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Changes in mangroves at their southernmost African distribution limit

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ABSTRACT

Mangroves in South Africa occur at one of the most southerly locations in the world, which provides a unique opportunity to study their dynamic responses to anthropogenic and natural perturbations. The exposed high-energy South African coastline restricts mangroves to 32 sheltered estuaries of which 18 (56%) are predominantly open to the sea. A large area of mangrove (47% of the country total) occurs in the uMhlathuze Estuary – a novel ecosystem formed by the creation of an artificial mouth. A Drivers-Pressures-State-Impacts-Response (DPSIR) framework was applied to understand factors of change and highlight governance and management responses. The largest mangrove area (440 ha) was lost during the construction of Durban Bay harbour. Mangroves (~7 ha) no longer occur in 10 small KwaZulu-Natal estuaries as a result of catchment and mouth disturbance. In the Eastern Cape, pressures are escalating in the form of harvesting for wood, cattle browsing and changes in mouth condition. Climate related warming and an increase in CO_2 are positive conditions for mangroves to expand their distribution to higher latitudes but this will depend on propagule dispersal between estuaries and the availability of suitable habitats. Many of the small estuaries are temporarily closed to the sea for different periods thus limiting recruitment. An increase in the intensity of freshwater floods will scour banks and completely remove mangroves. It is important that these dynamic responses are understood and incorporated into management plans so that mangrove forests can be better protected and conserved.

1. Introduction

Mangroves are woody trees and shrubs that occur at the interface between land and sea along tropical and subtropical coasts. They grow optimally within a mean annual temperature range of 5 °C–20 °C (Duke et al., 1998; Cavanaugh et al., 2014) and can tolerate some frosts particularly as adults (Osland et al., 2015; Chen et al., 2017). Human activities and environmental fluxes have altered the composition and extent of mangrove forests worldwide (Asbridge et al., 2015; Friess et al., 2019). Much has been written on the response of mangroves to climate change (Gilman et al., 2008; Record et al., 2013; Rogers et al., 2013; Saintilan et al., 2014) but there are geographical knowledge gaps where there is very little baseline information on factors that currently influence mangrove forests (Ward et al., 2016). Local studies are needed to understand the synergistic interactions between climate change and human impacts (He and Silliman, 2019) and to understand the processes that influence vulnerability and resilience of these forests. Accurate estimates of mangrove area and trajectories of change are needed to quantify and valuate ecosystem services such as carbon storage (Friess and Webb, 2014).

In South Africa, mangroves grow in sheltered estuaries along an 1800 km stretch of the east coast that encompasses warm temperate, subtropical and tropical bioregions. The dominant species are the white mangrove *Avicennia marina,* black mangrove *Bruguiera gymnorhiza* and red mangrove *Rhizophora mucronata.* Three other species (*Ceriops tagal, Lumnitzera racemosa* and *Xylocarpus granatum*) occur in the Kosi Estuary, recently classified as falling within the tropical biogeographic zone (Van Niekerk et al., 2020). The distribution of mangrove species across three biogeographic zones presents an opportunity to investigate environmental factors that could affect range expansions of species and their responses to climate change at a southern continental limit. Warm ocean currents extend along the eastern coastlines of the southern hemisphere favouring the poleward distribution of mangrove (Duke et al., 1998). Range expansions have been recorded over the past few decades with subtropical species moving down the east coast of South Africa (Whitfield et al., 2016; Peer et al., 2018). Mangrove expansion may also be facilitated by asymmetrical interspecific competition between mangroves and salt marsh as carbon dioxide levels increase in the

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atmosphere.

South Africa's coast experiences high wave energy together with low tidal ranges (Cooper, 2001). Estuaries are thus microtidal and shallow (water depth 2–3 m) with highly mobile sediments. On a global-scale, the nearly 300 systems are relatively small with 70% less than 50 ha in extent (Cooper, 2001; Van Niekerk et al., 2013). In >75% of cases, strong wave action and abundant sediment cause bars to form in mouth areas creating constricted inlets (Cooper, 2001; Whitfield, 1992; Van Niekerk, 2018). Mean annual run-off is variable and river flow fluctuates between floods and extremely low to zero flow. During times of low flow, the mouths of affected estuaries remain closed to the sea making them unsuitable for the establishment of mangroves. Floodplain area, mouth state and the flow regime of the estuary were identified as significant predictors of mangrove area (Raw et al., 2019). The topography of the coast determines mangrove distribution under wave-dominated, high-energy conditions of the southern hemisphere as seen in New Zealand, southeast Australia, Brazil and South Africa (Schaeffer-Novelli et al., 1990; Cooper, 2001; Roy et al., 2001).

Although their areal coverage is small (<2000 ha), mangroves in South Africa contribute significantly to estuarine biodiversity and provide important ecosystem services (Adams et al., 2016). They buffer the coastline against severe weather, filter and improve water quality, and sequester large volumes of carbon in above and belowground biomass (Donato et al., 2011; McLeod et al., 2011; Johnson et al., 2020). They provide productive nursery habitats and refugia for many fishes and invertebrates (Whitfield, 2017; Bornman et al., 2018; Kuer et al., 2019), with crabs and snails engineering the ecosystem by influencing benthic primary productivity (Cannicci et al., 2008; Raw et al., 2017; Peer et al., 2018). They also contribute to the livelihoods of local people by providing wood for fires, building material and fish traps (Hoppe-Speer et al., 2015; Naidoo, 2016; Rajkaran and Adams, 2016), and they are popular recreational, cultural and tourism venues.

