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Salt marsh at the tip of Africa: Patterns, processes and changes in response to climate change

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ABSTRACT

This study developed a conceptual understanding of climate change responses of salt marsh in open and closed estuaries and outlined changes in terms of implications for ecosystem services. Changes in salt marsh cover in South Africa were described in relation to prevailing pressures. Salt marshes occur in the sheltered estuaries distributed along the ~3000 km coastline. Supratidal salt marsh occurs at elevation greater than 1.5 m amsl and are dominant in the cool temperate (5328.28 ha) and intertidal salt marsh in the warm temperate region (2093.31 ha). Although small in total extent (14 955 ha), salt marshes play a central role in biodiversity conservation because they provide critical habitat for migratory fish and birds. Approximately 43% of salt marsh habitat has been lost due to encroaching development and agriculture from the 1930s to 2018. In addition, salinisation and desiccation resulting from upstream freshwater abstraction reduces freshwater inflow, which extends periods of mouth closure in temporarily closed estuaries causing inundation and flooding of salt marsh. Predicting the combined effects of multiple stressors (increase in storm surges, floods, droughts and reduced river flow) is critical to conserve these important habitats. Research and monitoring to understand salt marsh responses is ongoing because the interface between the subtropical and warm temperate coastal regions of South Africa is expected to be affected by mangrove range expansion. This study is globally relevant as little is known about southern hemisphere salt marshes in Africa and data are needed for comparative purposes.

1. Introduction

Salt marshes in South Africa occur in the sheltered estuaries distributed along the ~3000 km coastline. They lie alongside saline water bodies and support vegetation communities of herbs, grasses or low shrubs. Although mostly exposed to the air, the plants experience periodic flooding from tidal or non-tidal variations in water level of the adjacent water body (Adam et al., 2016). Some define salt marshes as areas subject to tidal influences (e.g. Weis and Butler, 2009) but in South Africa, they are also taken to include seldom flooded supratidal habitat that supports halophytic macrophyte communities. Supratidal salt marsh occurs at > 1.5 m amsl and leads into an ecotone area >2.5 m amsl that is inhabited by terrestrial plant species (Veldkornet et al., 2015a). The supratidal salt marsh may be flooded as little as twice a year during exceptional spring tide events (Adams et al., 1999). Habitat mapping for South African estuaries distinguishes between intertidal and supratidal salt marsh as they support different biotic communities and respond differently to abiotic drivers (Adams et al., 2019).

Although small in total extent South African salt marshes are important for biodiversity conservation as they serve as critical habitat for migratory fish and birds. Estuaries contain much of the only sheltered habitat along the highly exposed linear coastline (Beckley, 1984). Estuaries are important nursery habitats for juvenile marine fish species (Wallace et al., 1984; Beck et al., 2001; Whitfield, 2017) many of which are caught in coastal commercial and recreational fisheries (Lamberth et al., 2009; Whitfield and Pattrick, 2015; Edworthy and Strydom, 2016). Salt marshes serve as breeding, roosting and feeding areas for birds. In particular they provide important high tide and night time roosting areas and secondary feeding habitat (Saintilan et al., 2018). In the *Sarcocornia* intertidal salt marsh of the Langebaan Lagoon (South Africa) up to 5056 birds/km waders have been observed using the habitat as a food source at high tide (Summers and Kalejta-Summers, 1996). Little is known about the importance of the supratidal marsh but is a home to a diversity of spiders, rodents and reptiles. Peringuey's Leaf-toed Gecko (*Cryptactities peringueyi*) is the only gecko in the world that lives in salt marshes recorded at the Kromme Estuary, South Africa (Van Niekerk and Turpie, 2012).

Distribution of salt marsh along the South African coastline follows

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biogeographic zoning (Fig. 1). Mangroves replace salt marsh in the intertidal zone of open estuaries in the subtropical zone (Adams et al., 2016). Salt marsh species that have the widest distribution include *Bassia diffusa* (Thunb.) Kuntze, *Cotula coronopifolia* L., *Limonium linifolium* (L.f.) Kuntze, *Juncus kraussii* Hochst., *Phragmites australis* (Cav.) Steud and *Triglochin striata* Ruiz & Pav. Species occur in specific zones where the tidal elevation gradient is distinct; otherwise they form mosaics (Adams et al., 2016, Figs. 2 and 3). Global comparisons indicate that South African salt marshes are species rich as there are sharp transitions from fresh to saline and from lowland to upland areas or aquatic to terrestrial. At the land – estuary interface Veldkornet et al. (2015b) recorded over 95 different plant species many of which are halophytic in the supratidal salt marsh – terrestrial ecotone. Adam (1990) found only 45 species in saline areas in Britain whereas in the Georgia salt marshes (USA), Kunza and Pennings (2008) found 43 salt marsh species.

This study contributes to an understanding of the future of salt marshes and human benefits under climate change. Expected climate change conditions having a particular influence on salt marshes are sea level rise, increase in sea storms and wave height, changes in river discharge (droughts/floods), increased CO_2 levels and higher temperatures. This alters the key abiotic stressors – changing inundation patterns, salinity gradients and sediment biogeochemistry (e.g. organic matter supply). In this study, the relationship between these stressors, ecological processes and ecosystem attributes is described. The biogeographical patterns observed along the South African coastline present an important opportunity for climate change research as the transition between subtropical and warm temperate regions and between cool temperate and warm temperate regions are expected to be significantly influenced. Range expansions are already occurring due to warming as described in Whitfield et al. (2016). Van Niekerk (2018) has completed a recent assessment of climate change effects on South African estuaries providing an opportunity to evaluate salt marsh responses. Changes in ocean circulation processes are driving shifts in the coastal temperature regimes of the transitional zones, with related biological responses such as range extensions and contractions.

Fig. 2. Salt marsh plants occur in distinct zones along a tidal inundation gradient (Knysna Estuary).

