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Cover image: Woman collecting ascideans at Ponta Mazondue, Inhaca Island, Mozambique (© José Paula, 2005)

Long-term changes in seagrass coverage and potential links to climate-related factors: the case of Inhambane Bay, southern Mozambique

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Abstract
Changes in seagrass coverage in Inhambane Bay (southern Mozambique) from 1992 to 2013 were assessed using SPOT 5 and Landsat imagery mapping methods with support of extensive groundtruthing. Over a 21-year period, the total seagrass area was reduced from 12,076 ha to 6,199 ha (51% of the original area). 2001 was the year when seagrass occupied the smallest area in Inhambane Bay with 5,641 ha, apparently related to the impacts of tropical Cyclone Eline with winds of around 200 km/h, and lasting for 29 days with widespread damage on human and natural infrastructure, However, a steady seagrass recovery was observed between 2001 and 2004, where 958 ha of seagrass was restored naturally. Eight seagrass species occur in Inhambane Bay forming six seagrass community types. The three largest communities were *Thalassia hemprichii/Halodule uninervis* with 2,305.5 ha, followed by *Thalassodendron ciliatum/Cymodocea serrulata* with 2,280.3 ha, and *Halodule uninervis* with 1,393.9 ha. The loss of seagrass occurred mainly in the *T. hemprichii/H. uninervis* and H. *uninervis* communities. A specific study on *T. hemprichii* conducted at Barra Peninsula and Ilha dos Porcos showed that the total seagrass biomass varied between 947.08 ± 31.09 g DWm-2 and 1636.82 ± 80.52 g DWm^{-2}, respectively, being low at Barra Peninsula, where seagrass meadows have lower shoot density and appear to be more exposed to climate-related events such as cyclones compared to Ilha dos Porcos. This monitoring method creates a basis for better management and conservation, and a continuation of these types of evaluation actions to predict trends and impacts on marine habitats are recommended.

Keywords: Seagrass mapping, Satellite imagery, SPOT 5, Cyclone, Seagrass structure, Eastern Africa

Introduction
Soft-bottom marine ecosystems, such as seagrass meadows and mangroves, play an important role as nursery and feeding grounds for marine animals (Bell *et al.*, 1992; Hyndes *et al.*, 2003; Cocheret De La Morinière *et al.*, 2004; Whitfield, 2017). As a result, species richness in these systems is relatively high (Ferwerda *et al.*, 2007). Seagrasses are shallow-water coastal marine plants that supply food to mega-herbivores such as dugongs, sea turtles and sea urchins (Lyimo, 2016) and are significant contributors to the primary production of the global ocean (Smith 1981; Silva, 2009; Felisberto *et al.,* 2015). They are also known to provide ecosystem services such as carbon sequestration (Fourqurean *et al.*, 2012; Lyimo, 2016) and wave attenuation (Bradley and Houser, 2009; Maza *et al.,* 2016).

While seagrasses play a major role in the functioning of shallow-waters ecosystems, they comprise a small taxonomic group of marine angiosperms with a worldwide distribution (Short and Coles, 2001). In the Western Indian Ocean (WIO) region, 14 seagrass species occur comprising almost 25% of the total worldwide seagrass species diversity (Gullström *et al.*, 2002; Duarte *et al.*, 2012; Bandeira, 2011; Short and Coles, 2001). There is growing evidence that seagrasses are experiencing declines globally due to anthropogenic threats (Short and Wyllie-Echeverria, 1996; Hemminga and Duarte, 2000; Duarte, 2002; Bjork *et al.,* 2008) such as sedimentation (Ralph *et al.,* 2007; Wooldridge, 2017), aquaculture (Herbeck *et al.*, 2014), dredging (Fraser, 2017) and boating (Bishop, 2008).

