainable use.

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  $0.06 \text{ ha y}^{-1}$  from just 0.075 ha in 1969 to 1.62 ha in 2015 (Hoppe-Speer et al. 2014) indicating that temperature is not the primary limiting factor for mangrove distribution and future expansion. 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.

Mangroves in South Africa occur mostly in estuaries that are predominantly open (always connected to the sea) and estuarine lakes (variable salinity with either a permanent or periodical connection to the sea) 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 where optimal environmental conditions are limited (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 km<sup>2</sup> to 147 359 km<sup>2</sup>; an annual loss of 390 km<sup>2</sup>. 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, cattle browsing, footpaths and trampling from humans and livestock, livestock browsing and disturbance 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); forests with only mature mangrove trees, are not considered to be regenerating.

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 estuary 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. 2013). 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. 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. 2022).

## 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.cdngiportal.co.za/cdngiportal/>) and Google Earth images (30 m resolution). Mangrove cover data for 2011 was obtained using historical images and the area extent was obtained from Hoppe-Speer et al. (2014) who completed detailed habitat maps following field surveys. 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. Field surveys and ground-truthing was conducted between August and December 2021 using a handheld GPS and the Google Earth images to update and modify the 2021 area for mangrove forests. Manual digitizing and aerial drone imagery providing higher accuracy were used to

delineate vegetation transition zones following the ground-truthing. 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 are available at <http://bgis.sanbi.org/Projects/Detail/192>.

## Population structure

To measure population structure, transects were placed in dense 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 m<sup>2</sup> (total of 75 m<sup>2</sup>). If mangrove cover was more than 5 ha (Fig. 1), three transects were placed each with three quadrats 25 m<sup>2</sup> (total of 225 m<sup>2</sup>). 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 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 m<sup>2</sup>) in areas that showed signs of harvesting. These sites were identified by the presence of tree stumps. In each quadrat the number of adults and stumps were counted. Low harvesting intensity had a ratio of stumps to adults of 2:1, medium intensity 1:1 and, high intensity 1:2 (Rajkaran et al., 2004, Rajkaran and Adams 2010).

Table 1  
Description of human pressures that were used to determine the state of the mangroves  
(adapted from Hoppe-Speer et al. 2015).

| <b>Anthropogenic Impacts</b> | <b>Descriptions</b>                                                                                                                                                                  |
|------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 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.

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

## 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, an 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 where there was a 4.5% increase in

mangrove cover. At Mdumbi Estuary (Fig. 1), a 0.9% increase in mangrove cover occurred along the margins of the intertidal island from sedimentation, shallowing and mangrove colonization.

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 individuals were found along the landward edge adjacent to *Juncus kraussii*; there was a net increase in total mangrove area between 2011 and 2021. Areas of dieback of *A. marina* and *B. gymnorhiza* at Mnyameni 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, 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 and 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 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 was 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). 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 adjacent to mangrove stands at Mngazana, Mtata, Xora and Nqabara/Nqabarana estuaries.

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.

|                   | 2011<br>Extent (ha) | 2021<br>Extent (ha) | Percentage change (%) | Tree<br>Species |
|-------------------|---------------------|---------------------|-----------------------|-----------------|
| UMthavuna         | 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               |                       |                 |

Table 4

Summary of the pressures, mangrove extent and population structure in 2021. Ratios in the pressures 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><br>Trees: stumps | Population structure of <i>Bruguiera gymnorhiza</i><br>Trees: seedlings |
|-----------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------|-------------------------------------------------------------------------|
| Mnyameni  | Harvesting and mouth closure. Dieback of mangroves from sediment deposition.                                                                                                                                  | Scattered individuals with low seedling density. 1:1             | No seedlings                                                            |
| Mntafufu  | Livestock browsing, mangrove harvesting and trampling.                                                                                                                                                        | Low sapling density 1:6                                          | High adult density but low seedlings & sapling density. 1:2             |
| 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. Mangrove harvesting (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 mangrove cover & density. | Low sapling density 1:3                                          |                                                                         |
| Mngazana  | Livestock browsing, mangrove harvesting (1:1 for <i>A. marina</i> ). Canopy gaps, loss of mangrove 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                                       |
| Mzintlava | Harvesting of <i>B. gymnorhiza</i> (1:1). Canopy gaps, loss of mangrove density.                                                                                                                              | Scattered adult individuals.<br>No seedlings or saplings.        | Low density of adults, seedlings and saplings 1:3                       |
| 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                                          |                                                                         |

| Estuary      | Pressures & mangrove extent                                                                          | Population structure of <i>Avicennia marina</i><br>Trees: stumps                                                                   | Population structure of <i>Bruguiera gymnorhiza</i><br>Trees: seedlings |
|--------------|------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------|
| Xora         | Livestock browsing. Mangrove 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                                                  |
| 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                              |
| Bulungula    | Loss due to mouth closure & flooding.                                                                | No adults or juveniles present                                                                                                     | One adult in the middle reaches of estuary                              |

Table 5

Quantification of pressures (impact scores) 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    |

## Discussion

Mangroves in South Africa occur at their southernmost 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 just 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. *Bruguiera gymnorhiza* 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 gymnorhiza* 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. gymnorhiza* and the density of adults was higher than the seedlings.