Southern hemisphere estuaries differ from northern hemisphere systems in that they are predominantly microtidal (tidal range < 2 m) and small. In South Africa 70% of estuaries are less than 50 ha. Owing to strong wave action and high sediment availability, more than 90% of the estuaries have restricted inlets, with more than 75% closing for varying periods of time when a sandbar forms across the mouth (Cooper, 2001; Whitfield, 1992; Van Niekerk, 2018). The mean annual run-off of most South African rivers is variable, fluctuating between floods and

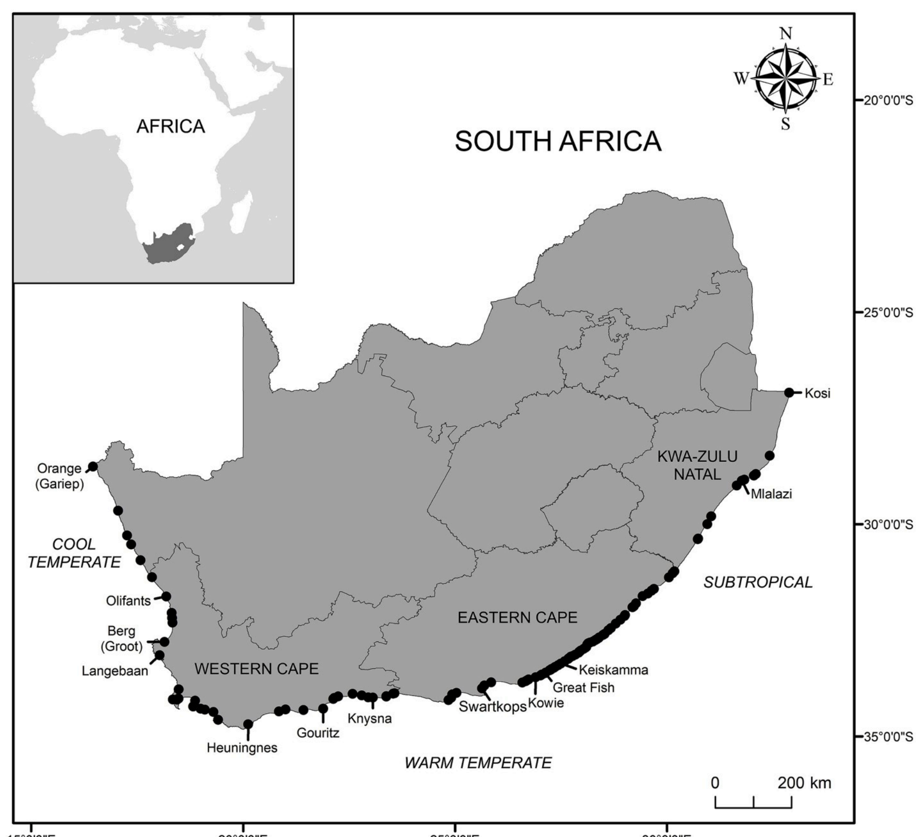

Fig. 1. Distribution of salt marsh along the coast of South Africa.

Fig. 3. Mosaic of salt marsh species in the Swartkops Estuary.

extremely low to zero flow; during low flow the mouth of the estuary remains closed to the sea. These factors and the dearth of coastal plain estuaries limit the establishment and development of salt marsh. Changes in salt marsh were considered for both open and closed estuaries as they will respond differently to predicted climate change. In closed estuaries the frequency and duration of open mouth conditions determines the extent of the salt marsh and the species found typically form a sub-set of the full suite of species occurring in permanently open estuaries (Adams et al., 2016). Similarly, in Australia fringing salt marsh persists during the closed phase of intermittently open coastal lagoons (Ross and Adam, 2013). Reduced freshwater inflow due to climate change will extend the duration of mouth closure resulting in high water level, flooding and dieback of salt marsh (Tabot and Adams, 2013).

Identification of ecosystem services (ES) is an important step towards the conservation of salt marsh habitats. The Millennium Ecosystem Assessment (2005) classified ecosystem services into four broad categories: supporting, provisioning, regulating and cultural services that are used in this study. In South Africa ES are usually described for the entire estuary rather than just the salt marsh. For example, Turpie et al. (2017) reported that the value of subsistence harvesting of estuarine and coastal habitats was approximately R35.7 million per year (*circa* USD 2.4 million) and the nursery value of estuaries was estimated at close to R803 million per year (*circa* USD 54 million). In terms of recreation and tourism, scenic views and vistas are created by salt marsh and this is desirable for coastal properties (Turpie et al., 2017). Research has started to investigate carbon storage (Johnson et al., this issue) and nutrient uptake (Els, 2019) as salt marsh ecosystem services. Barbier et al. (2011) outlined the most important ecosystem services provided by salt marsh habitats that include coastal protection, erosion regulation, water purification, maintenance of fisheries and carbon sequestration. A global model for wetlands ecosystem services was developed (Janse et al., 2018) but this excluded coastal wetlands. Himes-Cornell et al. (2018) completed a systematic review focussing on the valuation of blue forests and concluded that the ecosystem services of salt marsh are the most understudied, despite them having a greater global coverage than mangrove and seagrass habitats. Recently Davidson et al. (2019) assessed annual changes in the monetary value of coastal ecosystems based on their annual rates of change. The largest monetary values in temperate regions came from salt marshes, seagrasses and tidal flats. In tropical regions, coral reefs and mangroves were important coastal habitats.

This study identifies past patterns of change so these can be used to predict potential future change, and in so doing guide salt marsh conservation and restoration initiatives. Change in salt marsh extent over the last ~90 years was described. Published studies provided detail on the pressures influencing salt marsh in South Africa. Field studies have complemented laboratory research to provide a comprehensive understanding of responses of estuarine macrophytes to stress (Table 1). Detailed studies in the Olifants (Bornman et al., 2008) and Orange estuaries (Shaw et al., 2008; Bornman and Adams, 2010) showed the responses of salt marsh to changes in freshwater inflow and extreme saline conditions. Overabstraction of freshwater has resulted in an increase in the duration and frequency of mouth closure in temporarily closed estuaries. The dynamics of macrophytes including salt marsh was investigated in the East Kleinemonde Estuary; water level rather than salinity was most important in influencing macrophyte responses (Riddin and Adams, 2008).