Threats to mangroves globally are conversion to agriculture or aquaculture, coastal development, pollution, hydrological changes, climate change and extreme weather events. Harvesting for fuelwood, charcoal and construction materials occurs in undeveloped areas (Friess et al., 2019). Degradation of mangroves by overgrazing from livestock can also occur (Dahdouh-Guebas et al., 2006). Impacts of livestock in mangroves are the fragmentation of forests due to pathways, changes in vegetation structure and soil conditions (Dahdoub-Guebas et al., 2006; Hoppe-Speer and Adams, 2015; Minchinton et al., 2019). Table 1 shows the studies that have investigated the threats and pressures on mangroves in South Africa. As in other countries coastal development such as harbours, bridges and roads have removed mangroves. Developments also restrict tidal exchange impacting the mangrove habitat (Rajkaran and Adams, 2011; Taylor, 2016). Freshwater abstraction leads to closure of estuary mouths to the sea; this causes hyposaline conditions, high water level and flooding of mangroves (Adams et al., 2004). Because the mangrove areas are small, no commercial harvesting or large scale deforestation takes place in South Africa. There are also no aquaculture ventures. However harvesting of mangroves for local construction purposes, firewood and fish traps can change population structure and causes canopy gaps leading to dry, saline soil which are unsuitable for recolonization (Rajkaran and Adams, 2010). In the rural areas a major threat is cattle trampling and browsing as cows and goats roam free. Land use changes and removal of riparian vegetation can cause changes in run-off, increase sediment input and introduce nutrients, herbicides and pesticides depending on the surrounding agricultural use (Hoppe-Speer and Adams, 2015, Table 1). Disturbance also leads to alien plant invasion. Anthropogenic pollution effects include the detrimental influence of coal dust on mangroves and oil pollution (Naidoo, 2016) and the deposition and consumption of microplastics by juvenile fish in mangrove forests (Naidoo et al., 2020). Trace metals from urban and industrial pollution accumulate in roots and adversely affect morphological and physiological processes (Naidoo et al., 2014).

Over the past 80 years, ecologists in South Africa have built a comprehensive database on estuarine ecosystems that provides baseline information against which the response to global change by the continent's most southerly mangroves can be measured. The interactions between mangroves and people are fairly well studied. Using these historical records, change in mangrove distribution and extent was documented by Ward and Steinke (1982), Adams et al. (2004), Rajkaran and Adams (2011), Hoppe-Speer et al. (2015) and Adams et al. (2016). This paper updates previously published studies and includes records dating back to the 1930s when aerial photographs first became available. It aims to assess present mangrove status in terms of area cover and habitat loss, and identify past patterns of change so these can be used to predict future change and guide conservation and restoration initiatives. By documenting pressures, interactions between mangroves and people are highlighted. Results from this study were included in South Africa's 2018 National Biodiversity Assessment (Van Niekerk et al., 2019).

Table 1
Anthropogenic pressures causing abiotic and biotic changes in the mangroves of South Africa.

Pressure	Abiotic Change	Biotic Response	Reference
Coastal development	Removal of habitat	Loss of mangroves	Bruton and Appleton (1975) Rajkaran and Adams (2011) Adams et al. (2016)
Mangrove harvesting for building poles and firewood	Open canopies resulting in dry, saline sediment	Change in population structure	Adams et al. (2004) Rajkaran and Adams (2010) Hoppe-Speer et al. (2015)
Livestock browsing and trampling	Sediment compaction	Breaking of plants, patchy bare areas form	Adams et al. (2004) Hoppe-Speer and Adams (2015)
Restriction in tidal exchange	Freshening, decrease in salinity	Loss of mangrove trees and associated biota	Forbes and Demetriades (2009) Rajkaran and Adams (2011) Adams and Human (2016)
Freshwater abstraction	Estuary mouth closure, increase in water level	Die-back of mangrove trees and shrubs (*Avicennia marina*)	Hoppe-Speer et al. (2013) Adams and Human (2016) Mbense et al. (2016)
Heavy metal pollution	Low metal accumulation In anoxic and waterlogged sediments, fixation by clays and chelation by organic complexes and iron plaques	Adversely affect mangrove tree morphology and physiology	Naidoo et al. (2014)
Oil pollution	Oil settles with the tide in low wave energy areas	Smothers roots, reduced photosynthesis and growth	Naidoo et al. (2010) Veldkornet et al. (2020)
Coal dust	Coats leaves including stomata, reduces incident light and decreases CO_2 uptake	Reduced photosynthesis and growth of *Avicennia marina*	Naidoo and Chirkoot (2014)
Eutrophication	Increase in nutrients	Growth of macroalgae	Geldenhuys et al. (2016)
Disturbance of riparian vegetation	Bare banks and open areas	Spread of Invasive alien plants	Hoppe-Speer et al. (2015)

The objective of this study was to describe the responses of mangroves to human impacts and predicted climate change responses. Anthropogenic pressures included in the study were urban and industrial development, harvesting for wood, livestock browsing and trampling, restriction in tidal exchange from infrastructure, freshwater abstraction causing mouth closure and freshening. Natural or climate drivers were sedimentation, floods, estuary mouth dynamics, storm surges and marine sediment deposition. The response of mangroves to future climate change scenarios was considered. This focused on macroscale conditions likely to affect mangrove habitats. Predicted climate change effects for the east coast of South Africa are an increase in sea level rise, increase in sea storms and wave height, increase in intensity of flooding events, droughts, salinisation and closed mouth conditions, increase in atmospheric CO_2 and temperature. To understand mesoscale processes, information is needed on the effect of hydrodynamics and sediment supply on mangroves at an estuary scale level. Microscale site interactions within a mangrove stand include measurements of surface elevation, geomorphic processes (accretion, autocompaction, nutrient addition) and biological processes (production and decomposition) (Woodroffe et al., 2016). Local factors such as wind, coastal hydrology and geomorphology can also significantly influence mangrove distribution and species richness (Schaeffer-Novelli et al. 1990, 2016; Leong et al., 2018). We have recently started to measure in situ elevation changes in mangrove systems using RSET; therefore this article only contains observations from field surveys and historical imagery on sedimentation.

2. Methods

The study focused on mangroves inhabiting estuaries along the east coast of South Africa between and including the tropical Kosi Estuary in the north and Tyolomnqa at the southern extremity (Fig. 1). Changes in the mangroves were based on published literature, mapping, recent field surveys as well as contextual knowledge gathered by the authors over more than 25 years as researchers working in the mangroves. Published literature was reviewed to gain an overview of historical changes in mangroves of these estuaries (Table 1). This was updated with an assessment of aerial photographs and recent field visits. Aerial photographs taken approximately 80 years ago were compared with recent (2019) aerial photographs and all available Google Earth images to document and map changes in mangrove distribution and extent. The same suite of photographs were used to identify pressures in the form of commercial developments, houses, roads, open grasslands, grazing pastures and agriculture. Pressures were identified for existing and historical mangrove areas as well as in the surrounding catchment.

There has been a long history of research along the east coast where regular field visits have documented pressures (Table 1). This pressure database was updated with recent visits to all estuaries indicated in Table 3 except for Mtakatye, Mtata, Xhora and Nqabarana. A comprehensive study on the changes in mangroves at Kosi Estuary was undertaken in 2016 as part of an environmental flow requirement study of the Department of Water and Sanitation, South Africa (DWS, 2016). Similarly, a study was conducted at the Mzimvubu Estuary (DWS, 2017). Recent mangrove assessments were also completed at uMgobezeleni and uMlalazi (Taylor 2016, 2020). Annual long-term monitoring of mangroves takes place at the St Lucia, Mngazana, Nxaxo and Nahoon estuaries as part of our research activities (Figs. 1 and 2).