Forests at Mntafufu, Mdumbi, Mtakatye, Mtata and Mdumbi estuaries were in a degraded state as indicated by the numerous pressures and the low mangrove adult to seedling ratios (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 Mntafufu, Mdumbi, Mtata, Mbashe and Nqabara estuaries 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). Future research needs to investigate the reasons for low survival of seedlings to saplings.

*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 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 do not allow for growth and persistence of seedlings (Hoppe-Speer et al. 2014). Predation by herbivores and crabs also needs to be considered (Barnuevo et al. 2017).

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. gymnorhiza*. Our field observations indicated that selective harvesting of *B. gymnorhiza* 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. gymnorhiza* 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. gymnorhiza* poles were all greater than 4 m in length with a mean DBH of 6.5 cm (N = 14) compared with stockpiles of *B. gymnorhiza* 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 wood harvesting (mainly used as a source of fuel) between 1980 to 2006 in seven West Central African countries (Feka and Ajonina 2011). 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 elsewhere (He and Silliman 2016). The changes in tree morphology was indicative of the height at which livestock consume the 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).

Sedimentation has contributed to an expansion of mangroves since 2011 at the Mdumbi, Mbashe, Nxaxo and Kobonqaba estuaries as this increases 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).

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).

Marine sediment deposition and smothering of pneumatophores caused mangrove dieback at Mbashe Estuary in 2012 (James et al. 2020). In 2021 we recorded an increase in mangrove area at this estuary (Supplementary Fig. 1). Salt marsh vegetation may play a facilitative role for mangrove expansion as it

traps propagules (Begam et al. 2017, Smith et al. 2022); at Mbashe Estuary multiple new stands of *A. marina* formed in areas previously covered by salt marsh vegetation. Mangrove expansion into salt marsh areas is a global indicator of global warming (Friess et al. 2022) and continuous monitoring is needed along the South African coastline to track change.

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 et al. 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. 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.

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 (Quenum 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). 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 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 et al. 2025).

At their southernmost distribution in Africa, mangroves have shown notable changes as indicated in this and previous studies (Adams and Rajkaran 2020). In our study region anthropogenic pressures have remained persistent over a 10-year period resulting in localized mangrove degradation indicated by a decrease in the number of seedlings and saplings and increase in canopy gaps. This poses a threat to the resilience of mangrove forests in the face of future climate change. 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 management interventions to protect these endangered mangrove ecosystems.

## **Declarations**

## **Declaration of 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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## 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.