2. Materials and methods

The objective of this study was to provide an up-to-date understanding of the patterns and processes influencing salt marshes so that an accurate prediction can be made of their response to climate change. A present status assessment of salt marsh was made and changes in area cover described in relation to threats and pressures. Thereafter, expected responses to climate change and implications for ecosystem services were summarised using a comparative approach with information from other better studied areas, as there is limited information on local responses. A brief history of ecosystem services and natural capital can be found in Costanza et al. (2017).

The study area represents the estuaries from west (Orange River mouth) to east (Kosi Bay) (Fig. 1). Adams et al. (2016) provides detail on the study area. Aerial photographs taken approximately 90 years ago

Table 1
Published studies on responses of salt marshes to pressures in South African estuaries.

Pressure	Abiotic Change	Biotic Response	Reference
Restriction in tidal exchange	Freshening	Competition and loss of halophytes/ salt marsh	O'Callaghan (1990)
Freshwater abstraction Mining & wind blown dust	Salinisation, loss of flooding, drop in water table depth	Influence on dominant supratidal salt marsh species *Sarcocornia pillansii*	Bornman et al. (2002) Bornman et al. (2004)
Storm surge, Mouth closure and increase in water level	Increase in salinity & inundation	Increase in water level and loss of salt marsh	Riddin and Adams (2010, 2012)
Eutrophication	Increase in nutrients	Growth of macroalgae, shading and dieback of salt marsh	Nunes and Adams (2014) Human et al. (2016)
Spread of Invasive alien plants	Increase in marsh elevation	Spread of *Spartina alterniflora* and loss of indigenous salt marsh, ~5 different species	Adams et al. (2012) Adams et al. (2016) Riddin et al. (2016)
Livestock browsing and trampling	Sediment compaction	Breaking of plants, patchy bare areas form	Hoppe-Speer et al. (2013)

were compared with recent (2018) aerial photographs and all available Google Earth images to document and map changes in salt marsh distribution and extent. The changes were associated with development, roads, housing, grassed areas, grazing and agriculture. This represented direct and indirect anthropogenic pressures. The type of habitat lost (e.g. salt marsh, mangroves, and reeds/sedges) was determined by comparing historical aerial photographs and literature as well as physical features such as surrounding habitat, elevation, biogeographic zone and estuary type. Only salt marsh habitat destroyed to make way for development or related human activities was quantified. Habitats indirectly impacted through, for example, changes in freshwater inflow or water quality were excluded.

Salt marsh habitat was digitized for 115 estuaries 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. Past salt marsh area cover thus represents the situation in the 1930s and present in 2018 (Tables 2 and 3). Salt marsh cover in each image was mapped and the difference in area between images taken as habitat loss or gain. Recent satellite imagery (Google Earth) and field work were used to update present salt marsh cover (2018) following a similar approach to that of Fernandes and Adams (2016). Arcpad 10.1 loaded on Trimble Juno GPS was used to map the distribution of salt marsh in the field. Supratidal salt marsh was distinguished from intertidal salt marsh based on species composition identified during the field surveys. Previous field work including transects and measurements of elevation profiles have shown that supratidal salt marsh occurs at > 1.5 m amsl (Bornman et al., 2008; Shaw et al., 2008; Nunes and Adams, 2014; Veldkornet et al., 2015a&b; Bornman et al., 2016; Raw et al., 2020). From the texture and colour in the aerial photographs as well as present distribution it was possible to infer past distribution. The location of the salt marshes have remained fairly stable over the last ~90 years. Limitations of this method of mapping is that the poor quality of the earliest images could potentially result in an over- or underestimation of the habitat area. Furthermore, the mapping method takes into account the maximum extent and geographical boundary and not the integrity or intactness of the salt marsh. GIS vegetation maps are now available for approximately 40% of the estuaries in the country and can be downloaded from the following website http://bgis.sanbi.org/Projects/Detail/224.

Different estuaries are presented in Tables 2 and 3 to indicate those systems with the largest salt marsh or where the greatest loss in area has occurred. Details on the pressures were obtained from the mapping exercise, field work and available literature such as that identified in Table 1. In South Africa we have a good understanding of the pressures influencing our estuaries and salt marshes through application of the Estuarine Health Index over the last 20 years (Van Niekerk et al., 2013). To determine the proportion of salt marsh under legal protection, relevant data was extracted from the estuary component of South Africa's 2012 National Biodiversity Report (Van Niekerk and Turpie, 2012). This was however an over-estimation as large areas occur in provincial reserves where there is little active protection.

3. Results and discussion

3.1. *Present status: area cover and loss of salt marsh habitat*

Total salt marsh area is 14955 ha of which 10169 is supratidal salt marsh and 4786 is intertidal salt marsh. Nine estuaries in the country support greater than 100 ha of intertidal salt marsh and 17 estuaries over 100 ha of supratidal salt marsh. The largest intertidal salt marsh area occurs in the Berg Estuary followed by Langebaan and Knysna estuaries (Table 2, Fig. 3). The Berg Estuary also has the largest supratidal salt marsh area followed by the Olifants, Heuningnes and Orange estuaries (Table 3, Fig. 3). Approximately 27% of salt marsh habitat has been lost due to encroaching development and agriculture. The greatest loss of macrophyte habitats in the country has been of supratidal salt marsh (4881 ha, Table 3) as it forms the ecotone between salt marsh and terrestrial vegetation and therefore is the most likely habitat to be developed.

Intertidal salt marsh mostly occurs in permanently open estuaries and only 13% (37 of 289 estuaries between the Orange River and Kosi Bay) of estuaries are permanently open. Loss of intertidal salt marsh habitat is usually due to development such as causeways, bridges or encroaching housing and business developments. Intertidal salt marsh has been lost from Knysna (242 ha), Kowie (48 ha) and Great Fish estuaries (11 ha). Development such as the town of Knysna, Thesen Island, Leisure Isle, the N2 road bridge and embankments has removed large areas of salt marsh. The Port Alfred Marina, the town of Port Alfred and houses along the banks with jetties has removed intertidal salt marsh habitat from the Kowie Estuary. Footpaths and the caravan park in the lower reaches has disturbed habitat in the Great Fish Estuary. These estuaries can also be identified as those vulnerable to coastal squeeze; due to surrounding development there will be little chance of inland migration of salt marsh.

