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Socio-ecological change in estuaries of the Western Indian Ocean

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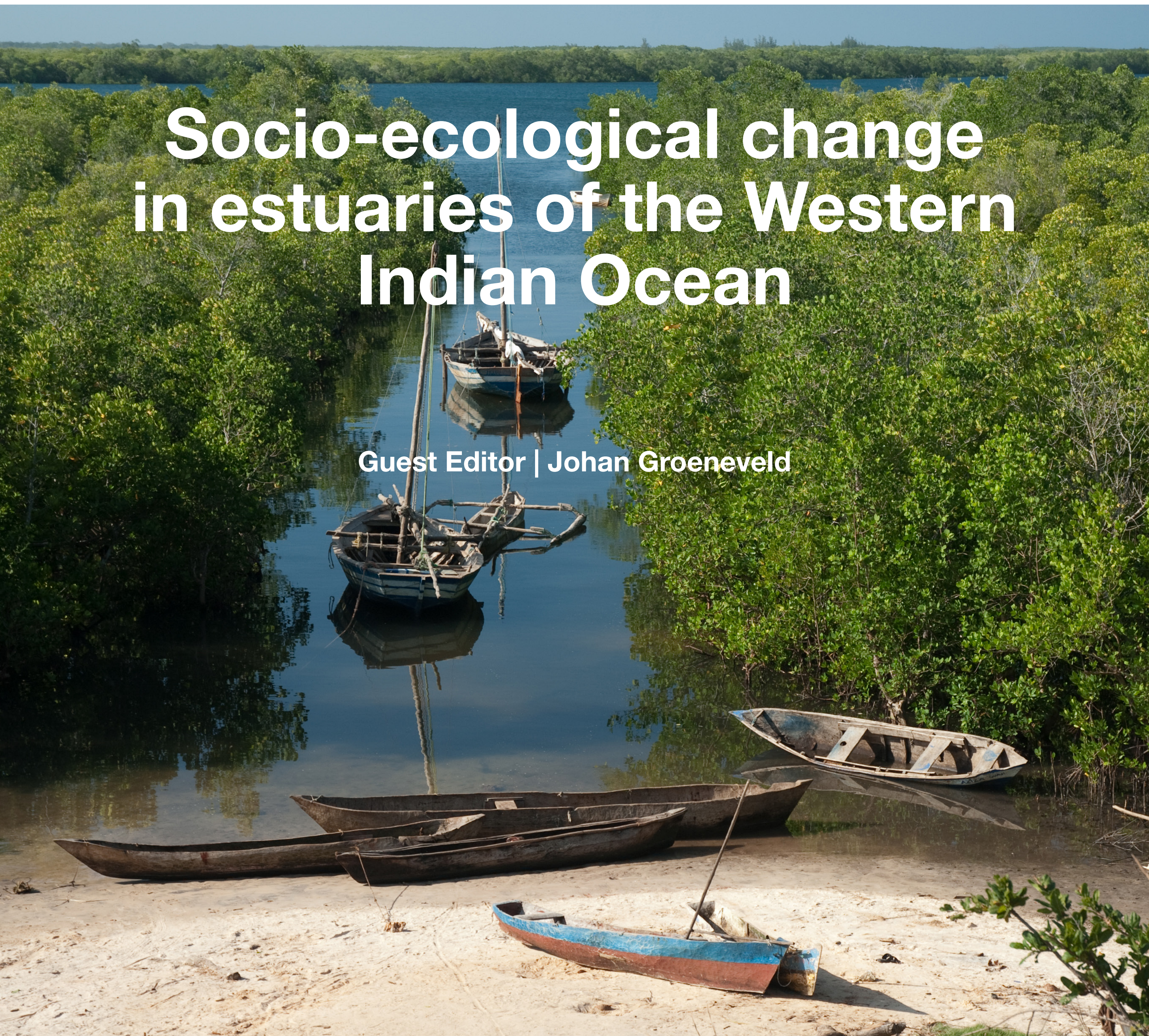

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Cover image: The Rovuma Estuary creeks near Quionga in Mozambique. © José Paula, 2007

Exploring urbanization and critical habitat loss through land cover change around the Bons Sinais Estuary, Mozambique

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Abstract

Estuaries supply direct and indirect multi-sectoral opportunities including for transport, natural resource use and climate protection. These provisions support livelihoods and contribute to social and economic development. The Bons Sinais Estuary in Zambézia Province, central Mozambique, is adjacent to the provincial administrative capital Quelimane, some 25 km from the coast. The rapid growth of Quelimane has increased the demand for natural resources from the estuary, including space, food, fuelwood, transport and raw materials for construction and economic activities. Expansion of the built environment has extended into low-lying lands, mostly within the critical estuarine functional zone with inevitable consequences, such as damage to natural habitats and flooding of occupied areas during rainy seasons. The aim of this study was to analyse three decades of change (1991 – 2018) in land use and land cover (LU/LC) in the Bons Sinais Estuary, focussing on the growth of Quelimane city and the transformation of estuarine and surrounding habitats. The method relied on open-access satellite images and a LU/LC change analysis to quantify the spatio-temporal changes brought about by economic development and related human activities. A combination of low-intensity fieldwork and satellite-derived data (Landsat-5, sensor: Thematic Mapper and Landsat-8; sensors: Operational Land Imager, Thermal Infra-Red Scanner) was used to generate LU/LC information classified according to the features: mangrove trees; wetlands; estuary intertidal areas; built-up area; cultivated trees; and cultivated land. From 1991 onwards, there was an overall increase in cultivated crops (66 %), development (79 %) (including rural human settlements) and intertidal mudflats (12 %) with a concomitant decline in critical wetlands (16 %) and mangroves (12 %). The study predicts a worsening of the impacts on the estuarine ecosystem with further growth of Quelimane city. To reverse the negative trend on estuary health, the recommendation is for management interventions that promote sustainable LU, and urban development plans that consider ecosystem conservation and active restoration.