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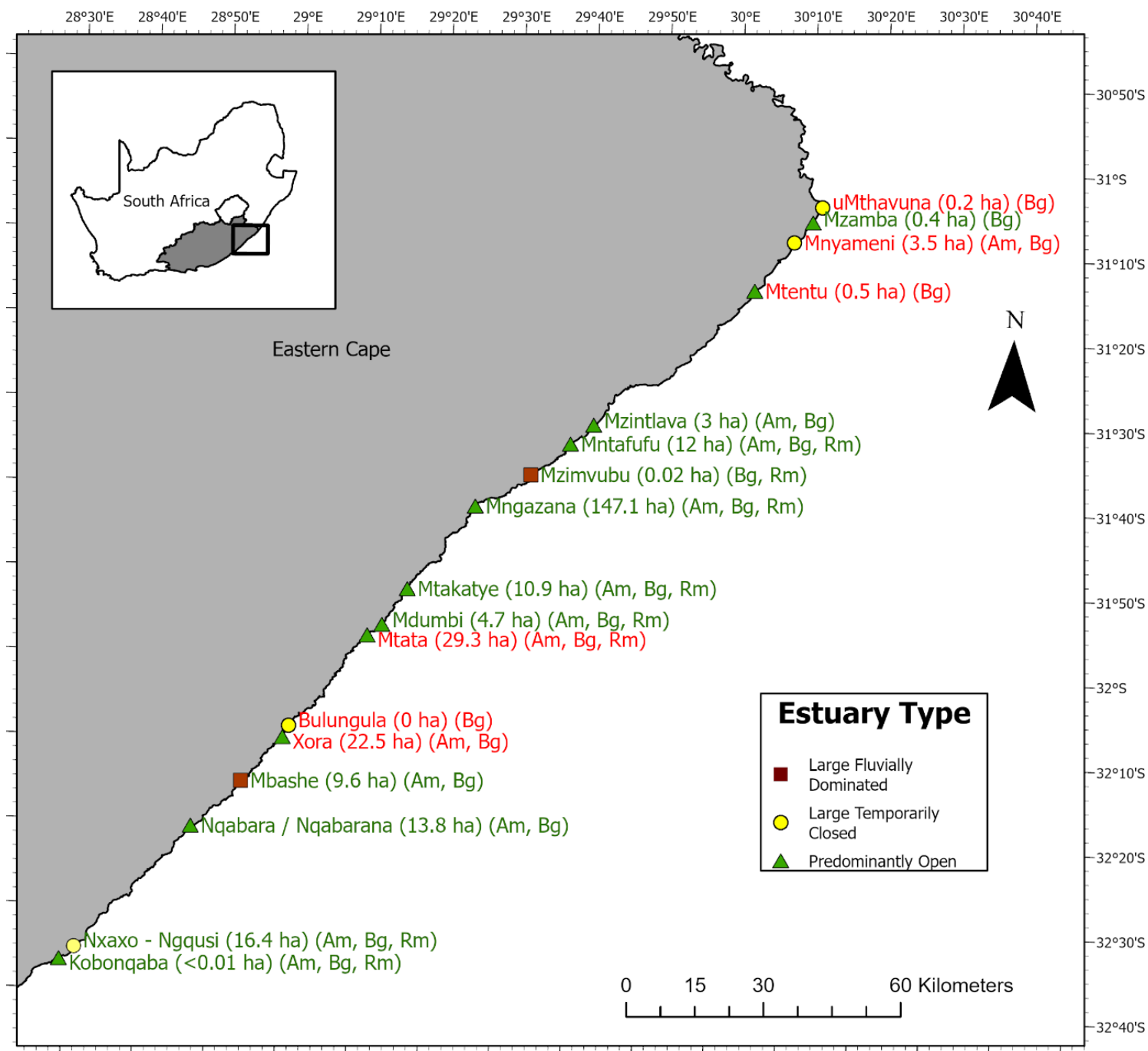
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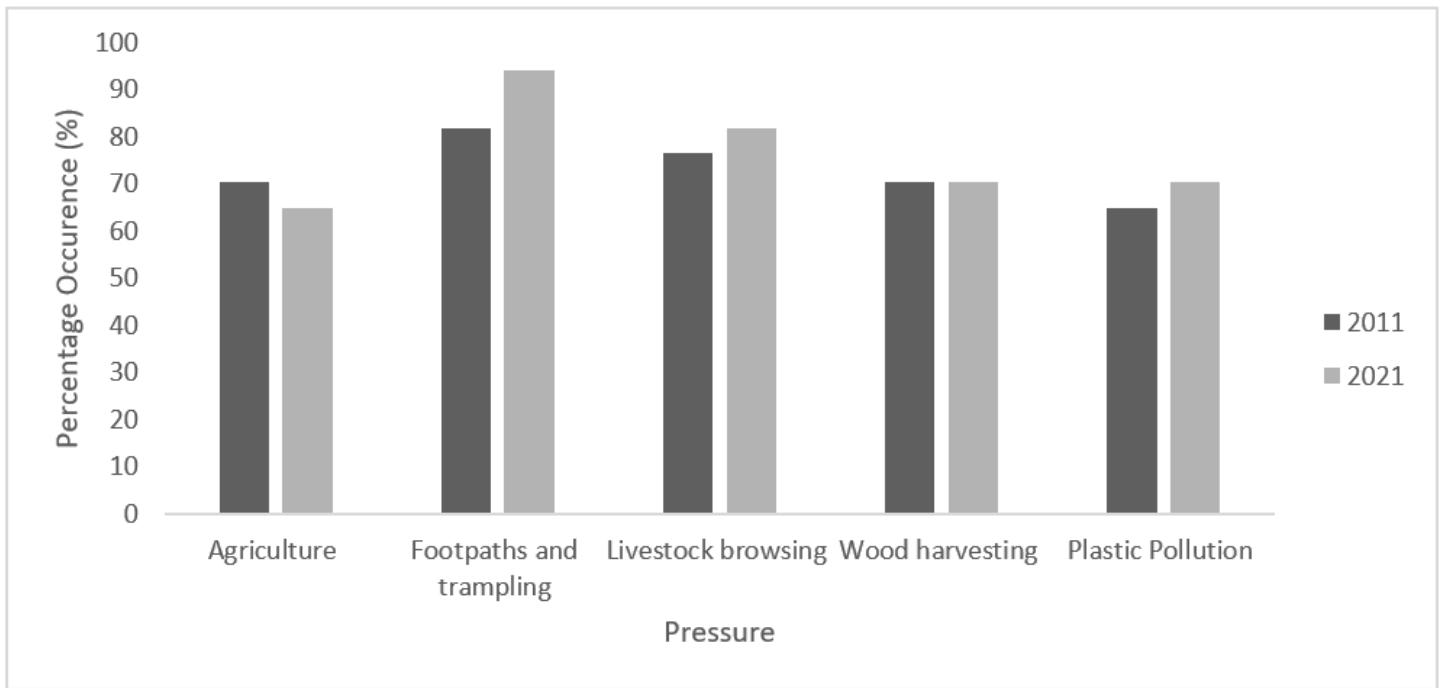
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## Figures