Agricultural impacts are largely responsible for the loss of supratidal salt marsh. In the floodplains of the Gouritz and Gamtoos estuaries, between 80% and 90% of habitat has been lost to vegetable cultivation and cattle grazing. Salinisation has also caused large habitat losses in the Orange River and Olifants estuaries (Table 4). The Orange River Estuary, lying at the boundary between South African and Namibia, is a Ramsar wetland of international importance that was placed on the Montreux Record in 1995 because 300 ha of salt marsh had become desertified (Shaw et al., 2008). This loss was attributed to factors such as leakage of diamond mine water, the impact of windblown dried slimes (waste) dam sediment on marsh vegetation, construction of flood protection works and the elimination of tidal exchange into the wetland by a causeway constructed at the river mouth (Shaw et al., 2008). Due to low rainfall on the west coast and the highly salinized nature of the desertified marsh area, there has been little change in the salt marsh status of this estuary over the past 10 years (Bornman and Adams, 2010).

Most of this coastal development took place between the years 1950s–1990s. Since then stricter implementation of legislation has limited removal of salt marsh. Significant loss of salt marsh in Europe and North America took place between the 1930s and the 1970s; thereafter international conventions such as Ramsar and vigorous protection laws provided some protection (Adam, 1990; Gedan et al., 2009). There is a clear evolution from a development narrative of exploitation and transformation in the industrial period (c. 1800–1980) to a crisis narrative of protection and risk in the postindustrial period (c. 1980–present) (Hatvany, 2008). This is true for South Africa too but with a delayed response because of our developing status. Further analysis is needed but preliminary data indicate that the loss of salt marsh has declined as the initial removal was related to development of coastal towns, encroachment by development and agricultural expansion from the 1950s to the 1970s. In some areas such as Langebaan Lagoon there has been an increase in salt marsh due to removal of farm animals and grazing; and expansion of the West Coast National Park (Table 3).

Other stressors that have been described (Table 1) but not quantified in terms of loss of salt marsh area include salinisation and desiccation due to upstream freshwater abstraction (Bornman et al., 2002, 2004). Reduced freshwater inflow causes extended mouth closure of temporarily open/closed estuaries, inundation and flooding of salt marsh (Riddin and Adams, 2010, 2012). In urbanized estuaries, salt marsh loss is related to a restriction of tidal exchange, freshening and invasion by alien invasive plants (O'Callaghan, 1990). Eutrophication, macroalgal blooms and smothering of salt marsh is a growing concern in South African estuaries (Nunes and Adams, 2014; Human et al., 2016). In the rural areas, livestock browsing and trampling of the salt marsh is extensive but largely unquantified. There are some success stories; for example early detection of the invasive grass *Spartina alterniflora* Loisel.

in the Great Brak Estuary resulted in successful eradication (Table 1).

Tables 2–4 indicate that there is some protection for estuaries with large salt marsh areas in South Africa. Approximately 25.5% of the total intertidal salt marsh area occurs in protected areas and 17.1% of the supratidal salt marsh (Table 3). In addition, estuary management plans are a requirement of the National Environmental Management: Integrated Coastal Management Act (Act 24 of 2008). These plans can be effective in protecting sensitive habitats e.g. salt marsh through zonation of destructive activities such as boating that leads to erosion. There is a need for formal protection status for the Berg Estuary. The estuary is currently designated as an IBA (Important Bird Area) where the water and intertidal habitat is managed by CapeNature and the local municipality. Restoration of the salt marsh at Orange River mouth is also needed as well as greater protection for the large intertidal salt marshes of Knysna Estuary. In the South African National Estuary Biodiversity Plan (Turpie et al., 2012) habitat targets were set as 20% of the total area of each estuarine habitat type but this has not been implemented or addressed in any way.

3.2. Future climate change responses and implications for ecosystem services

Climate change conditions having a particular influence on salt marshes are sea level rise, increase in sea storms and wave height, changes in river discharge (droughts/floods), increased CO_2 levels and higher temperatures. In South Africa responses in estuaries permanently open to the sea will be different compared to temporarily closed estuaries (Table 5).

3.3. Sea level rise

Present South African sea level rise rates fall within the range of global trends and are approximately: west coast +1.9 mm.yr^{-1}, south coast +1.5 mm.yr^{-1}, and east coast +2.7 mm.yr^{-1} (Mather et al., 2009; Mather and Stretch, 2012). Sea level rise will increase inundation and waterlogging altering sediment biogeochemistry, moisture and salinity (Table 5). This is the predicted scenario; however if the salt marshes build elevation at a sufficient rate then inundation and waterlogging may not increase (Rogers et al., 2019). Plant ecophysiology studies have informed our future predictions and shown that lower intertidal salt marsh species will be able to survive conditions typical of upper intertidal ranges, however the reverse is not true of upper intertidal species that are sensitive to waterlogging (Tabot and Adams, 2013). Depending on the plant's tolerance to flooding dieback will result; for example lower intertidal *Sarcocornia* spp. can die after 3 months of complete submergence (Adams and Bate, 1994). Studies completed on other local species can also inform these predictions (e.g. Naidoo and Mundree, 1993; Naidoo and Kift, 2006). If there is available land and the elevation is suitable then salt marsh will migrate inland (Tabot and Adams, 2013; Veldkornet et al., 2015a). In some cases, hard structures may need to be removed to allow upland salt marsh migration. The majority of South African estuaries occupy drowned river valleys that offer limited upland area into which to migrate and those estuaries that do have low-lying adjacent habitat have mostly been developed, creating a physical barrier to potential migration.

Table 2
Intertidal salt marsh area (ha), pressures and protection status.

