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Linking ecosystem pressures and marine macroinvertebrate ecosystem services in mangroves and seagrasses

Alice Resende Santos[1,2,*], Marta Bento[1,2], Stefanie Broszeit[3], José Paula[1,2], Alexandra Marçal Correia[1,2]

[1]Department of Animal Biology, Faculty of Sciences, University of Lisbon, Campo Grande, 1749-016 Lisbon, Portugal
[2]MARE – Marine and Environmental Sciences Centre, University of Lisbon, Campo Grande, 1749-016 Lisbon, Portugal
[3]Plymouth Marine Laboratory, Prospect Place, The Hoe, Plymouth, PL1 3DH, UK

ABSTRACT: African coastal ecosystems encompass high biodiversity that provides crucial ecosystem services (ES). However, the supply of these ES is threatened due to ecosystem degradation, which threatens human well-being and livelihoods. This study investigated the link between pressures and the ES provided by marine macroinvertebrates (MMIs) in mangroves and seagrasses. We assessed ecosystem condition (marine protected areas, MPAs), pressures, namely climate change (sea surface temperature and sea level), land-use and land-cover changes, overexploitation (mangrove deforestation and overfishing), and core MMI ES (provisioning, regulation, cultural). Our results revealed a low ratio of MPAs compared to the Aichi Target 11, emphasizing the need for a comprehensive conservation strategy. Sea temperature and level showed an increasing trend, indicating the vulnerability of coastal ecosystems to climate change. The decline in mangrove forest cover highlights the need to mitigate adverse effects of land-use change. The increasing number of artisanal fishery licences suggests increased pressure on MMIs, which can have severe consequences for local communities. MMI food production, particularly shrimp, and recreational fishing increased in the last 2 decades. Regulation services and cultural services related to research and education varied through time due to the limited availability of data. This information was used to develop an exploratory conceptual model illustrating the complex relationships among pressures, condition, MMI ES, and management goals for the sustainable use of marine resources and their connection with food security. Our findings underscore the importance of preserving MMI populations and habitats while addressing knowledge gaps to enhance the resilience of coastal ecosystems.

KEY WORDS: Marine macroinvertebrates · Ecosystem conditions · Digital data · Conceptual model · Food security · Future scenarios

1. INTRODUCTION

Ecosystem services (ES) are vital for sustaining the health and well-being of both humanity and the natural world. According to Potschin & Haines-Young (2016, ch. 3, p. 1), ES can be described as 'the contributions that ecosystems make to human well-being'. These ES are intrinsically linked to the fundamental structure, functions, and processes of ecosystems, and are distinct from the goods and benefits that people subsequently derive from them. Their assessment encompasses the production and synthesis of scientific knowledge to support informed decisions, through the evaluation of the condition, trends, and future trajectories of ecosystems and their services (Mace et al. 2012). The key to achieving reliable ES

*Corresponding author: alice.resende.santos@gmail.com

assessments depends on the availability and quality of data, as well as the selection of suitable, relevant, and, preferably, harmonized indicators and models (Müller & Burkhard 2012). Understanding ES and their sources is not sufficient for sustainable management; it is also necessary to identify and, where possible, reduce pressures that may decrease ES delivery. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) Global Assessment Report (IPBES 2019) summarised 5 key pressures that lead to biodiversity and ES loss. These pressures include land-use change (considered the most important impact on terrestrial and freshwater ecosystems), seafood exploitation (largest impact on marine systems), climate change, pollution, and invasive alien species, which are rapidly accelerating in terms of their impact. Knowledge about ecological processes that lead to ES is also fundamental. Therefore, the current research aims to understand the linkages between ecosystem functioning and the delivery of ES. These linkages underpin ES synergies and trade-offs between different ES. Considering these connections implies looking at multiple ES simultaneously to foster sustainable management and use of resources (Mace et al. 2012). Ecosystem services conceptual models (ESCMs) are useful tools that can support ES assessment and management (Olander et al. 2018). Conceptual models illustrate major relationships between ecosystem functions and ES. Although selective due to the complexity of natural systems, these models can help stakeholders and experts achieve a mutual understanding and communicate priorities in managing marine resources and marine space (Olander et al. 2018).

Mangroves are distinctive tidally influenced tropical and subtropical wetland ecosystems consisting of forests of trees, shrubs, epiphytes, and ferns (Aksornkoae & Kato 2011), whereas seagrasses are marine flowering plants which form extensive meadows in shallow coastal waters on all continents except Antarctica (Green et al. 2003). Both mangroves and seagrasses regulate freshwater infiltrations, retain large quantities of organic and inorganic matter, as well as pollutants, producing an environment of crystalline water low in nutrients that promote the growth of adjacent corals. The complex dynamics within biologically rich habitats, such as mangroves and seagrasses, has received considerable attention (e.g. Green et al. 2003, Lee et al. 2014). In fact, these ecosystems are associated with high productivity and biodiversity, providing vital goods and services to coastal communities (Moberg & Folke 1999, Lee et al. 2014). Consequently, the good ecological status of mangroves and seagrasses is fundamental to secure ecosystem functioning and the wellbeing of local communities.