Mangrove extent was digitized for those estuaries with mangroves using ESRI™ ArcMap 10.1 (2012) from orthorectified aerial photographs obtained from the Chief Directorate: National Geo-spatial Information (CD:NGI). These images have a 50 cm spatial resolution. The earliest images dated back to 1934/1937 and past mangrove cover thus represents the situation in the 1930s. Present mangrove cover in each image was mapped for 2018/2019 and the difference in area between images taken as habitat loss or gain. The poor quality of the earliest images could result in an over- or underestimation of the habitat area with an error of approximately 10%. Arcpad 10.1 loaded on Trimble Juno GPS was used to map the distribution of mangroves in the field for some estuaries. Mangrove loss was considered as that resulting directly from habitat removal for development or other human activities since the 1930s. It did not include loss from indirect causes such as density or biomass change or those related to water quality, flow or invasion by alien plants. The estimation of habitat change took into account physical features such as surrounding land use and elevation as the surrounding slope determines the sediment and other inputs to the estuary. Distribution of mangroves was evaluated according to estuary type based on the classification scheme of Van Niekerk et al. (2019) (Table 2). Table 2 provides detail on the percentage of time the mouth of the estuary is open to the sea on an annual basis, the tidal and salinity ranges, dominant mixing process and sediment stability. The latter refers to the estuary scale and the response of sediment to freshwater flooding. To determine the proportion of mangroves under legal protection, relevant data were extracted from the estuary component of South Africa's 2012 National Biodiversity Report (Van Niekerk and Turpie, 2012).

The study outcome was incorporated into the DPSIR (Drivers-Pressures-State-Impacts-Responses) framework to highlight governance and management responses. It is a useful way to understand links between the environment and stakeholders (UNEP, 2006; Atkins et al., 2011; Goble et al., 2017) and has been applied previously to the management of mangroves (Lin et al., 2007; Sarmin et al., 2016; Quinn et al., 2017). Drivers in the framework are anthropogenic activities causing Pressures that lead to specific environmental States and Impacts that affect the health and value of ecosystems. Impacts stimulate a societal Response usually in the form of legislation and policies (Maxim et al., 2009; Elliott et al., 2017).

3. Results and discussion

3.1. Mangrove distribution

Total mangrove area in South Africa is 1672 ha. Mangroves occur in 32 estuaries with 56% of the total area occurring in 18 predominantly open estuaries and 21% of the total area in three estuarine lakes (Tables 2 and 3). Less than 1% of the total mangrove area is found in large temporarily closed and large fluvially dominated systems. Mangroves occur in all predominantly open estuaries in the subtropical/tropical region (Fig. 1). They do not occur in estuarine lagoons as there is only one of these and it is located on the temperate west coast. In small temporarily closed and fluvially dominated estuaries, the intertidal habitat is either absent when the mouth is closed or too small (<5 m) for mangrove colonization.

3.2. Habitat gain

Table 3 shows the change in extent of mangrove habitat in 16 estuaries where the total estuary area is larger than 10 ha. Overall, mangrove area has increased in South Africa due to habitat expansion at the uMhlathuze Estuary (Table 3). Half of the natural system became a harbour, an artificial mouth was then created for the uMhlathuze sanctuary that produced a large intertidal habitat and delta (Bedin, 2001). *Avicennia marina* rapidly colonized this habitat increasing its area cover from 80 ha in 1975 to 793 ha in 2018. This novel ecosystem currently supports the largest mangrove area (47% of total in South Africa), which compensates for the losses experienced in estuaries such as Durban Bay.

Management interventions have maintained the mouth of the uMlalazi Estuary in an open state that has promoted mangrove colonization and expansion (Taylor, 2020). Historical records show that prior to the 1930s there were no mangroves present. These colonized later over several years and currently occupy 61 ha (Table 3). At Kosi Estuarine Lake, sediment accumulated by traditional fish traps creates new islands for mangroves to colonize (Green et al., 2006); they also regrow