Estuary	Present area 2018	Past area (% lost) 1930s	Pressures	Protection status
Orange	144	154 (7%)	Salinisation	Ramsar site
Olifants	97	97	Salinisation	None
Berg	1182	1573 (23%)	Agriculture	Partial, CapeNature
Langebaan	792	792	Grazing pressure removed	South African National Parks (SANParks)
Knysna	552	794 (30.5%)	Development	Partial SANParks
Swartkops	209	215 (3%)	Development and industry	None
Kowie	35	83 (58%)	Development	None
Great Fish	133	144 (8%)	Disturbance	None
Kosi	58	58	Grazing, trampling, fires	iSimangaliso Wetland Park, World Heritage site

Table 3
Supratidal salt marsh area (ha), pressures and protection status.

Estuary	Present area 2018	Past area (% lost) 1930s	Pressures	Protection status
Orange	627	1319 (52%)	Salinisation	Ramsar site
Olifants	910	1529 (40.5%)	Salinisation	None
Berg	3226	4589 (30%)	Agriculture	Partial - CapeNature
Langebaan	557	524 (33% increase)	Grazing pressure removed	South African National Parks
Gouritz	123	662 (81.4%)	Agriculture	None
Knysna	133	375 (64.5%)	Development	Partial SANParks
Gamtoos	81	711 (89%)	Agriculture	None
Swartkops	338	1013 (67%)	Development and industry	None
Kosi	229	229	Grazing, trampling, fires	ISimangaliso Wetland Park, World Heritage site

Table 4
Area cover of estuary habitats in South Africa, changes in area and percentage area occurring in protected areas.

Habitat	Past (ha) 1930s	Present (ha) 2018	Ha lost & % change	Protected area (ha) & % protected
Intertidal salt marsh	5354	4786	568 (10.6% loss)	1221 (25.5%)
Supratidal salt marsh	15 050	10 169	4881 (32.4% loss)	1744 (17.1%)
Submerged macrophytes	2515	2695	180 (7.2% gain)	1416 (52.5%)
Mangroves	1576	1664	88 (5.6% gain)	317 (19%)

In temporarily closed estuaries, the abiotic conditions are controlled by the condition of the mouth; whether it is open or closed to the sea (Table 5). Sea level rise will result in more open conditions through an increase in the tidal prism particularly if the mouth of the estuary is sheltered from wave action and little sediment is available (Van Niekerk, 2018). However, drought and a reduction in freshwater inflow will result in mouth closure, flooding and die-back of salt marsh plants (Table 5). There will be temporal and spatial variability associated with these processes.

3.4. Sea storms

An increase in the frequency and intensity of coastal storms and high water events is predicted for the 21st Century (IPCC, 2007). Storm

Table 5
Climate change responses of salt marsh and implications for ecosystem services in permanently open and temporarily closed (*italics*) estuaries.

Abiotic Change	Ecological Processes	Ecosystem Services
↑**Sea level rise + 1.5–2.7 mm.yr^{-1}** Inundation & waterlogging, coastal squeeze Change in sediment biogeochemistry	Salt marsh subsidence Dieback and salt marsh loss Changes in species composition	Change in biodiversity provision Nutrient cycling affected
↑*Open mouth condition*	*Expansion of salt marsh on exposed sand/mudflats*	*Potential increase in carbon storage*
↑**Sea storms & wave height** Erosion	Loss of salt marsh	Loss of bank stabilization, possible flooding of surrounding properties and loss of economic value.
↑*Sediment deposition, constricted mouth*	*Increase in water level, flooding and dieback of salt marsh*	
↑**Floods** ↑ Nutrient inputs & eutrophication ↑Sediment input	Macroalgal growth, smothering of salt marsh Salt marsh accretion	Loss of waste assimilative capacity. Negative effect on human health and wellbeing Reduced recreation and tourism value. Decreased value of surrounding real estate
Scouring of estuary, decrease in salinity	*Loss of salt marsh cover, change in species composition.*	*Change in biodiversity and habitat provision* *Loss of marsh nutrient processing*
↑**Droughts** ↑Salinity	Change in species and community composition. Decrease in productivity. Loss of salt marsh cover.	Aesthetic qualities reduced Loss of nursery habitat for fish
↑*Closed mouth condition*	*Increase in water level, flooding and dieback of salt marsh. Loss of intertidal habitat. Loss of marine connectivity, fish and invertebrate recruitment.*	*Reduced habitat for wading birds impacting bird and wildlife viewing. Loss of tourist appeal.* *Bank destabilisation and erosion.*
↑**CO_2** Higher C availability	Increase in plant growth & productivity	*Possible salt marsh expansion and loss of other habitats such as open water surface area.* Change in biodiversity provision. Increase in weedy, invasive species
↑**Temperature** Warming Higher aridity	Increase in plant growth & productivity Distributional range shifts and change in habitat diversity Increase in invasive species Change in salt marsh phenology, extinctions	Change in carbon storage and biodiversity provision. Loss of habitat for threatened species Possible mangrove expansion and change in habitat for other biota

surges will cause coastal flooding (IPCC et al., 2014). South Africa is a wave-dominated coast sensitive to increased sea storminess that can result in erosion or sediment deposition and accretion (Mather and Stretch, 2012). Sea storms and high waves can deposit sediment and close an estuary mouth; but storms can also increase the tidal amplitude eroding the mouth area and increase the duration of open mouth conditions (Van Niekerk, 2018). However, an increase in storminess will mostly lead to steeper beach slopes, more constricted mouths, a smaller tidal amplitude and thus less intertidal area for salt marsh growth.

Increased storminess could increase erosion of salt marshes although there is little evidence of this yet in South Africa. Marshes can keep pace with sea level rise if there is available sediment and land for expansion inland. Bornman et al. (2016) showed that in the Swartkops Estuary salt marsh surface elevation was keeping pace with historic sea level rise in the estuary. Subsidence/accretion of the marsh was measured using the Rod Surface Elevation Table (RSET) method. RSET changes are also being monitored in the Knysna and Kromme estuaries (Raw et al., 2020) as well as in the salt marsh/mangrove transition zones of the Nahoon and Nxaxo estuaries (Raw et al., 2019). In Australia RSET studies have shown that there is a lower rate of vertical elevation gain in salt marsh compared to mangrove relative to sea level rise (Rogers et al., 2005, 2013, 2014). This accretion difference results in the consistent trend of mangrove encroachment and replacement of salt marsh in the south of the country (Saintilan et al., 2018).