In the tropics and sub-tropics, coastal habitats such as mangroves and seagrasses provide important structures and resources for diverse communities of benthic invertebrates (Alfaro 2006). Marine macroinvertebrates (MMIs) are vital components of mangroves and seagrasses due to their abundance, diversity, interaction with multiple trophic levels in ecological networks, and occupation of a huge variety of ecological niches (Alfaro 2006), regulating the fluxes of matter and energy and thus, ecosystem functioning. MMIs play an important role not only in ecological terms but also to human well-being, namely food security; regulation and maintenance; and aesthetic, cultural, and recreational ES. Despite their relevance to sustain ecosystem functioning and services, MMIs have been increasingly subjected to anthropogenic pressures. This is aggravated by the lack of information on MMI biodiversity, abundance, and functional traits as well as coherent methods and approaches (Lam-Gordillo et al. 2020). To understand the linkages between habitats, species, and functions and how they create ecosystem services, data of their occurrences, quantities, and conditions are vital.

An increasing array of high-quality data is stored in digital repositories (e.g. Global Biodiversity Information Facility [GBIF], Food and Agriculture Organization of the United Nations [FAO], national statistical institutes) that can be used in downstream studies (Ladouceur & Shackelford 2021), such as ES assessments. In fact, according to Borgman et al. (2006, 2007), data are becoming scientific capital, and e-Science (a term used to represent the increasingly global collaborations of people and shared resources) promises to increase the pace of science via fast, distributed access to computational resources, analytical tools, and digital libraries (Hey & Trefethen 2003). Digital data can be used for several purposes, generally involving the compilation, standardization, and integration of data from different sources. The advantages of using data from digital sources are many, e.g. allowing the identification of knowledge gaps which can be addressed through an informed process, the use of broader spatial and temporal scales, the development of desk-based projects when the study area is difficult to assess, and overall leading towards better/more complete outcomes (Ladouceur & Shackelford 2021). Data repositories, such as GBIF, collect data from many different sources and are often spatially and temporally explicit. Though they differ from sustained monitoring practices (e.g. using the same sampling method each time data are collected), they still have value. For example, they can provide evidence that a particular species occurred in a specified location, which is helpful in understanding changes to biodiversity. These 'long-term' data sets can be used either alone, or in combination with newly generated data to produce new knowledge, discovery, and innovation. Subsequent data and knowledge obtained from such studies can be integrated and reused by the community after publication.

Mozambique is home to important areas of mangrove forests and seagrass meadows (Mumby et al. 2000), which provide important habitats and resources for diverse MMI assemblages (Alfaro 2006). MMIs are relevant components in the human diet greatly contributing to the food security of local communities, especially in developing countries such as Mozambique (Gillespie & Vincent 2019). Sustainable Development Goal (SDG) 2, established in the 2030 Agenda for Sustainable Development, is 'Zero Hunger' which aims not simply to 'eradicate hunger', but also to 'end hunger and ensure access by all people, in particular, the poor and people in vulnerable situations to safe, nutritious and sufficient food all year round' (SDG Target 2.1) and to 'eradicate all forms of malnutrition' (SDG Target 2.2) (UN 2015, p. 15). Achieving this is a grand challenge for society, while climate change and an expanding global population make global food security even more complex and demanding. Hence, achieving sustainable management of MMIs and reducing pressures on their habitats is vital to the communities that are dependent on them.

The main objective of this study was to use available digital data and information to link pressures in mangroves and seagrasses with the ES provided by MMIs, using Maputo Bay (MB), Mozambique, as the study area. This assessment adopted a holistic approach by addressing MMI ES knowledge gaps and providing an exploratory ES conceptual model. Emphasis was placed on the importance of MMIs to the food security of local communities, encompassing traditional practices in mangroves and seagrasses. The specific goals of this study were to (1) assess the condition of coastal ecosystems, focused on mangroves and seagrasses; (2) evaluate anthropogenic pressures: land-use change, overexploitation, and climate change; (3) identify, classify, and quantify the ES provided by MMIs (provisioning; regulation and maintenance; and cultural); (4) create an exploratory ESCM relating ecosystem pressures and condition with MMI ecological characteristics, the flow of ES, and different management goals; (5) identify and address knowledge gaps linked to MMI ES; and (6) understand the importance of MMIs and traditional practices to food security. This study provides baseline information for decision-makers, enabling them to identify appropriate conservation actions for MMIs in mangroves and seagrasses to promote their sustainable use while mitigating key pressures.