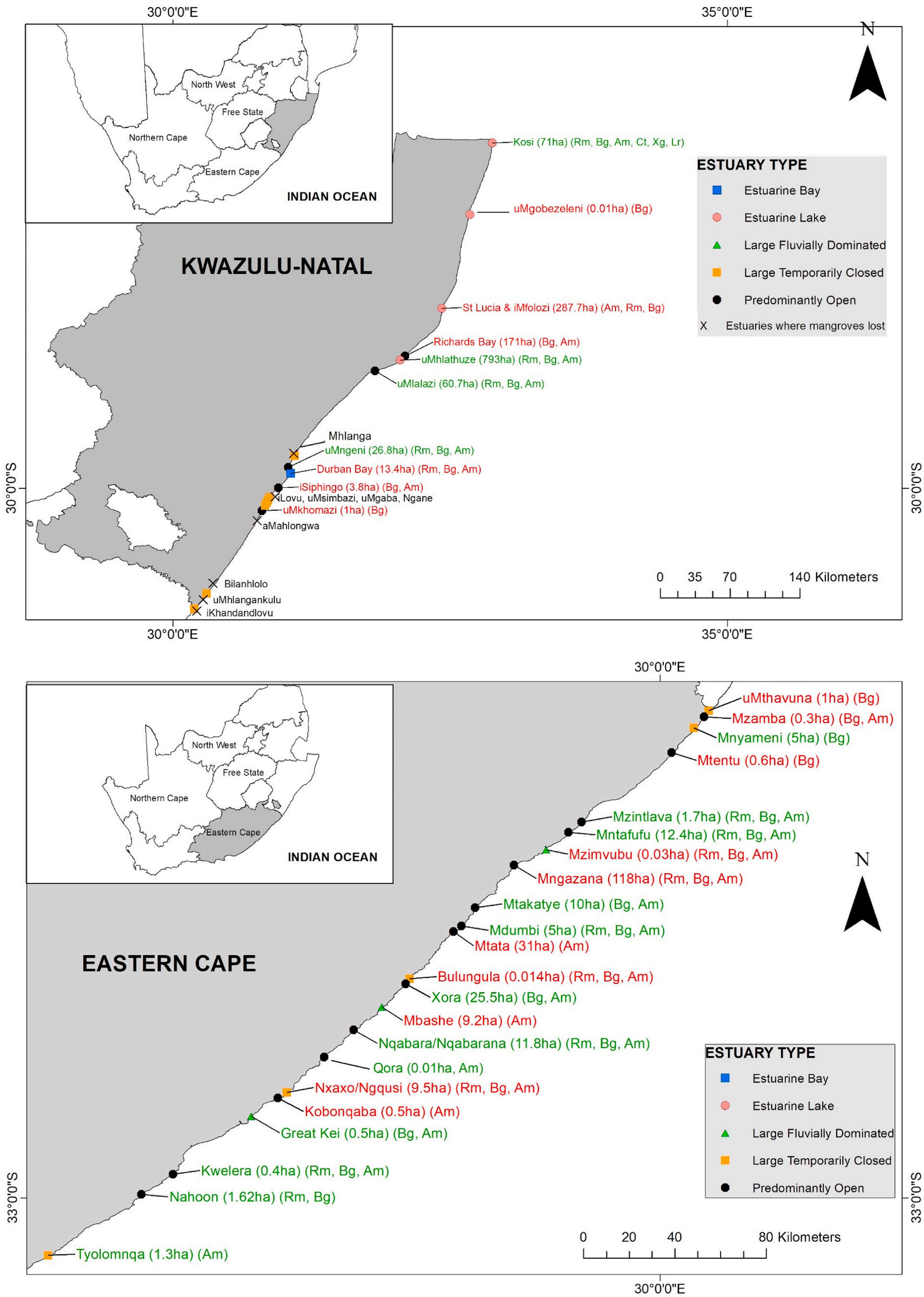

Fig. 1. Distribution and extent (ha) of mangroves in South African estuaries for the KwaZulu-Natal (a) and Eastern Cape (b) provinces. Red estuary name indicates where there has been a decrease in mangrove area and green, an increase. Distribution of dominant species is shown (Am = *Avicennia marina*, Bg = *Bruguiera gymnorrhiza*, *Ceriops tagal*, Lm = *Lumnitzera racemosa*, Rm = *Rhizophora mucronata* and Xg = *Xylocarpus granatum*). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

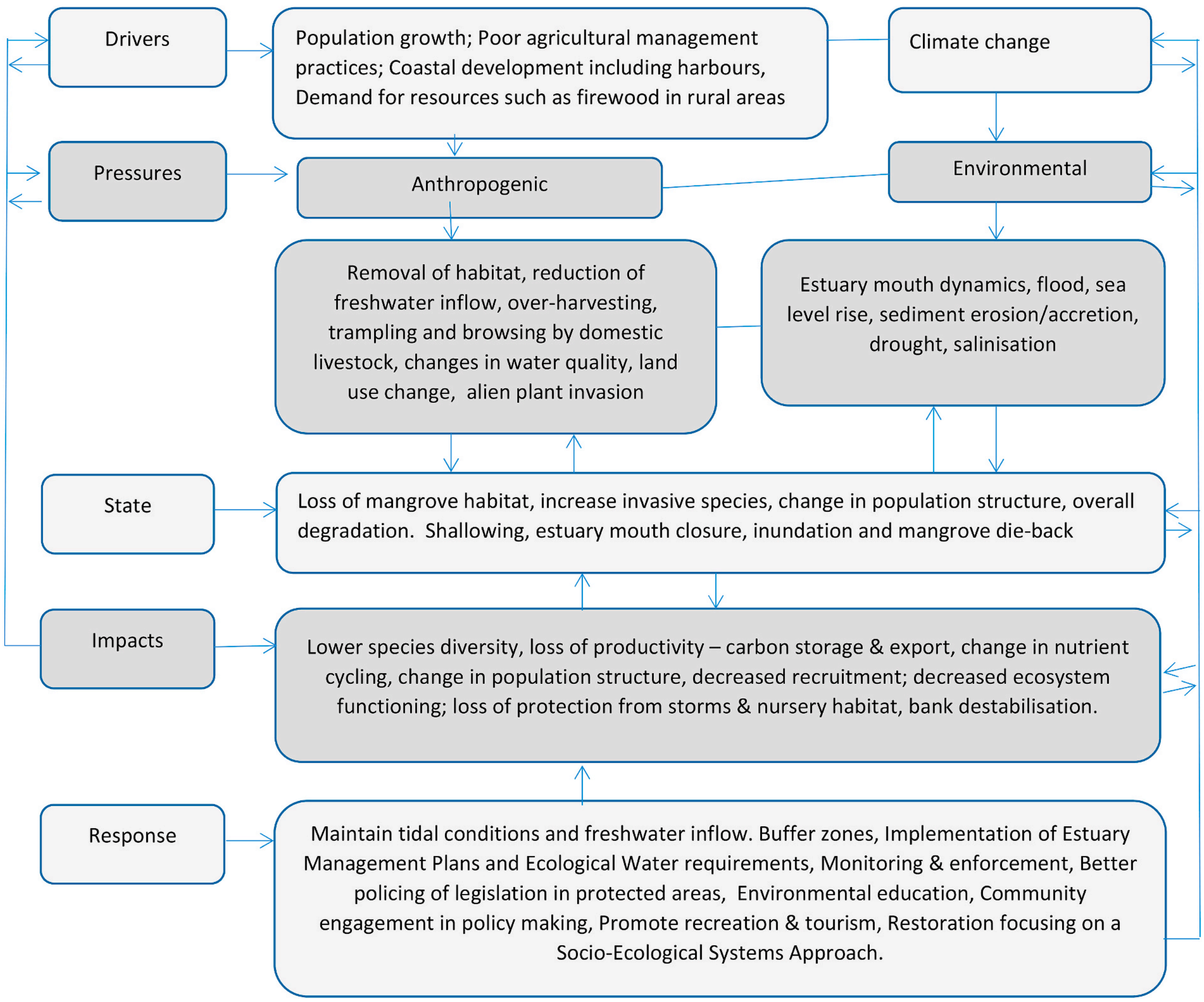

Fig. 2. Status of mangroves in South Africa described using the Driver – Pressure – State – Impact – Response framework. Maintain tidal conditions and freshwater inflow. Buffer zones, Implementation of Estuary Management Plans and Ecological Water requirements, Monitoring & enforcement, Better policing of legislation in protected areas, Environmental education, Community engagement in policy making, Promote recreation & tourism, Restoration focusing on a Socio-Ecological Systems Approach.

Table 2
Distribution of mangroves in different estuary types (number of estuaries and percentage of total mangrove area in the country). South Africa's nine estuary types occur in four biogeographic regions (characteristics revised from Van Niekerk et al., 2019).