Keywords: estuary land cover, urban expansion planning, mangroves, wetlands, human activities

Introduction

Estuaries are vulnerable to human pressure because they are easily accessible, have high diversity (species, habitats, natural resources) and have high utility for a broad range of human-related activities. Estuaries provide opportunities for transport (ports and shipping), harvesting of natural resources (fish and wood), flood-recession agriculture and protection against climate – all of which support local livelihoods and contribute to social and economic development (Barbier *et al.*, 2011; Calvão *et al.*, 2013; Khan and Kumar, 2009). Unplanned urbanization around estuaries can lead to natural habitat fragmentation, degradation and habitat loss (e.g., Alberti, 2005; Branoff, 2018; Davis, 2005; Grimm *et al.*, 2008; Lai *et al.*, 2015; McDonald, 2008; McKinney, 2006; Thanh *et al.*, 2004; Yi *et al.*, 2018; Zapata *et al.*, 2018;) and eventually to socio-economic decline (Jiboye *et al.*, 2019; Miah *et al.*, 2010; Rasyid *et al.*, 2016).

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The Bons Sinais Estuary in central Mozambique (Zambézia Province) is about 30 km long with the provincial administrative capital Quelimane located on its northern bank, some 25 km from the estuary mouth. The estuary has been popular in the recent literature, including accompanying studies in this Special Issue on estuarine hydrodynamics (Hoguane *et al.*, 2020; 2021), small-scale fisheries (Costa *et al.*, 2020; Mugabe *et al.*, 2021) and adaptation of associated livelihoods in rural and urban space (Blythe, 2014; Blythe *et al.*, 2014; Francisco *et al.*, 2021). The geographic setting, ecosystems and socio-ecological importance of the estuary have been summarised by Groeneveld *et al.*, 2021). The city of Quelimane grew rapidly during and after the Mozambican civil war (1977-1992) when up to 3 million people were displaced mainly from rural inland areas to the more densely populated coast (Wilson, 1994). Quelimane recorded an average annual growth rate of 4.5 % per year, increasing from 104,000 inhabitants in 1991 to 415,000 in 2020 (www.populationstat.com).

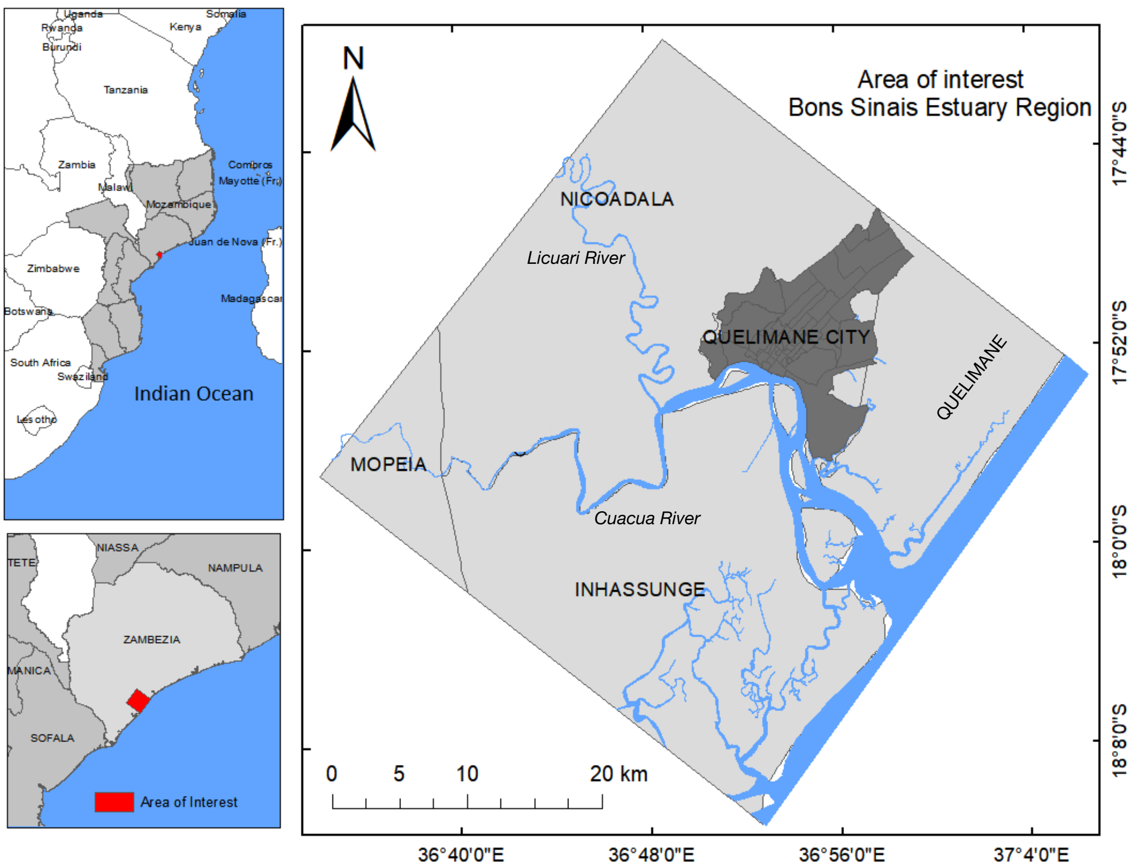


Figure 1. Location of the Bons Sinais Estuary relative to Quelimane city and adjoining districts.