2. MATERIALS AND METHODS

2.1. Study area

MB has an area of 2280 km^2 (approximately 90 km in length by 32 km width) and it opens to the Indian Ocean, lying between latitudes 25° 72′ 10″ –26° 28′ 30″ S and longitudes 32° 49′ 10″ –32° 85′ 40″ E (Datum WGS84). Different spatial data sets, consisting of vector files (polygon shapefiles) previously mapped (see Table S1 in the Supplement at www.int-res.com/articles/suppl/m732p015_supp.pdf) were used to map coastal habitats (mangrove forests and seagrass meadows) and protected areas (Fig. 1). The coastal belt of MB is a natural vegetated landscape and includes 2 important conservation areas: Ponta do Ouro Partial Marine Reserve (POPMR) and Maputo Special Reserve (MSR).

Mangroves in MB (Fig. 1B) comprise 6 species: *Avicennia marina*, *Rhizophora mucronata*, *Ceriops tagal*, *Bruguiera gymnorrhiza*, *Xylocarpus granatum*, and *Lumnitzera racemosa*. Seagrass meadows in MB (Fig. 1A), locally called 'Tanhi' in the language xiRonga, include 9 seagrass species distributed in 3 families: Cymodoceaceae (*Cymodocea rotundata*, *C. serrulata*, *Halodule uninervis*, *Syringodium isoetifolium*, *Thalassodendron ciliatum*, and *T. leptocaule*), Hydrocharitaceae (*Halophila ovalis* and *Thalassia hemprichii*), and Zosteraceae (*Zostera capensis*) (Bandeira 2002).

2.2. Data collection and analysis

2.2.1. Ecosystem condition and pressures

The assessment of condition and pressures, and the selection of related indicators, followed the EU Mapping and Assessment of Ecosystem Services framework (MAES 2014, 2018).

To assess the condition of MB's ecosystems, the ratio between the area of POPMR (which is a marine protected area) and the total marine area in the province of Maputo (Maputo's exclusive economic zone) was calculated and compared to a standard value

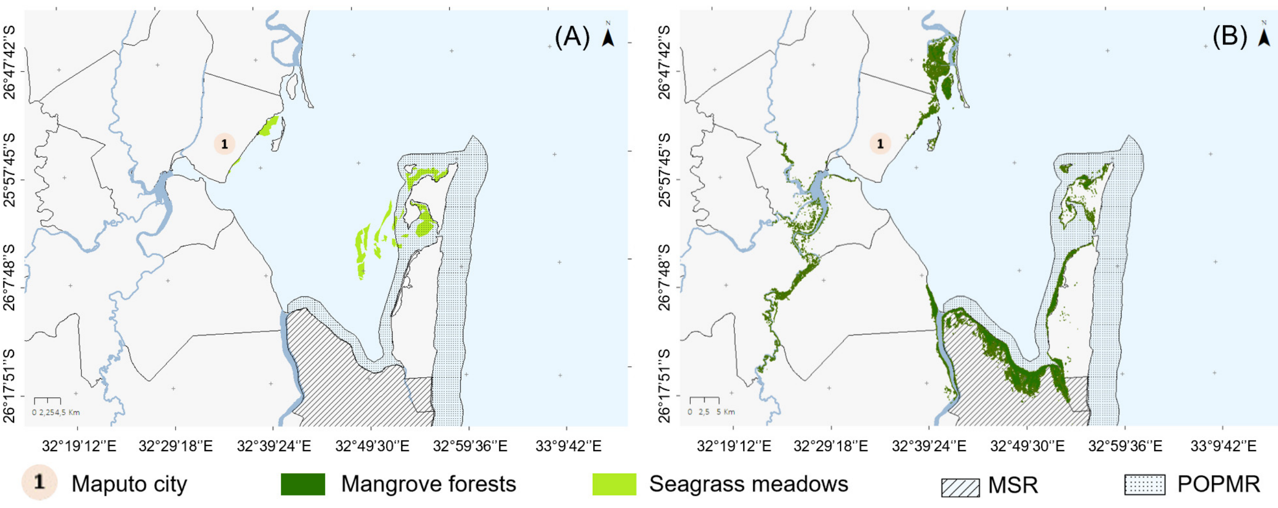

Fig. 1. Distribution of (A) seagrasses and (B) mangroves in Maputo Bay and the surrounding areas. MSR: Maputo Special Reserve; POPMR: Ponta do Ouro Partial Marine Reserve

proposed by Aichi Target 11: 'By 2020, at least 10 per cent of coastal and marine areas (...) are conserved through effectively (...) well-connected systems of protected areas' (CBD 2010; https://www.cbd.int/aichi-targets/target/11/). This indicator is also used by Mozambique (INE 2020, p. 8) in the context of the SDG 14.5: 'By 2020, conserve at least 10 per cent of coastal and marine areas', in line with the Aichi Target 11.