Climate change related events such as cyclones are also important contributors to seagrass growth and settlement patterns (Côté-Laurin, 2017), however, the detection of changes in seagrass distribution patterns may be complicated especially when seagrass sites are anthropogenicaly impacted (Bjork *et al.*, 2008). The Mozambique coastline forms the western border of one of the most active basins of tropical cyclones (the southwest Indian Ocean), and it is hence in the trajectory of tropical cyclones and storms (Mavume *et al.,* 2009; Roy and Kovordányi, 2012; Massuanganhe *et al*., 2015). At least five climatic events affected Inhambane coastline from 1992 to 2013 (the cyclones Bonita in 1996, Eline and Gloria in 2000, Japhet in 2003, and Favio in 2007). Rainfall associated with Eline was the most destructive event since 1976 (Reason and Keibel, 2004) and caused massive floods in southern Africa (Massuanganhe *et al.*, 2015), including southern Mozambique and Inhambane Bay. Runoff from strong rainfall reduces salinity as well as increases the transfer of sediments and nutrients from catchment areas to seagrass beds (Bjork *et al.*, 2008). Seagrasses as well as other marine and coastal habitats require active monitoring and management (Orth *et al*., 2006) to improve the understanding of their ecology at various spatial and temporal scales. Remote sensing data, especially the medium and high resolution satellite images, such as Landsat TM, ETM+, SPOT, IKONOS and Quick Bird, has made it possible to map and assess the distribution and health status of seagrass (Yang and Yang, 2009). In the WIO region, studies using satellite imagery have been conducted by Dahdouh-Guebas *et al.* (1999) on the Kenyan coast, Gullström *et al*. (2006), and Knudby and Nordlund (2011) in Tanzania, Ferreira *et al.* (2012) and Bandeira *et al*. (2014) in Mozambique. However, almost none of these studies were carried out using high resolution imagery. This study aims to assess seagrass coverage area variations during a 21-year period (from 1992 to 2013) in Inhambane Bay (Mozambique) by means of satellite image analysis using SPOT (2.5 m resolution) and Landsat images (30 m). The study also provides information on the structure of *Thalassia hemprichii*, the most common species within the Bay. The combination of SPOT 5 and Landsat TM imagery for assessment of seagrass vegetation changes was a means of capturing aerial and temporal details of seagrasses at different scales and coverage. The assumption is that changes in seagrass cover occur and may be driven by climate-induced events.

Materials and methods

Study Area

Inhambane Bay, with a size of about 25,000 ha, is situated on the southern Mozambican coast (Silva *et al*., 1991; Halare, 2012) between 23° 40'S and 23° 53'S, and 35° 19'E and 35° 29' E (Fig. 1).