The growth of Quelimane increased the demand for natural resources from the Bons Sinais Estuary, including space, fresh water, food, fuelwood, transport and raw materials for construction and economic activities. Expansion of the built environment extended into low-lying land, often within the estuarine functional zone, with predictable outcomes – damaged natural habitats and suburbs prone to flooding during rainy seasons (Mazzilli, 2015; Unaite, 2017). Urbanization is recognised as a primary driver of environmental degradation, including land use change (Hahs *et al.*, 2009), reduced water quality and pollution (Awaleh *et al.*, 2015; Seto *et al.*, 2013), modification of habitats, plant and animal communities, and biodiversity loss (Branoff, 2018; Yi *et al.*, 2018; Zapata *et al.*, 2018). The main livelihoods associated with the estuary are fishing and agriculture, collection and sale of firewood (from mangroves), small businesses trading fish and fish products and agriculture products (Blythe *et al.*, 2014; Unaite, 2017). Furthermore, the estuary provides nutrients that nourish adjacent coastal marine ecosystems and nurseries (Hoguane and Armando, 2015) and the dense mangrove forests are an important carbon sink and mitigation against climate change (Amade *et al.*, 2019).

Remote sensing and GIS techniques are often applied to detect change in LU and LC by season or over longer time frames (Mallupattu and Reddy, 2013; Berlanga-Robles and Ruiz-Luna, 2002; Hudak and Wessman, 1998; Ngondo *et al*., 2021). Analysis of satellite images is a cost-effective means of mapping physiognomic habitats, including mangroves, wetlands, sand and seagrass beds and coastline morphology (Dittrich *et al*., 2020; Dymond *et al*., 2019; Marzialetti *et al*., 2019). They can also be used to trace socio-economic and socio-anthropological effects and changes in coastal communities, such as the spatial and structural spread of urban areas and agriculture over time. Analyses of LU/LC can also contribute to the planning and management of land and water resources (Mallupattu and Reddy, 2013; Asselman and Middelkoop, 1995).

The aims of this study were to analyse decadal change (1991 – 2018) in LU and LC in the Bons Sinais Estuary, including the growth of Quelimane city and the transformation of estuarine and surrounding habitats. The study relied on open-access satellite images and a LU/LC change analysis to quantify the spatio-temporal changes brought about by economic development and related human activities (settlement, building, agriculture, commerce). The findings are intended to raise awareness of the implications of unplanned development in sensitive ecosystems, and the need for appropriate urban development plans to sustain the multiple goods and services on which settlements rely.

Materials and methods

Study area

The Bons Sinais Estuary extends from the confluence of the Licuári and Cuácua Rivers, with the Cuácua being the larger tributary into the estuary. The Licuári and Cuácua have a highly seasonal, torrential flow regime, with high flows for 3-4 months and low to nil flows for the remainder of the year (Barbieri *et al*., 2019; Inguane *et al*., 2014). Gauged flow data were available for the smaller Licuári tributary (basin size 3,775 km^2) during the peak wet season (January-April) measured 35 km northeast of Quelimane, ranging between 10 and 50 $m^3.s^{-1}$ (Mazzilli, 2015). Upstream pollution levels are considered negligible because of few known pollution sources. The estuary is approximately 30 km long, extending over four administrative areas: Quelimane City and the districts of Quelimane, Inhassunge and Nicoadala (Fig. 1). For this study, the area of interest (AOI) was taken as the estuarine area below 10 m amsl. The estuarine functional zone was characterised by mangroves, wetlands, mixed-forests, mudflats, agricultural land and developed areas. The area has high ecological and socio-economic diversity and supports riparian habitats connected to the water body, essentially the historical floodplain.

Datasets

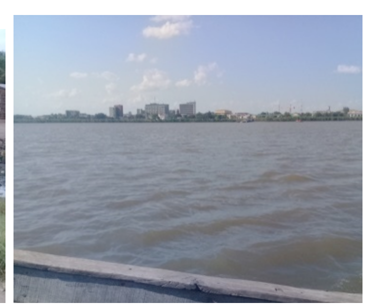
A combination of fieldwork and satellite-derived data from Landsat-5/TM (sensor: Thematic Mapper) and Landsat-8/OLI-TIRS (sensors: Operational Land Imager-Thermal Infra-Red Scanner) imagery (National Aeronautics and Space Administration (NASA)/ United States Geological Survey (USGS)) was used to generate accurate LU/LC information. Six geo-referenced Landsat images (1991 to 2018) were obtained via the USGS Data Access platform (https://earthexplorer.usgs.gov) at approximately five-year intervals. Images were selected between May and August of each study year to benefit from the lowest interference by cloud cover and standardise surface reflectance (depicted by sun elevation and azimuth) across the different classes. Selected images had a cloud cover of <10 % over the AOI (Table 1).

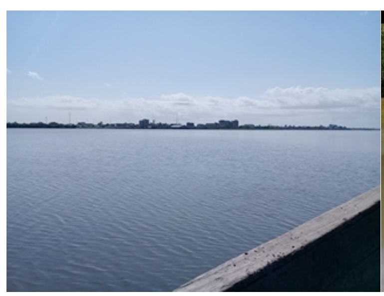
The images were Level 1 products (unprocessed, full resolution, georeferenced instrument data but with radiometric and geometric calibration) presented by

Table 1. Characteristics of satellite images used for LU/LC change detection in the Bons Sinais Estuary.

Date	Sensor ID	Cloud cover (%)	Sun elevation (º)	Sun azimuth (º)
1991-06-14	TM	0.00	34.43	44.34
1998-07-03	TM	1.00	36.48	42.31
2003-08-18	TM	2.00	42.95	51.86
2008-05-11	TM	8.00	43.05	42.69
2013-06-26	OLI-TIRS	0.01	40.03	36.43
2018-06-24	OLI-TIRS	8.90	39.62	36.98

Table 2. Land use and land cover classification classes applied in the study.