3.5. Floods

To understand the response of salt marsh to climate change it is important to consider extreme events (Morzaria-Luna et al., 2014). According to Zedler (2009) coastal wetlands could suffer catastrophic effects from sequential extreme events (e.g. floods) when the systems do not have time to recover before the next extreme event. Climate extremes are likely to be through sedimentary processes (Boorman, 2003). In the nearby Limpopo River Estuary, Mozambique, extensive river flooding in 2000 halved the original mangrove area enabling salt marsh colonization in the bare areas. This habitat now consists of extensive grassy (*Sporobolus virginicus)* salt marshes (Bandeira and Balidy, 2016).

An increase in extreme rainfall events is projected to occur along the southern and eastern coasts of South Africa during spring and summer (Engelbrecht et al., 2013). This increase in runoff will affect the nutrient load entering estuaries, with inflow being an important source of dissolved and particulate nutrients. As such, increased run-off (and nutrient input) from disturbed catchments may result in eutrophication (James et al., 2013). Estuarine ecosystems are increasingly no longer able to assimilate nutrient loads resulting in eutrophication (Lemley et al., 2015, 2017; Adams et al., in press). In temporarily closed estuaries (Table 5) flooding will open the estuary mouth and scour sediments deposited during periods of low flow. This will influence salinity, sediment supply and a number of other abiotic conditions. Salt marsh is likely to be reduced as the systems become fresher. Flooding can also result in Saintilan input from degraded catchments.

In South Africa episodic flood events were studied at the Orange and East Kleinemonde estuaries. The Orange River Estuary, an important RAMSAR site, has a large desertified salt marsh area due to restriction of tidal and flood waters by a causeway. The sediment and groundwater are hypersaline and despite predictions that a flood would dilute salts and promote salt marsh germination this did not happen as the causeway prevented the floods from reaching the degraded salt marsh area to reduce salinity (Bornman and Adams, 2010). In the East Kleinemonde Estuary, a sea storm surge increased salinity and inundation resulting in die-back of reeds, sedges and supratidal salt marsh (Riddin and Adams, 2010) providing insight on potential future responses to climate change. Salt marshes have shown to be resilient; massive germination from a large seedbank occurred at the East Kleinemonde Estuary when conditions were favourable (Riddin and Adams, 2009, 2019). At the Great Brak Estuary the indigenous salt marsh returned following removal of the invasive grass *Spartina alterniflora* (Adams et al., 2016). In situ long-term monitoring is needed to understand these dynamic processes.

3.6. Drought

Downscaled regional climate models project slightly drier conditions for the winter rainfall region of South Africa with an increase in interannual variability (Hewitson and Crane, 2006; Engelbrecht et al., 2009, 2013). This may result in a decrease in flows and in increase in flow variability (droughts) in estuaries along the west coast (James et al., 2013), with the west coast a ‘hotspot’ of hydrological change (Schulze et al., 2005). A decrease in freshwater inflow will increase salinity and decrease plant productivity in open estuaries (Table 5). In addition, an increase in the period between rainfall events, particularly along the west coast, could lead to reduced sediment moisture and higher salinity. Desertification has occurred at the Orange River mouth due to freshwater inflow reduction as well as the Berg Estuary. South Africa is a semi-arid country and salt accumulation is common in dry areas.

Where there is lower freshwater inflow salinity will move further upstream in open estuaries, resulting in a reduction in the extent of the river-estuary interface (REI) zone as well changing the location of the REI and moving the zone of reeds and sedges further upstream (Adams and Bate, 1999). Major reductions in river flow can result in the complete elimination of this zone (James et al., 2013). There will be an initial increase in detritus associated with this loss and then a longer term reduction as the reed/sedge habitats have high biomass and productivity. Increases in groundwater and sediment salinity can lead to extirpation of species because migration into less saline lower tidal zones is not possible in the event of drought (Semeniuk, 2013; Wasson et al., 2013).

Reductions in the amount of freshwater entering temporarily closed estuaries will lead to an increase in the frequency and duration of closed mouth conditions (Table 5). Depending on the rainfall there is either a decrease or increase in water level in the estuary that will influence the salt marsh (Riddin and Adams, 2008, 2012). Loss of this vegetation in response to flooding can result in bank destabilisation and erosion.

3.7. Temperature

Estuaries will be affected by changes in both surface air and ocean temperatures. Global surface air temperatures have increased by about 0.8 °C over the last century, in response to the enhanced greenhouse effect. However, recent climate trend analyses indicate that South Africa has been warming more than twice the global rate of temperature increase over the past five decades (Engelbrecht et al., 2015; Kruger and Nxumalo, 2016). An increase in temperature will increase plant growth and productivity. Mangrove expansion into salt marsh as a result of an increase in temperature is occurring on the south eastern coast of the USA (Osland et al., 2014; Saintilan et al., 2018). This is known as tropicalization whereas desertification occurs where there is an expansion of hypersaline coastal wetland ecosystems common to arid and semi-arid climates (Osland et al., 2014, 2017).

A recent species distribution modelling study (Quisthoudt et al., 2013) showed that climate change would create climatically suitable sites for the expansion of mangroves, particularly *Avicennia marina* (Forsk.) Vierh and *Bruguiera gymnorrhiza* (L.) Lam, south of their current limits in South Africa. Expansion could be into salt marsh habitats, as has been occurring elsewhere (Saintilan and Williams, 2000; Stevens et al., 2006; Rogers et al., 2014; Saintilan et al., 2014). However, at the Nahoon Estuary Hoppe-Speer et al. (2013) showed that expansion of planted mangroves was into bare sandflat areas rather than salt marsh habitats. These data plus that for all estuaries in South Africa are collated in a botanical database (Adams et al., 2016) to provide a baseline for future monitoring and research on these dynamic processes.