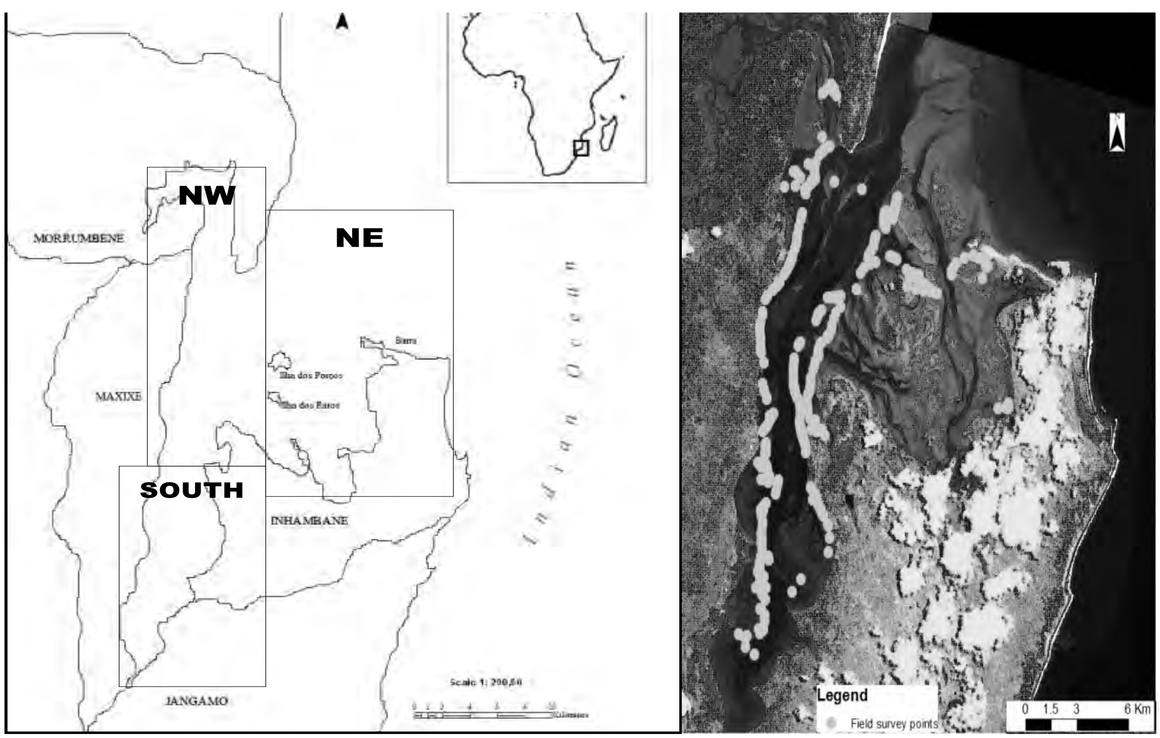

Figure 1. Map showing the location of the study area divided in three regions (NW, South, and NE) (left), and Spot 5 image of Inhambane Bay, Mozambique, captured in August 2013 showing field survey points in grey (right).

Administratively, the bay is composed of the four districts of Maxixe, Inhambane, Jangamo, and Morrumbene (Halare, 2012). In order to analyse seagrass cover changes, the bay was divided, based on physiographic aspects, into North West–NW (sandy dunes stretching from northern Maxixe to Morrumbene), Southern (sand flats of south Inhambane City, Jangamo and southern Maxixe), and North East-NE (sand flats of north Inhambane City, the islands of Porcos, Ratos and Barra Peninsula) bay regions (Fig. 1). Average depth varies between 5 and 10 m and the bottom sediment is composed of sand, mud and biogenic matter. The shores are relatively sheltered at Ilha dos Porcos (IP) and at the other sites in the bay, with the exception of Barra Peninsula (BP) and east of Morrumbene (Linga-linga), which are exposed to strong ocean currents. Tides are semi-diurnal and water temperature ranges from 21°C to 27°C (Halare, 2012). The average annual rainfall is 927 mm (Zacarias, 2013) and the mean salinity is 36 PSU (Gove, 2006). Sand flats are affected by channels, currents and freshwater coming from the Sambe and Mutamba rivers, which deposit terrestrial sediments during cyclone-related floods.

Use of satellite images

Landsat TM (Thematic Mapper) images captured in August of 1992, 1998, 2001 and 2004 (Table 1) were obtained from the National Centre of Cartography and Remote Sensing (CENACARTA) in order to map historical seagrass distribution. The current cover of seagrass was obtained from a Spot 5 image of August 2013. Temporal resolution of imageries was selected in order to depict the impacts of cyclones (Eline, Gloria, Japhet and Favio). The 1992 imagery represents the year before a cyclone, and 2013 is the year after a cyclone. The spatial resolution of Landsat and Spot 5 imagery is 30 m x 30 m and 2.5 m x 2.5 m respectively, and the selected dates of images reflect spring low tides (Table 1).

Spot 5 images covered the overall study area (25,000 ha) while Landsat TM images covered an area of 24,145 ha of Inhambane Bay (96.6% of the total). Geometrical and spectral corrections of the images were performed at CENACARTA and useful spectral bands were selected in order to support the computation of a Normalized Difference Vegetation Index (NDVI). Spot 5 and Landsat TM had the same band set in the visible and infrared wavelengths. These bands were Band 1 (0.45-0.52 μm), Band 2 (0.52-0.59 μm), Band 3 (0.63-0.69 μm), and Band 4 (0.77-0.89 μm). Seagrass distribution was retrieved using the bands 1, 2, 3 and 4 combined in the form of the NDVI. NDVI, a tool used to compute seagrass chlorophyll, was first proposed for seagrass cover by using combination of red spectral band and near infrared by Tucker (1979), followed by authors such as Tucker *et al.* (1981), ESRI (1998) and Moreira (2001). This combination is utilized in the following equation:

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{R}}{\mathrm{NIR} + \mathrm{R}}$$

Where: NIR is the near infrared band, and R is the red band. The value of the "pixel" resulting from this estimation ranges from 0.1 to 1 (Tucker, 1979; Tucker *et al.*, 1981; Moreira, 2001). The highest values of the vegetation index correspond to denser seagrass cover, reducing with the reduction of digital values (ESRI, 1998).

In order to fully explore the useful spectral data, the red band reflectance of NDVI was replaced by the green and blue band reflectance.