Classes	Description
Coastal bare	Substrates (usually sand) within the coastal intertidal zone (beach) that are denuded of vegetation and may be redistributed due to tidal action.  
Cultivated crops	Subsistence agricultural areas that are managed to produce harvested crops; mainly rice, maze and cassava. Crops also exist in-between fallow areas.  
Cultivated trees	Characterised by planted vegetation (orchards/plantations) that are not croplands; including coconut trees, banana, oranges, mango, etc.  
Developed	Includes medium density formal developments (Quelimane town and suburbs) and low density-informal development (sparsely distributed informal rural settlements).  

Classes	Description
Intertidal mudflats	Areas of non-vegetated, natural cover that is subject to seasonal and tidal ponding, soil saturation, or flooding in the functional zone of the Bons Sinais Estuary.  
Mangroves	Forested wetland areas and floodplain forests, influenced by tides and dominated by densely or sparsely distributed mangroves, dominated by *Avicennia marina*.  
Water	All areas of water, generally estuarine (i.e. a partially enclosed water body where salt water is measurably diluted with fresh water).  
Wetland	Wetlands, marshes or areas where the soil or substrate is periodically saturated, fed by rain or river water, and which may or may not be associated with vegetation (other than mangroves) but is not tidally influenced.  

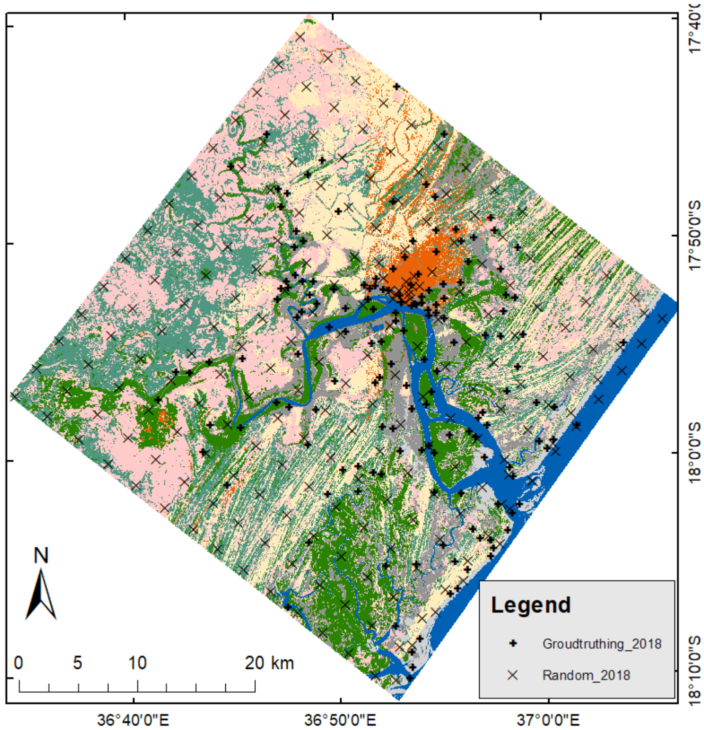


Figure 2. Location of the ground truthing and randomly selected validation points.

a 16-bit Digital Number (DN) for each OLI band, with a 30 m spatial resolution across sensors. The path and row, as used by the Worldwide Reference System (WRS), was 166 and 72 for the six images, respectively.

Image pre-processing

Radiometric calibration (RC) was performed by converting digital numbers (DN) to surface reflectance values to accurately compare different images and the thematic maps of LU/LC changes. The RC eliminates the differences in solar zenith angles associated with the time and date of acquisitions. The RC was performed by converting the original DN on each pixel into Top of Atmospheric (TOA) reflectance ($\rho\lambda$). The TOA reflectance for each spectral band was calculated using Equation 1:

$$\rho\lambda = \frac{(M_\rho * Q_{cal} + A_\rho)}{\sin(\theta)} \quad [1]$$

where M_ρ is reflectance multiplicative scaling factor, A_ρ is reflectance additive scaling factor, θ is sun elevation angle and Q_{cal} is DN.

Training data, LU/LC classification

True composite bands were used for each image, with Band 1 Visible (0.450 - 0.520 µm), Band 2 Visible (0.520 - 0.600 µm), Band 3 Visible (0.630 - 0.690 µm) and Band 4 Near-Infrared (0.760 - 0.900 µm) for Landsat-5 set, and Band 2 Visible (0.450 - 0.510 µm), Band 3 Visible (0.530 - 0.590 µm), Band 4 Visible (0.640 - 0.670 µm) and Band 5 Near-Infrared (0.850 - 0.880 µm) for the Landsat-8 set. A four-band combination was used to identify the LU/LC features for the AOI using a supervised classification algorithm. The training samples sites were selected randomly within the AOI, based on similarities in the spectral characteristics of the Landsat images combined with existing local knowledge and Google Earth imagery. A total of eight LU/LC classes were identified as follows: coastal bare; cultivated crops; cultivated trees; developed; intertidal mudflats; mangroves; water; and wetlands (Table 2).

Post-classification validation and change detection

After sufficient training samples were collected, the eight LU/LC classes in each time stamp were pre-validated. Evaluation of collected signatures was conducted through exploratory analysis of histograms and through observation of the level of association of the training samples. The validation of LU/LC classes was carried out through a combination of ground truthing points (160 field photos) used for training and a random sample of 220 points validated using Google Earth imagery from the year 2018. The most recent 2018 LU/LC image (Fig. 2) captured the main estuarine LU/LC features that included mangrove trees, freshwater

Table 3. Overall accuracy estimate given by combined ground truthing and random selected validation points for 2018.