**Figure 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*)



**Figure 2**

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

a)



b)



c)



d)



Figure 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.

| Low intensity                                                                    | Medium intensity                                                                   | High intensity                                                                      |
|----------------------------------------------------------------------------------|------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|
|  |  |  |
| <i>Bruguiera gymnorhiza</i> at Mnyameni Estuary                                  | <i>B. gymnorhiza</i> at Mzintlava Estuary                                          | <i>B. gymnorhiza</i> and <i>Rhizophora mucronata</i> at Mtata Estuary               |

Figure 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

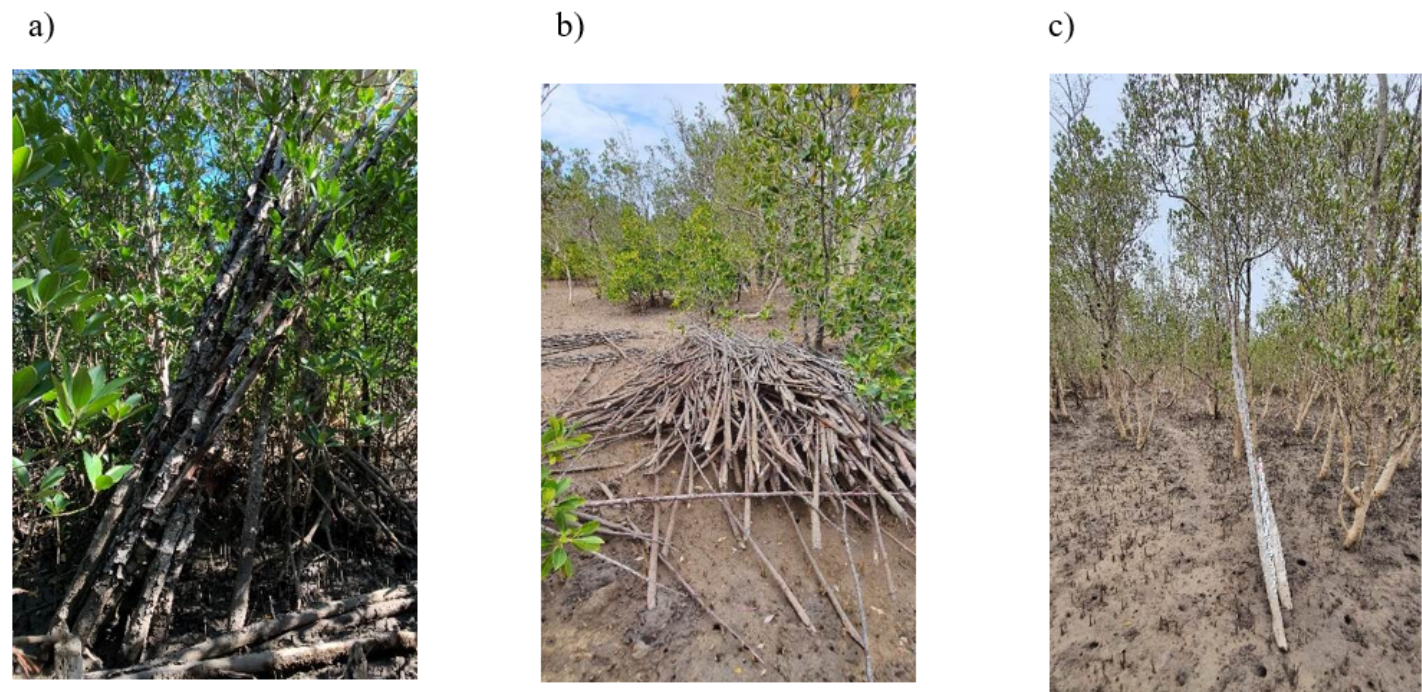


Figure 5

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

## Supplementary Files

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- [MachiteandAdamsSupplementary.docx](#)