ESTUARINE TYPE	Mangrove area % of total for country (no. of estuaries)	ESTUARINE AREA (ha)	% TIME OPEN TO THE SEA	AVERAGE TIDAL RANGE (m)	TYPICAL SALINITY RANGE	MIXING PROCESS	SEDIMENT STABILITY	MEAN ANNUAL RUNOFF (x 10^6 m^3)
Estuarine Bay	11 (2)	>1000	100	1.5–2.0	30–35	Tidal	Stable	40–80
Predominantly Open	56 (18)	10–7500	90–100	0.75–1.5	0–40	Tidal/riverine	Mobile reset by floods	10–1790
Estuarine Lake	21 (3)	>800	Variable	0.1–0.15	0–35	Wind/riverine	Stable	20–650
Large Fluvially Dominated	1 (3)	100 - 3700	>90	0.5–1.0	0–10	Riverine	Highly mobile reset annually	370–10 830
Large Temporarily Closed	1 (6)	>15	>50	0.25–0.5	0–60	Tidal/riverine/wind	Mobile breachings & floods	1–280
Small Temporarily Closed	0	<15	<50	0.15–0.3	0–30	Riverine/wind	Mobile breachings & floods	0.1–70
Estuarine Lagoon	0	>5000	100	1.5–2.0	35–36	Tidal	Stable	0
Small Fluvially Dominated	0	<15	100	0.5–1.5	0–5	Riverine	Highly mobile & reset annually	20–50
Arid Predominantly Closed	0	10–500	<5	0	Hypersaline	Evaporation/seepage/wind	Stable, but reset on decadal-scales	0.2–10

Table 3
Past and present mangrove areas (ha) in South Africa for estuaries with greater than 10 ha, pressures and protection status. Shaded pink rows indicate estuaries where there have been mangrove losses and grey gains in mangrove area.

Estuary	Past area (ha) 1930s	Present area (ha) 2019	Pressures	Protection status
TOTAL FOR COUNTRY	**1537**	**1672**		
Kosi Bay	60.7	71	Harvesting for wood & fish traps, cattle trampling Increase due to sedimentation and expansion	iSimangaliso Wetland Park Authority
St Lucia & iMfolozi	331	288	Relinked to degraded Mfolozi catchment, mouth closed, freshening and silt	iSimangaliso Wetland Park Authority
Richards Bay	267	171	Harbour expansion and removal of habitat	Echwebeni site of conservation significance
uMhlathuze	80	793	Expansion in response to artificial mouth and increase in intertidal area, current pressures :dredging, silt and sediment deposition	Ezemvelo KwaZulu-Natal Wildlife
uMlalazi	30	60.7	Sedimentation, mouth is kept open allowing expansion	Ezemvelo KwaZulu-Natal Wildlife
uMngeni	20.3	26.8	Sedimentation and natural expansion, growing water quality threats and mouth restriction.	Beachwood Mangrove reserve, Ezemvelo KwaZulu-Natal Wildlife
Durban Bay	451	13.4	Harbour expansion and removal of mangroves	Bayhead Natural Heritage Site
iSiphingo	12.5	3.8	Development, tidal restriction, poor water quality	None
Mntafufu	10	12.4	Expansion due to sediment stability Harvesting for wood and bark	None
Mngazana	145	118	Harvesting, cattle and human trampling, sand mining	None
Mtakatye	7.7	10	Increase due to sedimentation, cattle browsing, harvesting	None
Mtata	42	31	Harvesting	None
Xhora	16	25.5	Cattle browsing, harvesting	None
Mbashe	12.5	9.2	Cattle browsing, harvesting	Dwesa-Cwebe Marine Protected Area
Nqabarana/ Nqabara	9	11.8	Increase due to sedimentation, cattle browsing, harvesting	None
Nxaxo/Ngqusi	14	9.5	Cattle browsing, harvesting, trampling	None

Mangroves have been completely lost from the Little Amanzimtoti, Lovu, Msimbazi, Mgababa, Ngane, Mhlongwa, Kongweni, Bilanhlolo, Mlangankulu, Khandandlovu estuaries (approximate total area 7 ha)
Due to range shifts and planting mangroves now present in Kei, Kwelera, Nahoon and Tyolomnqa estuaries (approximate total area 3.1 ha)

from cut stems used for the fish traps (Plate 1a). In 1995, a cyclone that caused mouth closure and subsequent flooding decimated the mangrove community. Of management concern are future mouth closures that can destroy this important habitat, and intensive harvesting of trees and shrubs for fish trap maintenance that has resulted in shorter, coppicing trees.

Due to possible range shifts (Kei, Kwelera, Gqunube estuaries) and tree planting (Nahoon and Tyolomnqa estuaries) mangroves have extended their distribution southwards where their total area is 3.1 ha (Fig. 1). These new occurrences have occurred over the last 10 years and thus range expansion is slow. Only one individual of *A. marina* was recorded in the Gqunube Estuary. There is a stand of *A. marina* close to the mouth of the Kwelera Estuary and seedlings are establishing upstream (Bolosha, 2017). While at Tyolomnqa, the mangroves occur as patches with intact canopies but do not occur amongst the salt marsh. Mangroves were planted here in the 1990's and occur as three specific populations along the estuary.

Plate 1a. Mangroves at Kosi Estuary growing from the fish traps.

In Nahoon Estuary, a transition from salt marsh to a marsh-mangrove ecotone and finally a zone of only mangroves occurs in the lower to mid intertidal area (Geldenhuys et al., 2016). Mangroves were planted here between 1965 and 1975 and although the community is small in extent, it has expanded at a rate of 0.06 ha per annum and is expected to grow faster in the higher temperatures predicted for future climate change scenarios (Hoppe-Speer et al., 2015). These mangroves are protected within the Nahoon Estuary Nature Reserve; they grow rapidly experiencing few pressures, and are recognised as an important conservation and ecotourism site. Overall, mangrove area along the South Africa coast has increased because new habitat or intertidal areas have been created by changes in mouth condition and marine connectivity as indicated for example by recorded changes in the uMhlathuze, uMlalazi and Nahoon estuaries. In contrast, expansion at a southernmost site in New Zealand was related to land-based changes such as a loss of forest cover in catchment areas, erosion and downstream sediment accumulation, which caused mangroves to expand seawards into mudflats (Suyadi et al., 2019).