The above equation was altered as follows:
Red NDVI RNDVI = (NIR-Red)/(NIR+Red)
Green NDVI GNDVI = (NIR-Green)/(NIR+Green)
Blue NDVI BNDVI = (NIR-Blue)/(NIR+Blue)

Three classes of seagrass distribution were classified and validated in the field. The main difficulty encountered in validating NDVI digital numbers (DN) was the fact that the substrate in Landsat TM and Spot 5 varied

Table 1. Date and time of capture of the Landsat and Spot 5 imagery (source: CENACARTA)

Image	Year	Date	Time (h)	Tides (m)
Landsat	1992	14 August	11:45	0,57 - Spring
Landsat	1998	11 August	13:13	0,41 - Spring
Landsat	2001	21 August	12:35	0,57 -Spring
Landsat	2004	03 August	12:48	0,57 -Spring
Spot 5	2013	23 August	12:22	0,29 Spring

greatly. In order to make an accurate classification, typical ground objects, such as sand banks, dunes and sea cover were used to normalize the digital numbers of the whole images. Seagrass classification accuracy was calculated by comparing the pixels of satellite remote sensing data with *in situ* observations. For each location, a score of the match was assessed and the sum of the scores was normalized as the detection accuracy (ESRI, 1998; Jensen, 1996; Trisurat *et al*., 2000; Mather, 2004).

Field survey

Groundtruthing was performed during 2012-2014 between July and August based on stratified random sampling to validate NDVI imagery digital numbers (Jensen, 1996; Trisurat *et al*., 2000; Mather, 2004). Based on pre-classified shape files, the Inhambane Bay was divided systematically into quadrates. Thereafter, 538 quadrates of 0.5 m x 0.5 m were randomly selected along transects running perpendicularly from the coastline to the low water tide level to be able to sample seagrass species (McKenzie *et al*., 2001). Along each transect, 0.5 m x 0.5 m quadrates were surveyed in order to assess the zonation patterns, species composition, substrate type and percentage cover of seagrass. In subtidal areas, photographs were taken using snorkeling in shallow waters (< 2 m depth), whereas in waters deeper than 2 m, SCUBA diving was performed, especially where the seagrass was not visible from the surface. The area occupied by each seagrass community was determined using a *calculate geometry* tool in ArcGIS 10.1. The communities were then characterized by one or two highly frequent species (Bandeira, 2002; Massingue and Bandeira, 2005) and seagrass composition was classified using a nominal scale of frequency of species occurrence (Bandeira, 2002; Sidik *et al.,* 2001; Massingue and Bandeira, 2005). The percentage cover was estimated using density classes (Tomasco *et al*., 1993; Massingue and Bandeira, 2005).

The structure of seagrass was obtained by measuring seagrass biomass, shoot density and leaf length in two intertidal meadows dominated by *T. hemprichii* at Ilha dos Porcos (IP) and Barra Peninsula (BP). Twenty quadrats (0.25 m x 0.25 m) were sampled, 10 at each site on 12 and 13 August 2014, respectively. Samples were collected randomly within seagrass beds, then washed in freshwater and divided into above-ground and below-ground components (Duarte and Kirkman, 2001). The samples were dried for approximately 48h at 80°C to obtain the dry weight (DW) and processed in a muffle oven at 425°C for 2h to obtain the AFDW (ash-free dry weight). Leaf length was determined by the average of 10 leaf lengths measured per quadrat at each site, and shoot density by counting the total number of shoots per m^2.

Water temperature, depth, and light penetration were measured *in situ.* Water temperature and water depth were measured with a console instrument (ScubaPro). Light penetration was measured with a Secchi disk.

Data analysis

Results from seagrass community distribution and extent were used to assess the changes in seagrass cover over larger areas. The data met the assumptions for normality and homoscedasticity, and therefore, one-way analysis of variance (ANOVA) and T-test were used to test if there were any significant differences between the means of the different parameters measured (seagrass biomass, shoot density and leaf length) between the Ilha dos Porcos and Barra Peninsula.