	Water	Coastal Barrier	Mangrove	Intertidal Mudflat	Wetland	Developed	Cultivated trees	Cultivated crops	Total	User Accuracy
Water	32	1	0	0	0	0	0	0	33	0.97
Coastal Barrier	1	22	0	3	1	0	0	0	27	0.81
Mangrove	0	0	52		3	1	8	0	64	0.81
Intertidal Mudflat	1	0	1	31	6	7	0	0	46	0.67
Wetland	0	0	0	3	56		1	6	66	0.85
Developed	0	0	0	0	2	29	1	2	34	0.85
Cultivated trees	0	0	3	0	7	2	49	6	67	0.73
Cultivated crops	0	1	1	1	6	0	1	34	44	0.77
Total	34	24	57	38	81	39	60	48	381	
Producer Accuracy	0.94	0.92	0.91	0.82	0.69	0.74	0.82	0.71		0.80

wetlands, built-up areas, cultivated trees, and cultivated land. The number and location of the validation points were selected to ensure adequate reference data from field observation and Google Earth images in the interpretation of the main LU/LC features.

The accuracy assessment of the processed satellite images, through the combined ground truthing and random selected validation points (Table 3), determined a kappa coefficient of 77 % for overall assessment. The producer's accuracy (i.e., false negatives or errors of omissions) varied from 0.69 to 0.94, with the lowest accuracy in wetlands, and the user's accuracy (i.e., false positives or errors of commission) varied from 0.76 to 0.97, with the lowest accuracy for intertidal mudflats.

The recorded signature files created from training samples were then applied to detect changes in LU/LC in the Bons Sinais Estuary using a Maximum Likelihood Classifier (MLC). The MLC is widely used for thematic map production since it reduces the data redundancy that is common in remotely sensed estimations, where only a pixel with the maximum likelihood is classified into the corresponding class (Fan *et al*., 2007; Manandhar *et al*., 2009; Tan *et al*., 2010).

In the post-classification procedure, the time series was combined for detecting LU/LC changes over the 27-year period. Change detection in LU/LC compared the area of each class between time stamps and then overall for the period 1991-2018. Continuous change was evaluated using the Continuous Change Detection and Classification (CCDC) algorithm.

Results

Major land use/land cover categories

The total area of the AOI was 1,516 km². Figure 3 and Table 4 show the allocation of this land into the major land cover categories for the Bons Sinais Estuary from 1991-2018. Wetlands constituted the major land cover at 25.4-31.3 % (average, 27.8 %) of the area, over the study period. This was followed by cultivated trees ranging from 19.5 % to 26.2 % of total overall cover, but which showed a steady decrease in cover from 1991. Mangrove forests, ranging from 15.7-17.1 % over the AOI, did not change notably overall but did show a decline in cover over time. Cultivated crops, which are used mainly for subsistence agriculture, showed a steady increase from 10 % to 16.5 %, averaging 13 % of the total area from 1991-2018. Developed land, representing urban development and rural human settlements, increased from 1.8 % to 3.2 %, averaging 2.4 % coverage throughout the study period.

In 1991, Quelimane City (indicated by white arrow), was a small, sparsely occupied urban area (Fig. 3a). At that time, wetlands (to the north and west), and mangroves (to the south and east), dominated the area. Cultivated trees, dominated by coconut palm trees, appeared as 'strips' running NE-SW, interspersed by narrow bands