3.3. Habitat loss from anthropogenic pressures

Mangrove cover has declined in small and large temporarily closed systems but increased in estuarine bays (Table 3). This is attributable to the increase recorded at uMhlathuze Estuary which supports 793 ha and contributes 47% to the total mangrove cover in the country. The second highest area cover was found at St Lucia Estuary (288 ha) to the north (Table 3). There is an almost equal number of estuaries where mangrove extent has increased or decreased (Fig. 1). The driver of change is mostly linked to mouth condition and connection with the sea. Multiple pressures can make it difficult to assess the direction of change. For example at Kosi Estuary man-made fish traps have caused shallowing in some places encouraging mangrove growth, but fires, tree harvesting, cattle browsing and trampling in other places have countered this apparent expansion (DWS, 2016).

Mangroves have been completely lost from 10 temporarily closed estuaries (large and small); amounting to an approximate total area of 7 ha (Table 3). This is indicative of changes in freshwater inflow that can cause the mouth of an estuary to close to the sea and to become freshwater dominated; both conditions unfavourable for mangrove colonization and growth (Adams et al., 2004). Comparing historic (1930s) and more recent (2006) states of stands in small estuaries from uMlalazi to uMthavuna illustrates this decline, which was attributed to infilling for road and railway bridges, sugar cane cultivation, siltation, and reduced freshwater inflow (Rajkaran et al., 2009). At uMgobezeleni Estuary a road bridge built across the estuary in the 1970s raised the water level and killed the mangrove trees (Taylor, 2016). Currently a few tall (>18 m) *Bruguiera gymnorrhiza* trees remain with some seedlings observed by Peer et al. (2018).

Although the mangrove areas lost are small, the effect has been a reduction in habitat connectivity along the coastline (Fig. 1). Further south along the Eastern Cape coast, pressures related to harvesting, cattle browsing and changes in mouth condition are increasing (Table 3). The Mngazana Estuary supports the largest mangrove area in the temperate/subtropical transition area (Fig. 1) and the largest *R. mucronata* stand in the country. Measures are needed to protect this species such as restricting harvesting and preventing trampling of seedlings by livestock and people.

Almost 440 ha of mangrove was removed from Durban Bay during construction of the Port of Durban, the busiest harbour in the country. Development of the port started in the 1840s. At that time the bay contained the largest mangrove community in the country of which only 13.4 ha remains within a protected natural heritage site (Begg, 1978; Forbes and Demetriades, 2009). Infilling, reclamation and dredging lead to the loss of wetlands, marshes and intertidal reaches that made way for the harbour's concrete walls. The last remaining area of seagrass habitat was lost in the 1960s. Storm water drains flowing through industrial and residential areas deposit nutrient and chemical laden water and large quantities of litter into the estuary. Similarly, the second largest loss of mangrove resulted from the construction of Richards Bay harbour (Table 3). Built for the export of coal, construction began in 1972 and the first phase of the harbour was opened in April 1976 (http://www.kzntransport.gov.za/public_trans/freight_databank/kzn/ports/Richards_Bay/index_xml.html).

Dynamic changes in the St Lucia/iMfolozi estuarine system have also led to loss of mangroves. Extensive dredging over 50 years kept the mouth open and allowed tidal exchange and mangrove expansion (Adams and Human, 2016). Since 2002, the mouth has been closed to the sea because of drought and changes in management practices. To restore freshwater inflow into the system, the iMfolozi River was reconnected to St Lucia Estuary but without catchment rehabilitation. Freshwater inflow and silt loading increased causing flooding and reed encroachment in mangrove areas (Plate 1b). Long-term monitoring reported on mangrove dieback in response to inundation (Adams and Human, 2016) which is the ongoing situation.

From the Mntafufu to Nxaxo estuaries harvesting of mangrove trees and shrubs takes place in all estuaries (Fig. 1, Table 3). This part of the country is the rural Eastern Cape where wood is used for construction and firewood. Mangroves occur as fringe stands along the main estuary channel making them easily accessible to harvesters (Adams et al., 2004). Harvesting took place at 75% of estuaries included in an Eastern Cape study (Hoppe-Speer et al., 2014) and a rate of loss of 1 ha year^{-1} was recorded at Mngazana Estuary (Rajkaran and Adams, 2010). *Rhizophora mucronata* was harvested intensively wherever it occurred (14 of 19 sites) because it provides sturdy poles for building material (Rajkaran et al., 2004). Measures are needed to protect this species at the Mngazana Estuary. Bark harvesting for medicinal uses is commonly observed for *Bruguiera gymorrhiza* at Mntafufu, this activity does not kill the individual but these trees may be more susceptible to changes in health.

Plate 1b. Reed encroachment at St Lucia Estuary and die-back of mangroves.

The absence of mangrove seedlings in at least 35% of rural estuaries visited in research surveys is evidence of the severe impact cattle trampling and browsing has on mangrove habitats (Hoppe-Speer et al., 2015). At the Nxaxo and Bulungula estuaries, long-term monitoring pointed to these stressors and changes in rainfall patterns as causes of notable mangrove die-back and salinisation (Plate 1c) (Adams et al., 2004). While the obvious solution would be to exclude cattle (Minchinton et al., 2019), this would be difficult to implement in cases of communal land ownership where traditionally livestock roam free. At Kobonqaba Estuary, drought, mouth closure and flooding caused *Avicennia marina* die-back. Mangroves in this system were inundated for five months and dead trees were subsequently harvested by the local community (Mbense et al., 2016).

3.4. Response to climate change

Macroscale conditions likely to affect mangrove habitats in future climate change scenarios are presented in Table 4. Predicted rates for relative sea level rise on the east coast of South Africa is 2.74 mm yr^{-1} (Mather et al., 2009; Van Niekerk and Turpie, 2012). This scenario may lead to an increase in open mouth conditions in temporarily closed estuaries creating favourable habitat for mangrove colonization. Where the steepness of adjacent terrestrial areas and coastal development prohibit expansion, mangroves may be lost but without these limitations, mangroves are likely to continually expand into areas of newly accreted sediment. Mangroves can adjust to sea-level rise but this depends upon the rates of rSLR and sediment supply (Woodroffe, 2018). At Mngazana Estuary (South Africa) Yang et al. (2014) showed that if there is sea level rise and horizontal accommodation space then mangroves will expand landward. Accommodation space is that available for potential sediment accumulation. Mangroves will persist in conditions where there is a continual increase in vertical accommodation space as ocean height increases and land subsides (Krauss et al., 2013). Mangroves quickly generate roots that grow into newly accumulated sediment, promoting soil development and elevation change. They can modify their surface elevation and so maintain their relative position in

Table 4
Response of mangroves to predicted climate changes.