Results

Seagrass diversity and distribution mapping

Eight seagrass species were identified in Inhambane Bay in 2013: *Thalassia hemprichii* (Ehrenberg) Ascherson, *Halodule uninervis* (Forskål) Ascherson, *Thalassodendron ciliatum* (Forskål) den Hartog, *Cymodocea serrulata* (R.Br.) Ascherson & Magnus, *Cymodocea rotundata* Ehrenberg & Hempr. Ex Ascherson, *Halophila ovalis* (R Br.) Hook.f., *Syringodium isoetifolium* (Ascherson) Dandy, and *Enhalus acoroides* (Linnaeus f.) Royle. The most common species were *T. hemprichii,* followed by *T. ciliatum* and *H. uninervis*. In contrast *H. ovalis* and *S. isoetifolium* were scanty and found mostly in permanent subtidal areas (around 1.5 m at low spring tide). *E. acoroides* was only found in a localized area near Morrumbene shore. These seagrass species form six main community types: *T. hemprichii/H. uninervis*, *T. ciliatum/C. serrulata*, *H. uninervis*, *C. serrulata/H. uninervis*, *E. acoroides* and *H. ovalis/H. uninervis*. The *T. ciliatum/C. serrulata* community occurred in shallow channels from north to south and also on flats at the NE and NW Inhambane Bay regions. The *T. hemprichii/H. uninervis* community formed dense meadows on sand flats and biogenic platforms of the NW and NE bay regions. The *C. serrulata/H. uninervis* community occurred in the NW and in the lagoon at the NE. *H. uninervis* and *E. acoroides* communities occurred in intertidal areas where they were dominant on muddy substrates, while *H. uninervis* also occurred in subtidal areas. *T. hemprichii/H. uninervis* followed by *T. ciliatum/C. serrulata* were the most species-rich communities with seven and six species represented, respectively (Fig. 2; Table 2).

Figure 2. Map of Inhambane Bay showing the distribution of seagrass communities in 2013 produced from a combination of field – and SPOT 5 imagery data.

T. hemprichii/H. uninervis and *T. ciliatum/C. serrulata* communities, together with the monospecific *H. uninervis* community, form the three largest community types covering 96.4% of the total seagrass cover of Inhambane Bay (Table 3).

In 2013, seagrasses occupied an area of 6,199 ha, which was around 25% of the total bay area (25,000 ha) (Table 4). The NW bay beds covered the largest area of seagrass with 2,602 ha followed by the southern bay beds with 1,908 ha. The NE bay is widely dominated by dispersed patches in an area of 1,689 ha.

Assessment of seagrass dynamics

In 1992, seagrass covered 12,076 ha of Inhambane Bay (Fig. 3; Table 5). Between 1992 and 1998, large areas of seagrass (5,714 ha, 47.3%) were lost (Fig. 3). Furthermore, 712 ha of seagrass disappeared between 1998 and 2001. Although 26 ha of seagrass disappeared in the southern bay between 2001 and 2004, a total of 958 ha of seagrass recovered naturally in the entire bay for the same period. The NE bay registered an increase of 76% of seagrass and in the western bay there was a slight increase of 1% (Table 5). In the 12-year span (i.e. from 1992 to 2004), the NW bay had

Table 2. Species composition in each seagrass community.

Community type	Species							
	Th	Tc	Hu	Cs	Cr	Ea	Si	Ho
Th/Hu	***	*	***	**	*		*	*
Tc/Cs	*	***	*	***	*		**	
Hu			***					
Ea	**		**		*	***		
CS/Hu			***	***	*			
Ho/Hu	*		***		*			***

*** -highly frequent,**-frequent, *-present. Th-*Thalassia hemprichii,* Hu-*Halodule uninervis,*Tc-*Thalassodendrom ciliatum,* Cs-*Cymodocea serrulata,* Cr-*Cymodocea rotundata,* Ea-*Enhalus acoroides,* Si-*Siringodium isoetifolium,* Ho-*Halophila ovalis*

Table 3. Seagrass communities' coverage in 2013.

Seagrass Community	Area (ha)	Percentage of total
Thalassia hemprichii/Halodule uninervis	2305.5	37.18
Thalassodendrom ciliatum/Cymodocea serrulata	2280.3	36.78
Halodule uninervis	1393.9	22.48
Enhalus acoroides	136.0	2.20
Cymodocea serrulata/Halodule uninervis	43.0	0.70
Halophila ovalis/Halodule uninervis	40.7	0.66

the highest losses of seagrass among the three areas studied (3,024 ha or 56.4%) followed by the southern zones of the bay (1,352 ha or 40%). Although the NE bay region showed the lowest loss of seagrass (1,101 ha, 33% of its total 1992 area), it seems to be more dramatic as the remnant seagrass occupied only 18.6% of the NE bay region.