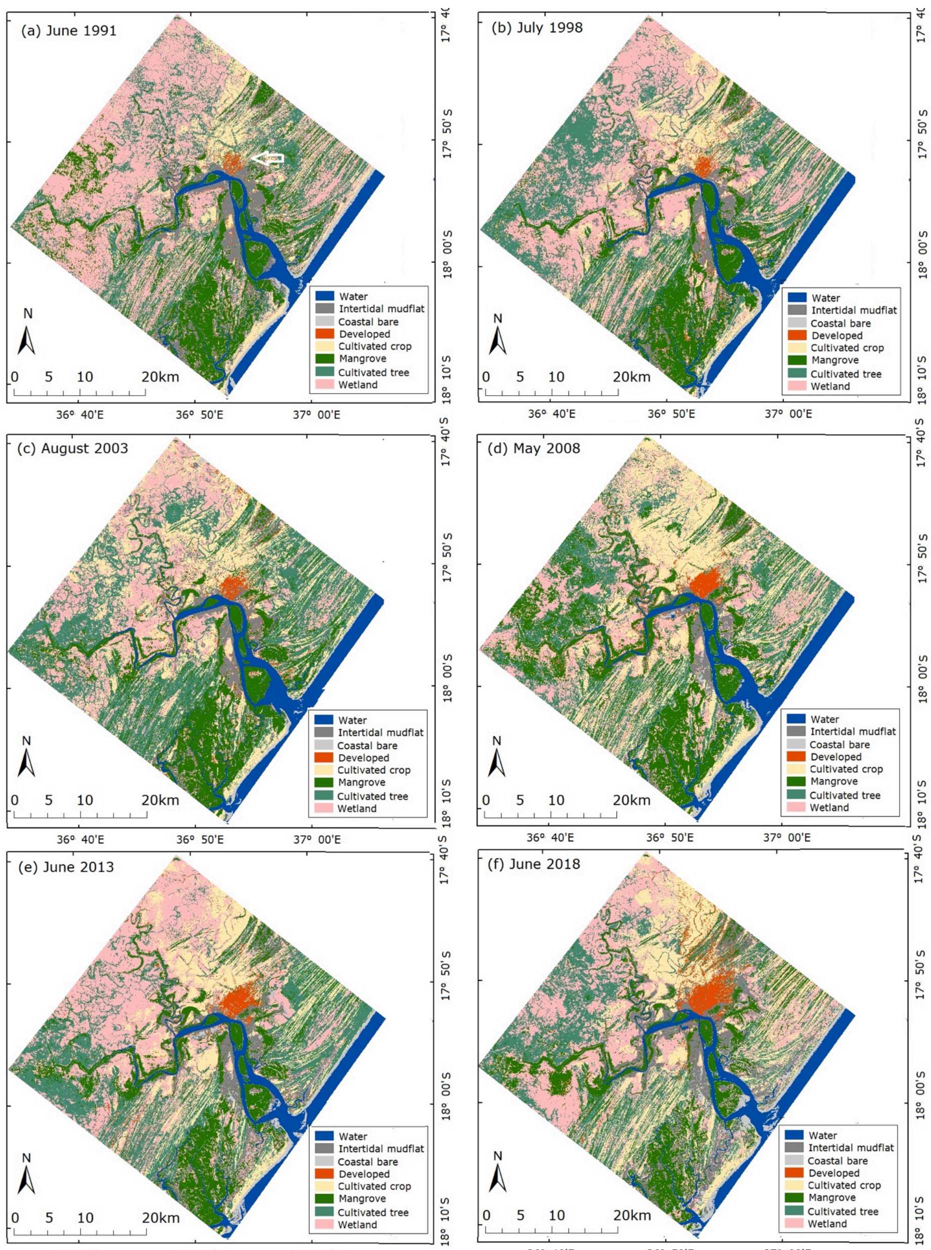


Figure 3. LU/LC in the Bons Sinais Estuary in (a) June 1991, (b) July 1998, (c) August 2003, (d) May 2008, (e) June 2013 and (f) June 2018. Quelimane City is indicated by the white arrow in (a).

of cultivated land in the western and southern side of the study area. By 1998 (Fig. 3b), densification of Quelimane City had begun with new, patchy human settlements noticeable north and west of Quelimane City. This was a clear indication of the expansion of the city. Extensive areas of cultivated crops, interspersed by wetlands, dominated the northern and western side of Quelimane. Areas of cultivated trees diminished in favour of cultivated land (croplands). Mangroves continued to dominate along the estuary and in the southern part of the study area. In 2003 (Fig. 3c). Villages continued to spread northwards, from Quelimane, and few, but less dense settlements were scattered in the northern margin of the estuary, near the mouth. The reduction in cultivated trees was replaced by cultivated croplands. Wetlands and cultivated land still dominated the northern and western part of the study area. In 2008 (Fig. 3d), Quelimane expanded, becoming denser but also new scattered patches of small villages appeared in the northern, north-eastern, eastern and south-eastern areas of the AOI. Areas under agricultural crops surpassed wetland extents. Cultivated trees were hardly noticeable in the remote sensing assessment, having been replaced by

Table 4. Major LU/LC categories in the Bons Sinais Estuary during the 1991 – 2018 period.

Categories	1991		1998		2003		2008		2013		2018		1991-2018	
	Area [km²]	[%]	Area [km²]	[%]	Area [km²]	[%]	Area [km²]	[%]	Area [km²]	[%]	Area [km²]	[%]	Area [km²]	[%]
Coastal Bare	27	1.8	22	1.5	20	1.3	28	1.8	35	2.3	56	3.7	29.0	107.4
Cultivated Crop	151	9.9	160	10.6	200	13.2	207	13.7	213	14.1	251	16.5	100.0	66.2
Cultivated Tree	356	23.5	382	25.2	397	26.2	355	23.4	336	22.1	296	19.5	60.1	-16.9
Developed	27	1.8	31	2.1	34	2.2	38	2.5	42	2.7	48	3.2	21.3	78.9
Intertidal Mudflat	115	7.6	118	7.8	121	8.0	122	8.1	125	8.3	129	8.5	13.6	11.8
Mangrove	260	17.1	259	17.1	253	16.7	246	16.2	238	15.7	228	15.0	-32.0	-22.3
Wetland	475	31.3	438	28.9	384	25.4	413	27.2	419	27.7	400	26.4	-75.5	-15.9
Water	106	7.0	106	7.0	107	7.0	107	7.1	109	7.2	109	7.2	3.7	3.5
Total	1,516	100.0	1,516	100.0	1,516	100.0	1,516	100.0	1,516	100.0	1,516	100.0		

cultivated land. In 2013 (Fig. 3e), Quelimane expanded and densified, including adjacent settlements and the appearance of new villages. There was a clear use of wetlands by villages for crop production in the northern and north-eastern parts of the AOI. Cultivated crops dominated the northern and southern parts of the study area and in the areas earlier occupied by cultivated trees, with a noticeable reduction in mangroves. In 2018 (Fig. 3f), Quelimane City continued to expand and was a prominent, developed area accompanied by further reduced natural wetland areas, particularly in the northern, eastern and south-eastern parts of the area. Cultivated land was the dominant LU, over cultivated tree areas and further reduced mangrove cover.

Changes in LU/LC

Over three decades (1991-2018) there was an overall increase in cultivated crop, development and intertidal mudflat categories, with a decline in wetlands, mangrove and cultivated tree areas (Fig. 4). Figure 5 presents the changes in the LU/LC main categories using sets of inter-annual comparisons. Except for the first interval (1991-1998), all were changes over five-year spans, compared with the overall change (1991-2018). Cultivated trees showed the largest decrease of all classes, from 356 km² in 1991 (23.5 % of surface cover in the AOI) to 296 km² in 2018 (19.5 %) (Table 4). The average reduction rate was 2.2 km² per year, with a 16.9 % decline in coverage over the 27-year period. Notable declines occurred in 2003-2008 (-42 km²) and in 2013-2018 (-40 km²), corresponding to 10.6 % and 11.9 % reduction rates, respectively. Wetlands declined from 475 km² in 1991 (31.3 % of surface cover) to 400 km² in 2018 (26.4 %) (Table 4). The overall decrease of 75 km² corresponded to a reduction rate of 2.8 km² per year, and a 15.8 % decline in coverage over 27 years. Major