	Abiotic change	Mangrove response
↑Sea level rise +1.5–2.7 mm.yr^{-1} ↑Open mouth condition	Inundation & waterlogging Change in sediment biogeochemistry	• Expansion of mangroves in intertidal • Inland/landward migration of mangroves
↑Sea storms & wave height	Erosion Deposition of marine sediment	• Loss of mangroves • Smothering e.g. of pneumatophores
↑Floods	↑ Nutrient inputs & eutrophication ↑Sediment input	• Mangrove expansion • Or mangrove loss due to sediment deposition & smothering
↑Droughts ↑Closed mouth condition	↑Salinity and aridity ↑Water level & inundation, loss of intertidal habitat	• Decrease in productivity. • Loss of mangrove cover • Flooding and loss of mangroves
↑CO_2	Higher C availability	• Increase in plant growth & productivity
↑Temperature	Warming	• Increase in plant growth & productivity. • Mangroves replace salt marsh. • Distributional range shifts and change in habitat diversity. • Increase in invasive species.

the tidal frame. If accretion does not keep pace with increases in sea level the ecosystem will collapse (Asbridge et al., 2015; Friess et al., 2019). To conserve mangrove habitat it is important for us to identify those estuaries for climate change adaptation and protection where mangroves can expand inland. In South Africa we do not know if mangrove habitats are accreting or subsiding and have started to install relative surface-elevation tables (RSETs) to measure this (Adams et al., 2020). Preliminary data for the mangroves at Nxaxo and Nahoon estuaries showed an increase in surface elevation between 2018 and 2019. Accretion marker horizons and isotope analysis from soil cores are also needed to assess the vulnerability of mangroves to sea level rise.

Climate change predictions point towards an increase in the intensity and frequency of seasonal sea storms accompanied by increased heat and moisture (Van Niekerk and Turpie, 2012). In some cases this can cause the deposition of marine sediments leading to smothering and die-back. In 2009, a severe sea storm at Mbashe Estuary resulted in the deposition of large sediment volumes that smothered the pneumatophores of *A. marina*. By 2012, many trees had died and the mangrove habitat had become colonised by salt marsh plants (James et al., 2020). Sediment smothering of aerial roots inhibits oxygen exchange, enhances root anoxia and consequently kills the tree. This phenomenon has also been recorded at the Mbashe, Mzamba and Nqabarha estuaries (Hoppe-Speer et al., 2015).

Inundation of mangroves and die-back following cyclones occurred at the Kosi and St Lucia estuaries (Breen and Hill, 1969; Steinke and Ward, 1989). In 1984, Cyclone Domoina increased water depth in the St Lucia Estuary, South Africa by 10–14 m, flooding the mangroves and causing widespread mortality after four months inundation. Cyclone winds also damage trees through breaking branches and defoliating canopies (Doyle et al., 1995; Macamo et al., 2016).

Expected increases in precipitation and intense flooding impact mangroves through eroding habitats or smothering by catchment-derived sediment. Higher rainfall volumes increase riverine discharge and allochthonous sediment inputs, elevating mangrove surfaces and resilience to sea level rise (Ranasinghe et al., 2013). The quality, rate, magnitude and timing of freshwater runoff to estuaries is expected to differ between the east and west coasts of South Africa with more rain days and higher rainfall predicted for the east coast (Van Niekerk and Turpie, 2012). These changes will alter the frequency and duration of estuary mouth closures and rework salinity profiles resulting in modified nutrient and sediment budgets. Whether mangrove growth is stimulated or inhibited depends on prevailing estuarine conditions. In Kobonqaba Estuary, drought combined with low freshwater inflow and sediment deposition following a turbulent sea storm caused the mouth to close for the first time (Mbense et al., 2016). Salt marsh replaced the mangrove habitat over the next four years.

In other small estuaries, mangroves were removed after flooding events but returned. For example no mangroves were found at Mnyameni, Mzimvubu and Bulungula estuaries in 1999 surveys but were recorded later in 2011/2012 (Adams et al., 2004; Hoppe-Speer et al., 2015) (Table 5). Freshwater flooding at Mnyameni and Mzimvubu caused temporary dieback with trees becoming re-established 11 years later; mangroves were replanted at Bulungula Estuary. These natural dynamics need to be taken into consideration in conservation and management plans.

Expected continental air temperature warming of 1 °C–3 °C and an increase in CO_2 are conditions conducive to mangroves expanding their distribution beyond their existing ranges and latitudes (Naidoo, 2016). Poleward range expansion has been documented (Saintilan et al., 2014; Cavanaugh et al., 2014; Osland et al., 2017). In South Africa successful colonization however depends on the effectiveness of propagule dispersal between estuaries and the availability of suitable habitats. The mangrove plantation in the Nahoon Estuary is located south of the widely acknowledged mangrove range limit. Mangroves are healthy and the stand is expanding indicating that species range limits are not in equilibrium with climate induced or physiological limits (Quisthoudt et al., 2013; Saintilan et al., 2014; Hoppe-Speer et al., 2015). Global warming creates suitable sites for expansion beyond current distributional levels. In temperate areas, especially those that are near the latitudinal limit of mangrove distribution cold temperatures that are less than 5 °C (freezes/frost) may kill mangroves. A reduction in the frequency and severity of freeze events has been identified as a critical driver of mangrove expansion along the eastern United States (Stuart et al., 2007; Cavanaugh et al., 2014; Osland et al., 2017).

Along the east coast of South Africa, predicted meso-scale meandering of the Agulhas current will alter coastal climate, increase shelf upwelling and limit connectivity between estuaries (Van Niekerk and Turpie, 2012). Changes are expected in the dispersal patterns of mangrove propagules and therefore gene flow. Dispersal is a key process in mangrove survival because it allows species to shift their distributions and regenerate elsewhere in response to a changing climate (Van der Stocken et al., 2019). Genetic studies indicate that there is limited connectivity between *A. marina* communities along the east coast of South Africa (De Ryck et al., 2016). Our field work shows that successful recruitment can be linked to flooding and connectivity with the sea. In the freshwater dominated Mzimvubu Estuary, trees are of similar size and occur in a straight line parallel to the bank amongst the reeds (Plate 1d), suggesting colonization through one large recruitment event possibly associated with king tides (1 in 18.6 year events). An increase in the intensity of freshwater floods predicted for the east coast will however scour banks and completely remove mangroves in the small estuaries (Table 5). The fragmented distribution of mangroves along the

Table 5
Recorded changes in mangrove area (ha) in small estuaries.