An increase in temperature may also increase the number of invasive plant species as well as insect abundance and feeding thus impacting salt marsh growth and reproduction. The influence of environmental cues on life cycle strategies and plant phenology is not well known. As temperature changes, the geographical distribution of species, depending on their tolerances or preferences, may contract or expand, leading to new and unpredictable species interactions (Murawski, 1993; Perry et al., 2005; Harley et al., 2006; USEPA, 2009).

3.8. CO_2 and pH

Concentrations of CO_2 in the atmosphere have increased exponentially (~40%) since the industrial revolution from 280 to 387 ppm, with 50% of this increase having occurred in the last 30 years (Feely et al., 2009). Increases in atmospheric CO_2 levels will stimulate above and below ground salt marsh productivity (Anderson et al., 2010; Morzaria-Luna et al., 2014). Higher rates of organic matter production may lead to sediment accretion and changes in elevation. These feedback loops need to be understood in order to predict the response of salt marsh to climate change.

The pH of surface open ocean waters may decrease by 0.3–0.4 units by 2100 under the influence of rising atmospheric CO_2 levels (Caldeira and Wickett, 2003). Changes in pH in coastal ecosystems may be caused by ocean acidification as well as a multitude of other (natural or anthropogenic) factors such as eutrophication, upwelling and freshwater inflow (Duarte et al., 2013), which cause greater pH variability than in the open ocean (Strong et al., 2014; Cai et al., 2011). Upwelling can create hotspots of coastal pH change. This is because of naturally high levels of CO_2 combined with increased anthropogenic CO_2, as well as an increase in the intensity of upwelling in some regions (Strong et al., 2014). Thus, by the end of this century, acidification may become a dominant process in permanently open estuaries, especially on the west coast of South Africa where there is regular upwelling (Van Niekerk, 2018). Lower pH will affect all calcifying organisms as structures made of calcium carbonate dissolve requiring more metabolic energy for an organism to maintain the integrity of its exoskeleton (Azevedo et al., 2015). This will influence biotic controls and species interactions in salt marshes. Tidally inundated salt marshes play an important role in oxygenating the water column and buffering acidification by withdrawing excess CO_2 (Duarte et al., 2014a).

3.9. Changes in ecosystem services

To support sustainable ecosystem service provision we need to know which species and communities drive ecosystem processes that underlie ecosystem services under particular abiotic conditions (Helfer and Zimmer, 2018). Functional relationships between ecosystem services and marsh characteristics have not yet been developed (Skov pers comm. SaltmarshNET 2018; https://research.bangor.ac.uk/portal/en/researchprojects/saltmarshnet-workshop(9dd8ea3c-76fa-409a-82db-044757616f6e).html). Table 6 indicates those studies that have described or quantified changes in salt marsh ecosystem services in response to climate change. This was used to infer changes in the ecosystem services of South African salt marshes (Table 5).

A decrease in the spatial extent of salt marshes will result in a change in ecosystem service provision. For example the loss of salt marsh extent not only reduces the capacity to act as a natural carbon sinks but degradation and disturbance of these habitats also directly releases large amounts of carbon back into the atmosphere in the form of CO_2 emissions (Pendleton et al., 2012; Siikamäki et al., 2012). Changes in species and community composition of the salt marsh will influence many different ecosystem services such as grazing and fishing. For example, the grass *Spartina* versus the succulent *Sarcocornia* species offer different food sources and structural protection for fish (Whitfield, 2017). Understanding the traits of different species rather than the species themselves will foster our understanding of the link between biodiversity and ecosystem processes and services (Helfer and Zimmer, 2018).

Loss of salt marsh habitat and habitat diversity in response to sea level rise reduces the available area for wading birds reducing activities such as bird and wildlife viewing (Guo et al., 2017). This also influences regulating services such as the filtering function through reduced nitrogen uptake (Nelson and Zavaleta, 2012). Salinisation and an increase in unvegetated salt marsh in response to reduced rainfall and freshwater input results in a loss of ecosystem services (Osland et al., 2014, 2016). The dieback of foundation salt marsh species and a loss of biodiversity has been reported in response to drought (Angelini and Silliman, 2012; McFarlin et al., 2015). Warming can increase tidal wetland productivity and decomposition resulting in enhanced carbon storage and vertical accretion. However if warming enhances decomposition more than it

Table 6
Studies that have described or quantified changes in salt marsh ecosystem services in response to climate change. (Supporting = blue, Regulating = orange, Provisioning = green, Cultural = pink).

Climate change parameter	**Ecosystem Service (supporting)**	**References**
Sea level rise, loss of intertidal habitat	Reduced habitat for wading birds impacting bird and wildlife viewing. Loss of habitat threatened bird species. Loss of nursery function.	Clausen & Clausen 2014 Guo et al. 2017 Rosencrantz et al. 2018 Boesch & Turner 1984
Sea level rise, drowning of salt marsh	Reduced N uptake, buffering from eutrophication and coastal filtering function.	Nelson & Zavaleta 2012, Wasson et al. 2017.
Sea level rise	Change in carbon sequestration. Models used to show effect of sea level rise on carbon sequestration and denitrification. Restoration of tidal exchange and increase in carbon storage.	Craft et al. 2009, Theuerkauf et al. 2015 Kirwan et al. 2012 Macreadie et al. 2017
Change in sediment supply	Needed to maintain salt marsh habitat elevation.	Thorne et al. 2014, Carrasco 2019
Increase in floods, nutrient input and eutrophication	Loss of marsh nutrient processing.	Deegan et al. 2012, Caçador et al. 2016, Wasson et al. 2017
Increase in droughts	Loss of foundation species and biodiversity. Loss of species due to range distribution change	Angelini & Silliman 2012, McFarlin et al. 2015 Prahalad & Kirkpatrick 2019
Climate change parameter	**Ecosystem Service (regulating)**	**References**
Increase in CO_2	Marsh growth, marsh accretion, reduction in erosion and improvement in coastal protection.	Langley et al. 2009 Ratliff et al. 2015
Increase in storms and erosion	Loss of protective barrier function	Shepard et al. 2011, Siikamäki et al. 2014 Spencer et al. 2016, Leonardi et al. 2018.
Increase in temperature Reduction in freezing events	Mangrove expansion and change in ecosystem services such as carbon storage, habitat for waterbirds and threatened species, cultural services and values. Commercially important species influenced.	Santilan & Williams 1999, Morzaria-Luna et al. 2014, Kelleway et al. 2016, Kelleway et al. 2017, Smee et al. 2017.
Sea level rise	Loss of grazing, crops, saline agriculture.	Bless et al. 2018.
Reduced rainfall and freshwater input	Salinization and increase in unvegetated salt flats, loss of ecosystem services.	Osland et al. 2014, Osland et al. 2016.