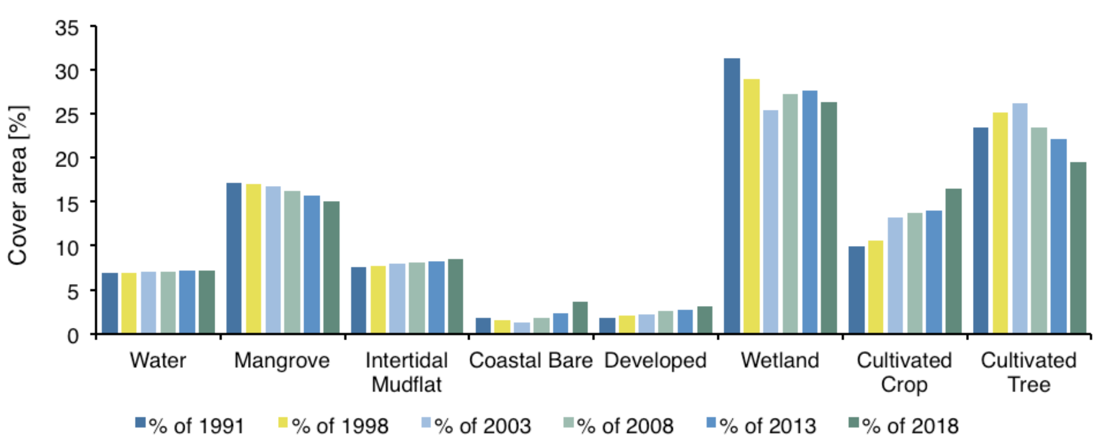


Figure 4. Temporal trends in the major LU/LC categories in the Bons Sinais Estuary between 1991 and 2018.

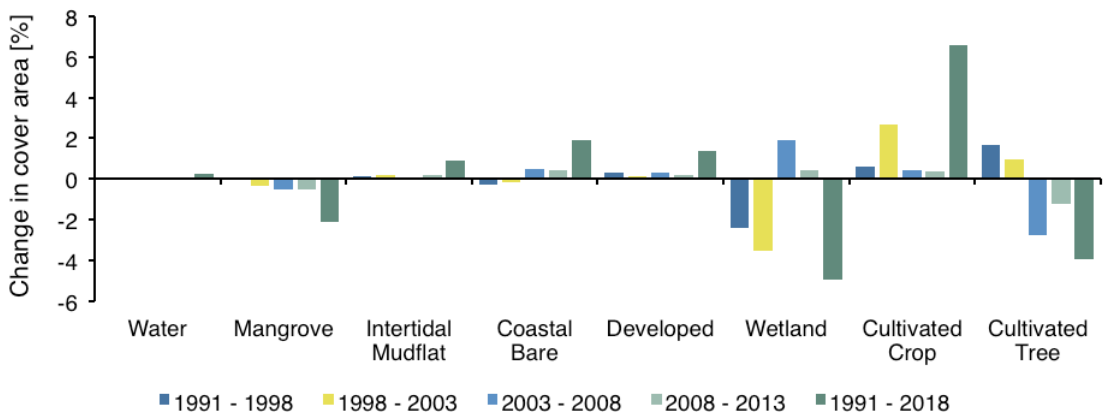


Figure 5. Changes in major categories of LU/LC in the Bons Sinais Estuary between 1991 and 2018.

reductions in wetlands were observed in early years, between 1991-1998 (-37 km²) and 1998-2008 (-54 km²), corresponding to 7.8 % and 12.3 % reductions, respectively. However, for the periods 1998-2008 and 2008-2013, small increases in wetlands of 7.6 % and 1.5% were noted. Mangroves declined from 260 km² in 1991 (17.1 % of surface cover) to 228 km² in 2018 (15 %). The average reduction rate was 1.2 km² per year or 12.3 % over the 27-year period.

Coastal bare land registered the highest increase of all classes, from 27 km² in 1991 (1.8 % of surface cover) to 56 km² in 2019 (3.7 %). The average increase rate was 1.1 km² per year, corresponding to an overall increase of 107.4 % over 27 years. Developed areas increased from 27 km² in 1991 (1.8 % of surface cover) to 48 km² in 2018 (3.2 %), an increase rate of 0.8 km² per year or 78.9 % over 27 years. Cultivated crops increased steadily from 151 km² in 1991 (9.9 % of surface cover) to 251 km² in 2018 (16.5 %). The rate of increase was 3.7 km² per year or 66.2 % over 27 years. The greatest increase (25 %) took place in 1998-2003. Intertidal mudflats increased from 115 km² in 1991 to 129 km² in 2018, an increase rate of 0.5 km² per year or 11.8 % over the study period.

Discussion

LU/LC changes

The study indicated a clear increasing trend in certain LU/LC categories around the Bons Sinais Estuary, such as cultivated crops (66 %), development (79 %) (including urban and rural human settlements), intertidal mudflats (1 2%) and coastal bare ground (107 %) from 1991 to 2018. Importantly, there was a concomitant effect on natural habitats, some being critical ecosystems, through an evident trend in reduced mangrove areas and wetlands. Although cultivated trees declined through time, they would have initially replaced natural coastal habitats. The results showed an anomalous increase in wetlands through the years 2008 to 2013. However, this was attributed to heavy rains observed in the years 2012-2013 (Fig. 6) and consequent flooding into low-lying habitats.

Most of the changes observed for the Bons Sinais Estuary may be attributed to human related activities. Notably, wetlands have been converted into agricultural farms and rural human settlements. Furthermore, mangroves, apart from being depleted for firewood, charcoal production and building material, have been converted into salt pans and aquaculture ponds (Unaite, 2017), or have been cleared and converted into human settlements (Fig. 7).

The increase in the area required for habitation and agricultural land, and the increased pressure on mangrove resources are attributed to the population growth observed in the Bons Sinais area during the last two decades (2000-2020). According to the National Statistics (INE, 2007; INE, 2017), the population of Quelimane city was 193,343 in 2007, increasing by 2.5 % per year over the next 10 years to 259,293 inhabitants in 2017.