Estuary	1982	1999	2012	2019
	Ward & Steinke	Adams et al. (2004)	Hoppe-Speer et al. (2014)	This study
Mnyameni	3	0 (floods)	5	5
Mzimvubu	1	0 (floods)	0.03	0.03
Bulungula	3.5	0 (mouth closure)	0.01	0.04
Kobonqaba	6	3.5 (mouth closure)	0.05	0.05

coast and the lack of seedlings in many systems makes them sensitive to disturbance and may limit their resilience.

This study has shown that while anthropogenic disturbances are confined mainly but not exclusively to harvesting and cattle browsing and occur widely and continuously over decades, natural events that lead to flooding and mouth closures are unpredictable, take place less often but have the potential to cause die-back of entire mangrove stands.

3.5. Protection status and future management

Table 3 indicates that there is some protection status for estuaries with large mangrove areas in South Africa. Approximately 75% of the total mangrove area occurs in protected areas. This is good news but does not imply that the mangroves are healthy. For example at St Lucia Estuary there is dieback due to freshening, closed mouth conditions and a high silt load. Mangrove expansion has been related to protection afforded by nature reserves and inaccessible terrain particularly along the Eastern Cape coast where increased colonization and growth of seedlings were recorded in the Mtentu, Mzintlava, Mntafufu, Mtakatye, Mtata, Xora, Mbashe and Nxaxo estuaries (Adams et al., 2004). Along the KwaZulu-Natal coastline, large mangrove communities of St Lucia and Kosi Bay estuaries are well protected within the isiMangaliso Wetland Park, a World Heritage and Ramsar site (Table 3). Other estuaries that fall within a nature reserve or protected area include uMthavuna, Mnyameni, Mtentu and Mbashe.

Fig. 2 describes the status of mangroves using the Driver – Pressure – State – Impact – Response (DPSIR) framework. Climate change, population growth, agriculture and coastal development result in reductions in freshwater inflow, over-use of mangroves, increased browsing by livestock, and changes in water quality and land use. A practical response to illegal harvesting is to provide alternative sources of fuel through establishing wood lots in rural areas. Other actions necessary to protect mangroves are the introduction of buffer zones to prevent sediment and nutrient inputs. Domestic animal browsing is a growing threat causing extensive die-back particularly in drought-stricken areas (Plate 1c). Each estuary is a unique case study with specific drivers, state and management responses. A single DPSIR model cannot be applied in all cases.

The location of an estuary determines its management issues and specific typologies can be compiled for rural, urban and protected systems. In terms of governance response, appropriate and excellent legislation is available to address the range of problems. Environmental legislation is however not implemented. For example, the failure to police illegal freshwater abstraction in support of the ecological water requirements of estuaries as promulgated under the National Water Act has resulted in mouth closure and mangrove die-back in several estuaries (Hoppe-Speer et al., 2015; Mbense et al., 2016). In addition, although Estuary Management Plans (EMPs) are legally required for every estuary as part of the Integrated Environmental Management Act,

Plate 1c. Dieback of mangroves at the Nxaxo Estuary due to drought and cattle browsing.

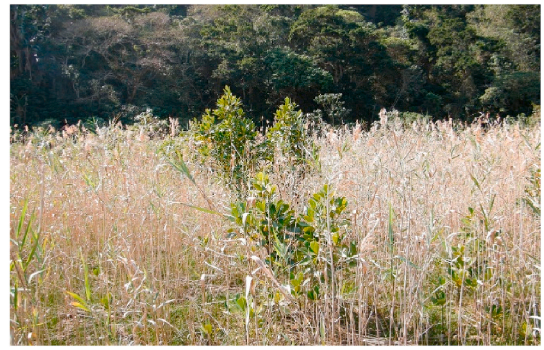

Plate 1d. The distribution of mangroves in the Mzimvubu Estuary a freshwater dominated system.

EMPs are available for only four mangrove supporting estuaries, namely Nahoon, iSiphingo, Durban Bay and uMhlathuze. According to the Natural Forest Act (Act No. 84 of 1998), harvesting mangrove trees (*B. gymnorrhiza* and *R. mucronata*) is illegal yet observed regularly during research excursions.

The outcome of this study can be used to highlight mangroves in need of formal protection such as those at Mngazana Estuary. In another positive development, several environment oriented government departments have been amalgamated into a unified Department of Environment, Forestry and Fisheries, which will facilitate the essential process of co-operative governance. Future activities aimed at conserving and protecting mangrove ecosystems needs to prioritize and track changes in the health of the Kosi (only estuary supporting five mangrove species), uMhlathuze (largest mangrove area) and Mngazana (largest area of red mangroves) estuaries. Although long-term monitoring research is ongoing at the St Lucia, Nxaxo and Nahoon estuaries, a co-ordinated national programme is needed to address the health and restoration of mangrove ecosystems. Long-term datasets are also needed to understand the change in the frequency and intensity of climatic cycles such as El Nino. A socio-ecological systems approach may be key to addressing the lack of alignment between legislation, governance, implementation and social commitment.

4. Conclusion

Mangroves situated at latitudinal limits provide interesting sites to monitor long-term climate change responses. South Africa mangroves provide insight on the expansion of mangroves into salt marsh, response of closed estuaries to increases in sea level and response of small mangrove systems to floods and droughts. Future increases in mangrove habitat in South Africa are likely to be constrained by the absence of suitable habitat because of the limited number of permanently open estuaries with intertidal habitat. Assessing and understanding the connectivity between mangrove forests and the minimum requirements for successful seed dispersal and colonization of new areas are important future research areas.

Assessment of changes in mangrove extent provides a baseline against which future ecosystem shifts can be measured. Although their total area is relatively small in South Africa, mangroves are important biodiversity elements that persist in high energy, mobile coastal environments. Historical data have allowed long-term changes to be tracked and the outcome has contributed to global knowledge on mangrove responses at a range limit. Future research is needed to generate change-related data equivalent to those in better studied regions such as Australia/New Zealand and the Americas. Without baseline data on responses to individual stressors, we cannot understand or predict responses to interacting stressors. Estuary conservation and management plans need to include future changes in climate to ensure the protection of mangrove forests at this southern distributional limit.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Janine B. Adams: Funding acquisition, Formal analysis, Writing - original draft, Conceptualization, Data curation. **Anusha Rajkaran:** Writing - review & editing, Conceptualization, Data curation.

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