Structural complexity of *Thalassia hemprichii*

The total biomass of *T. hemprichii* differed significantly between Ilha dos Porcos or Porcos Island (IP) and Barra Peninsula (BP) in 2014. The area of IP had high total biomass (Table 6). The aboveground/belowground ratio was lower at IP compared to BP (Table 6). Shoot density was also significantly higher at IP than at BP (Table 7). Leaf length did not significantly differ between the two sites, although a tendency could be discerned that IP appeared having a higher leaf length than BP (Table 7). The seagrass cover at IP ranged from 75 to 100 % and was clearly higher ($p<0.01$) than the seagrass cover at BP, which had a range between 25% and 60%.

Biomass (Mean ± SE) of *Thalassia hemprichii*. N = 10, DW = dry weight, AFDW = Ash free dry weight. Asterisks denote values which are significantly different from one another determined by one-way ANOVA. *significant at 5%; ** significant at 1%.

Table 4. Seagrass areas in 2013 apportioned per bay zone (southern, NW and NE Bay).

Region	Mapping area (ha)	Seagrass (ha)
Southern Bay	6,592	1,908
NW Bay	6,408	2,602
NE Bay	12,000	1,689
Total	25,000	6,199

Table 5. Change in seagrass coverage in Inhambane Bay over the years 1992, 1998, 2001 and 2004.

Zone	Mapping area	1992		1998		2001		2004	
	Ha	Ha	%	Ha	%	Ha	%	Ha	%
Southern	6,592	3,380	51.0	2,504	37.9	2,054	31.2	2,028	30.8
NW	5,553	5,365	96.6	2,506	45.1	2,321	41.8	2,341	42.1
NE	12,000	3,331	27.8	1,352	11.3	1,266	10.6	2,230	18.6
Total	24,145	12,076	50.0	6,362	26.3	5,641	23.3	6,599	27.3

Asterisks denote values which are significantly different from one another determined by T-test. ** significant at 1%; NS: not significant.

Environmental variables

There were no statistical differences ($p > 0.05$) in water temperature, light penetration and water depth between the two sites (Table 8), although BP tended to have slightly higher visibility and depth compared to IP.

Asterisks denote values which are significantly different from one another determined by T-test. NS: not significant.

Discussion and conclusion

Seagrass diversity and distribution

Inhambane Bay, with eight seagrass species (comprising around 13% of world seagrass biodiversity) within only 25 000 ha can be considered an area unusually

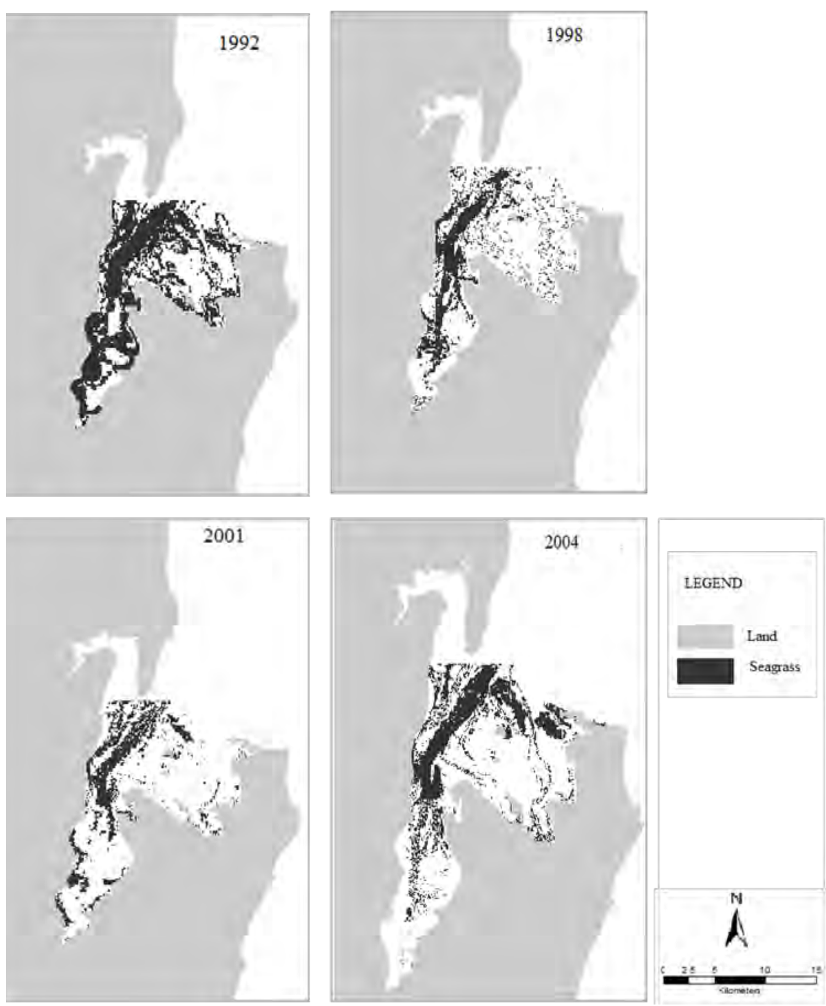

Figure 3. Distribution of seagrass cover in Inhambane Bay in 1992, 1998, 2001 and 2004.