The reduction in the cultivated trees was attributed to the disappearance of coconut palm plantations. Cultivated coconuts dominated the category 'cultivated trees' up until 1998, whereafter lethal yellowing disease resulted in mass mortalities of coconut palm trees in Zambézia province (Bila *et al.*, 2015). Lethal yellowing is a phytoplasma disease spread by the plant hopper *Haplaxius crudus* in global tropical environments and infects many palm species including commercially important coconut and date plantations. The incidence in East Africa is still puzzling as the

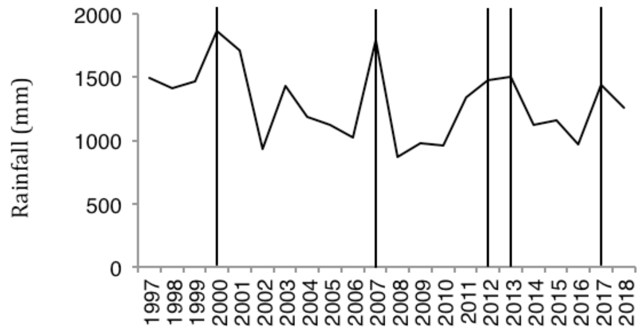


Figure 6. Total annual rainfall recorded at the Meteorological Station in Quelimane. The vertical lines indicate the periods of occurrence of heavy rain and flooding.

plant hopper is not native there (Brown *et al*., 2006; Howard, 1992). The local population has initiated an extensive re-planting effort of alternate fruit trees such as mango, orange and banana. However, these efforts had not yet completely replaced the previous extent of coconut palm trees.

The small observed increase in intertidal mudflats, despite the movement of people and their settlements into these areas, was attributed to increased inundation – potentially because of sea-level rise. Several studies have shown evidence of sea level rise attributed to melting ice in polar regions and to thermal expansion of sea water due to global warming (Holgate *et al*., 2013; PSMSL, 2020; Schneider, 1989). Mozambique is not an exception. Based on historical Monthly Mean Sea Level data (1961-2015), Maueua and Canhanga (2018) estimated that the sea level on the Mozambique coast has risen by 0.9-1.8 mm per year. Brown *et al*. (2011) used the global DIVA (Dynamic Interactive Vulnerability Assessment) model to estimate that African sea levels will rise from 0.17 m in 1995 to 1.26 m in 2100. Concerningly, Mozambique is predicted to be heavily impacted by such rises. The Bons Sinais Estuary and Quelimane city are both in a low-lying area (mostly <5 m amsl) and are likely to be heavily impacted by sea-level rise.

Possible impacts of the observed LU/LC changes

The reduction of coastal wetlands and mangroves are of major concern, given their important role in flood and storm mitigation (Blankespoor *et al*., 2017; Leon *et al*., 2018; Menéndez *et al*., 2020; Sheng and Zou, 2017; Song *et al*., 2014) and provision of goods and services on which the livelihoods of many local people entirely depend (Carugati *et al*., 2018; Shapiro *et al*., 2015). The destruction of these important habitats will exacerbate the effects of sea storms and flooding, predicted to increase as the climate changes. These factors are likely to worsen poverty levels, especially of

Figure 7. Aerial photo showing part of Quelimane City where mangroves and intertidal mudflats were cleared for human construction in 2014. Source: Silvermoz.com, obtained from Unaite (2017).

low-income groups. Mangroves are important nursery grounds for many fauna, including for those harvested by fishers (e.g. Ayub, 2010; Hatcher *et al.*, 1989; Loneragan, 1999) and their continued degradation is likely to result in reduced fisheries production (Malik *et al.*, 2017) with implications for livelihoods.

Proposed management strategies

Local livelihoods are strongly dependent on fisheries and fish products, which in turn depend on healthy natural ecosystems. Anthropogenic impacts on estuarine ecosystems are predicted to increase along with population growth, necessitating sustainable land use and urban planning strategies to ameliorate the potentially disastrous effects of lost critical habitats. Several studies (e.g. Basconi *et at*., 2020; Martin, 2017; Matzek *et al.*, 2021; Lai *et al.*, 2015) have reiterated the importance of restoration and conservation strategies to reverse the downwards trends in estuarine goods and services. Mangroves in Mozambique are protected by law (Barbosa *et al.*, 2001) under the Forests and Land Legislation Act which envisages community participation in the protection of natural resources. The act was revised in 1998, stipulating that all mangroves are subject to partial protection, prohibiting development within 100 m inland from the upper tidal limit, and calling for communities to participate in the protection of natural resources (including mangroves) including conflict resolution. Even so, mangroves are still heavily exploited by coastal communities dependent on their wood for fuel and building, and law enforcement remains weak (Nicolau *et al.*, 2017). The need for restoration and conservation of estuarine ecosystems, including mangrove habitats, have never been greater. To be successful, strategies must involve local communities and promote alternative livelihoods, such as 'smart agriculture practices' that increase the yield and the efficiency of water and land use (Bach and Mauser, 2018; Kimaro, 2019). Effective law enforcement through capacitation and knowledge transfer to government departments are additional lines of defence for the protection of critical estuarine habitats.

Conclusion

In conclusion, the reduction in mangrove and other wetland habitats of the Bons Sinais Estuary over the past 27 years resulted mainly from accelerated urban development (often unplanned) and increased exploitation of estuarine resources by a growing population, as indicated by increases in areas under development and cultivated crops. The reduction in areas covered by cultivated trees stemmed from mass coconut palm mortalities caused by lethal yellowing disease in plantations. An increase in intertidal mudflats was tentatively attributed to climate-driven sea-level rise.

The study predicts a worsening of the anthropogenic impacts on the estuarine ecosystem with further growth of Quelimane city. To reverse the negative trend on estuary health, the recommendation is for management interventions that promote sustainable LU, and urban development plans that consider ecosystem conservation and active restoration. The present study contributes to the understanding of past and present changes in LU/LC in the Bons Sinais Estuary, including the socio-economic and ecological implications thereof.

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