(Bless et al., 2018, Boesch and Turner, 1984, Cacador et al., 2016, Carrasco, 2019, Clausen and Clausen, 2014, Craft et al., 2009, Deegan et al., 2012, Harrison, 2004, Leonardi et al., 2018, Macreadie et al., 2017, Prahalad and Kirkpatrick, 2019, Ratliff et al., 2015, Rosencranz et al., 2018, Saintilan and Williams, 1999, Shepard et al., 2011, Smee et al., 2017, Spencer et al., 2016, Theuerkauf et al., 2015, Thorne et al., 2014, Wasson et al., 2017).

does productivity then there will be a new loss in organic substrate, decline in carbon storage and surface elevation. Because of this biogeomorphic feedback it is important to understand the interaction between abiotic and biotic factors (Fagherazzi et al., 2012). Long term temperature responses will be complex due to species replacements and interactions with rates of sea-level rise (Kirwan and Megonigal, 2013). According to Langley et al. (2009) an increase in CO_2 will increase marsh growth, reducing erosion and improving coastal protection. Waste remediation and nutrient cycling are the focus of ongoing research that has started to investigate carbon storage (Johnson et al., this issue) and nutrient uptake (Els, 2019) as salt marsh ecosystem services. Where salt marsh has been removed the service of erosion control, coastal protection and flood attenuation is visible.

The provision of ecosystem services will change in response to distributional range shifts. As temperature changes, the geographical distribution of species, depending on their tolerances or preferences, may contract or expand, leading to new and unpredictable species interactions Harley et al., 2006). Range shifts can bring about changes in ecosystem services; for example in response to increasing temperature and sea level rise the replacement of salt marsh by mangroves can lead to an increase in carbon storage but a loss of biodiversity (Kelleway et al., 2016; Saintilan et al., 2018). The habitat available for waterbirds and threatened species changes as well as cultural services and values (Kelleway et al., 2017). If a salt marsh species is replaced by another with similar structure (e.g. low lying grass to low lying succulent) the shift in Ecosystem Service delivery may be minimal. However, this requires further investigation. In South Africa there are a number of mangrove-associated invertebrates that have already shifted further than mangroves and colonised "surrogate" salt marsh and sedge habitat to the south. This includes the tropical fiddler crab *Uca annulipes* and mangrove snail *Cerithidea decollata* in the Knysna Estuary, a new southernmost limit for both genera (Hodgson and Dickens; 2012; Peer et al., 2015; Whitfield et al., 2016).

In order to protect salt marsh and their services we need to understand the connectivity and exchanges with adjacent ecosystems as salt marshes are at the interface of marine, freshwater and terrestrial influences. For example, sea level rise and an increase in water level could distribute contaminated salt marsh material to other habitats (Duarte et al., 2014b). We also need further studies on the complexity and non-linearity in ecosystem service delivery associated with climate and sea level rise changes. For example, moderate rates of sea-level rise may enhance carbon accumulation and preservation rather than release carbon (Rogers et al., 2019).

South Africa has world-class environmental legislation; so it is not this that fails to protect estuaries and their salt marshes but rather the implementation thereof. Legislation and policy protecting South African salt marshes and ecosystem services includes the National Water Act (1998), Integrated Coastal Management Act (2008) and National Biodiversity Act (2004). However, as highlighted for Australia (Rogers, 2016) there are limited policies and planning mechanisms to set aside buffers for landward migration under sea level rise. For migration of intertidal salt marsh, the important estuaries would be those where there is currently intertidal and supratidal marsh as intertidal salt marsh would migrate into the supratidal zone. This is likely to occur at the Berg, Olifants and Langebaan estuaries on the west coast where there is well-developed salt marsh zonation along an elevation gradient. Along the south and east coast important systems would be Gouritz, Keurbooms, Swartkops, Bushmans and Kariega estuaries. The supratidal areas of Heuningnes, Great Fish and Gamtoos are disturbed by cattle, people and agriculture and the compacted sediment may initially inhibit intertidal salt marsh expansion. The expansion of supratidal areas landward will need to be monitored, as this will be into mostly transformed areas and influenced by coastal squeeze.

4. Conclusions

The loss of salt marsh habitat has been quantified and estuaries with intact undisturbed habitat identified. We have been able to map our salt marshes and provide a baseline for future monitoring and assessment of changes over time. This also provides a baseline for future research that can quantify changes in ecosystem services over longer time scales. Protecting salt marsh ecosystems requires recognizing the patterns, processes and expected responses to disturbance events. Predicting the combined effects of multiple stressors associated with environmental instability (increase in storm surges, floods, droughts and reduced river flow) is critical to conserve salt marsh habitats. Research and monitoring to understand salt marsh responses is ongoing because the interface between the subtropical and warm temperate coastal regions of South Africa is expected to be significantly affected by changes predicted for the future (Quisthoudt et al., 2013; Whitfield et al., 2016). Climate change is an additional stress to that of human pressures and in this study, the latter was quantified as the loss of salt marsh habitat due to development or agriculture. More subtle changes are occurring in response to climate change such as drying out of salt marshes and salinisation. Long-term monitoring of permanent plots and transects are needed to identify these changes. Field studies need to monitor changes in both expansion and elevation of different zones, and changes in ecotone habitats to understand responses to sea level rise.

Author contributions statement

The work presented represents the efforts of the author JBA, other contributions are acknowledged as indicated.

Declaration of competing interest

The work was carried out with no personal, professional or financial relationships that could potentially be construed as a conflict of interest.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.ecss.2020.106650.

Declaration of interests

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.

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