Table 6. Comparison of Thalassia hemprichii biomass (gm-2) at two sites in Inhambane Bay, Mozambique.

Structure		IP	BP	Df	F-value	P-value
Above ground	DW	564.93±38.06	425.08±35.26	1	7.264	0.015*
	AFDW	249.30±25.42	123.67±22.42	1	13.729	0.002**
Below ground	DW	1071.89±107.92	522.00±48.12	1	21.654	0**
	AFDW	365.48 ±30.81	272.17 ± 26.68	1	5.239	0.034*
Above/Below ratio	DW	0.57±0.07	0.83±0.60	1	7.646	0.013*
	AFDW	0.71±0.09	0.43±0.05	1	7.215	0.015*
Total Biomass	DW	1636.82±80.52	947.08±31.09	1	15.964	0**
	AFDW	614.78±23.57	395.85±24.04	1	10.571	0.002**

Table 7. Comparison of leaf length and shoot density between Ilha dos Porcos (IP) and Barra Peninsula (BP) of Inhambane Bay, Mozambique.

Structure	IP	BP	Df	F-value	P-value
Leaf length (cm)	9.8± 0.32	7.7± 0.47	1	0.577	NS
Density (shoots/m^2)	1413±15.89	812±71.06	1	12.193	0.003**

rich in this kind of habitat. (Short and Coles, 2001). This pattern may be repeated across Mozambique and eastern Africa tropical regions such as Bazaruto, Inhaca and Zanzibar (de la Torre-Castro, 2006; Lyimo *et al*., 2008; Bandeira *et al*., 2008; Bandeira *et al*., 2014). Inhambane Bay has around 60% of the total number of seagrass species occurring in WIO region (Bandeira, 2011; Gullström *et al*., 2002). *Zostera capensis* Setchell and *Thalassodendron leptocaule* Maria C. Duarte, Bandeira and Romeiras, was not found within Inhambane Bay although documented elsewhere in eastern Africa (Bandeira and Gell, 2003). *T. leptocaule*, the only eastern African seagrass occurring in rocky habitats, was documented nearby only at Tofo village (with rough waters facing the Indian Ocean, outside Inhambane Bay) (Duarte *et al.,* 2012). Inhambane is the southern limit of *E. acoroides* across Africa. The occurrence of 8 species in such a small bay almost equals the seagrass diversity of the entire Caribbean (Creed *et al.* 2003). *T. hemprichii* co-occurred with *H. uninervis* and was the most species-rich community type within Inhambane Bay. This community has also been reported from northern Mozambique and Tanzania (Bandeira and António, 1996), Inhaca Island (Martins and Bandeira, 2001; Bandeira *et al.*, 2014) and other parts of the region (Gullström *et al.,* 2002).

Assessment of seagrass dynamics

This study indicates a dramatic change in seagrass cover over a 21-year period (1992 to 2013). It was found that from 1992 to 1998 5,714 ha (nearly half of original area of seagrass coverage) was lost, primarily within *T. hemprichii/H. uninervis* and *H. uninervis* communities, similar to the findings of Côté-Laurin *et al.* (2017) who recently documented a short-term impact of Cyclone Haruna (150 km/h winds) within the *T. hemprichii* communities in Madagascar. It appears that the above mentioned change within Inhambane Bay could have been an impact caused by Cyclone Bonita (winds of around 180 mm/h), that struck the

Table 8. Comparison of environment conditions between two sites in Inhambane Bay.

Environment conditions	IP	BP	Df	F-value	P-value
Water temperature (˚C)	22.9±0.35	22.2±0.29	1	2.384	NS
Light penetration (m)	2.4±0.16	2.9±0.18	1	4.245	NS
Water depth (m)	1.1±0.06	1.4±0.14	1	4.151	NS

region in 1996. A global analysis of seagrass decline by Waycott *et al.* (2009) indicates various root causes, mostly anthropogenic, for seagrass decline, mostly in north America, Europe, and Australia, and includes some localized cases of seagrass increase as well, but with fewer examples of widespread seagrass decline from South America, Africa or NE and SE Asia (Waycott *et al*., 2009). Anthropogenic impacts in the Inhambane area still need to be tested, however it is surrounded by a relatively small rural population of up to 200,000 inhabitants with limited activities such as motor boating, point sewage discharges, and earth moving operations that are likely to have major impacts on seagrasses. It was further noted in this study that 721 ha had been lost between 1998 and 2001, coinciding with cyclone Eline that transited the region with winds of around 200 km/h in February 2000. In 2001 Inhambane Bay had the lowest seagrass cover (23% of its original area) in the period analysed. The cyclone Eline brought very strong winds associated with intense rainfall and created the worst natural disaster in a century (Mavume *et al*., 2014). It is suggested that the rainfall and flooding might have brought sediments into the bay impacting the seagrass meadows. Halare (2012) showed that 2001 was the year with the lowest annual catch of the sardine *Amblygaster sirm* in Inhambane Bay between the years 1999 and 2006. This pattern probably also represents an indicator of seagrass losses in Inhambane Bay during this period. *A. sirm* is a pelagic species, partly occurring in shallow waters and lagoons. It feeds on nauplii of crustaceans, bivalves and gastropods larvae (Halare, 2012) living in seagrass habitats. The 4% (958 ha) gain between 2001 and 2004 was the only large gain of seagrass cover. Between 2004 and 2013, 400 ha were lost, possibly from an anthropogenic impact, but it should be noted that the cyclone Favio (approx. 200 km/h winds) struck the region in 2007 as well. Related anthropogenic impacts on seagrass in WIO was documented in NW Maputo Bay where seagrass meadows are intensively dag for clam collection, a recurring activity mostly during spring tides; nonetheless also heavily impacted by an extreme climate event as documented during the 2000 floods (Bandeira and Gell, 2003; Bandeira *et al.*, 2014)

Structural complexity of *Thalassia hemprichii*

The environmental conditions at Inhambane Bay were in general similar to other southern Mozambique sites (Paula *et al*., 1998; Bandeira, 2000; da Silva and Rafael, 2014; Canhanga and Dias, 2014). The sediment at BP was composed of coarse sand, which reveals this site to be more exposed than IP. Exposure usually enables sedimentation of heavier sands and may also display greater variability of seagrass distribution, or in the structure of seagrass meadows. Such analysis may help in understanding the roles of seagrass species in protection of sandy and exposed shores (Paul, 2017). Van Rijn (2011) showed that the presence of coarse sand played a role in erosion control. In general, the total biomass of *T. hemprichii* obtained in this study seems to be similar to that obtained at Inhaca Island (southern Mozambique) for the same species (Martins and Bandeira, 2001), and is also corroborated in studies elsewhere (Chiu *et al.,* 2013). Within Inhambane Bay, IP had slightly higher above- and belowground seagrass biomass compared to BP, although environmental parameters in the two areas did not differ significantly. At IP, the aboveground biomass was about half of the belowground biomass, implying a greater allocation of resources belowground. This might indicate a survival strategy by seagrasses to minimize anthropogenic pressure from heavy collection of invertebrates, or exposure to desiccation at low tide, and to increase stability when exposed to high tides (Lyimo *et al.*, 2008). SE Asia studies on biomass revealed a higher biomass for Inhambane Bay (Heijs, 1984) and similar shoot densities (Brouns, 1985). The higher shoot density was shown to coincide with lower canopy height (Eklöf e*t al*., 2005; Gullström *et al.,* 2006).

In conclusion, this study has demonstrated that the spectral and spatial resolution of Landsat TM and SPOT 5 imagery was appropriate for assessing seagrass dynamics creating a basis for better management of this habitat. Seagrasses in Inhambane Bay have decreased in their coverage between 1992 and 2013. The decrease was about 5,877 ha, which implies losses of 50% over these 21 years. It is postulated that some of this decrease may be related to recorded climate events. *T. hemprichii* seagrass biomass varied between 947.08 ± 31.09 g DWm-2 and 1636.82 ± 80.52 g DWm^{-2}, respectively, being low at BP, where seagrass meadows have lower shoot density and appear more exposed compared to IP. It is recommended that there is a continuation of these types of evaluations to predict trends in seagrasses.

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