The assessment of anthropogenic pressures encompassed the review of digital databases, scientific literature, and reports related to Mozambique, more specifically MB, to gather data on 3 main pressures: climate change (sea surface temperature and sea level change), land use/land cover (LULC) changes (related to habitat destruction), and overexploitation (mangrove deforestation and overfishing).

Data sets referring to the sea surface temperature (SST) and sea level (SL) were used to analyse the effects of climate change on MB and were downloaded from Nasa Earth Observations (NEO 2020) and the Permanent Service for Mean Sea Level (PSMSL 2005), respectively. The data sets used from each source were NEO SST (1 mo, AQUA/MODIS), dating from 2002 to 2010; and PSMSL Maputo mean SL, dating from 1961 to 2001. To better understand if any climate change sign has been registered over time in the MB region, a scatterplot was produced for each variable, where the dependent variable was SST or SL, and the independent variable was time (in years). Subsequently, a linear regression was applied to the data of each scatterplot to obtain an overall perspective on the evolution of each dependent variable over time (SST and SL).

The data sets used for mapping LULC in the Maputo district were downloaded from the European Space Agency (ESA 2017), covering a time series from 1992 to 2015. All raster files (1 for each year) were converted to the datum D_WGS_1984 and projected to WGS_1984_UTM_Zone_37S. Each pixel was reclassified to strictly represent one of the following classes: (1) (semi)natural land cover (where seminatural cover stands for areas modified by human influence but retaining many natural features), (2) agricultural land cover, (3) urban land cover, and (4) bare land cover; (0) zero was used for pixels with no data. For the final step, all raster files were handled to obtain the areas of the main classes (multiplying the area of one pixel by the total number of pixels from each class).

The deforestation analysis aimed at understanding the evolution of mangrove forests in MB over time. Therefore, the method behind it was the same as for LULC, but a different file was used here because raster files from LULC did not differentiate mangrove cover within the class (1) (semi)natural land cover. Specific data (Table S1) were used to assess mangrove deforestation from 1996 to 2016. MMI overfishing was assessed through fishing effort using data collected from various official reports (Sousa 1989, Ministério das Pescas 2012, António et al. 2017). The information available for MB consisted of the number of fishing licences, which was used as a proxy indicator for overfishing following the assumption that more licences represent higher fishing effort and a more severe impact on MMI stocks.

2.2.2. Assessment of MMI ES

A thorough literature search was conducted to identify, classify, and quantify MMI ES in MB. ES were categorised into provisioning; regulation and maintenance; and cultural ES according to the Common International Classification of Ecosystem Services (CICES) V5.1 with correspondence to the IPBES typology (Haines-Young & Potschin 2017). The MMI ES identification and classification refer specifically to the services quantified here. The ES indicators were selected according to the available data (Table S2).

Fishing activities were explored to understand the quantitative supply of provisioning ES provided by MMIs. Provisioning MMI ES were estimated through the artisanal and semi-industrial fisheries production data retrieved from the Ministério das Pescas (2012) and António et al. (2017).

The quantification of MMI regulation and maintenance ES was based on the analysis of an MMI data set constructed with data from MB. This data set was extracted from a larger MMI data set from Mozambique (Bento et al. 2023) which aimed to list any species occurrences in MB recorded through time, either for museum collections or other sampling strategies. Data sources included biodiversity repositories such as GBIF, museum collections, and scientific literature. As a result, data do not represent sustained time series data collection or monitoring but a compilation from different databases and origins. However, the data set from Bento et al. (2023) is georeferenced, with each entry associated with latitude and longitude. Additionally, it has been standardized according to the Darwin Core format and validated. Therefore, we utilized this data set to generate the data set used in our study. The filtering process involved the selection of entries within the physical/ geomorphological boundaries of MB. The latitudes considered were between 25° 72′ 10″ and 26° 28′ 30″ S, whereas the longitudes ranged between 32° 49′ 10″ and 32° 85′ 40″ E. The resulting data set (https://doi.org/10.5281/zenodo.7074686) encompasses the following information for each occurrence: taxonomic level to genus or species; locale (name and georeferences) and date of sampling; ecosystem type (e.g. mangrove, seagrass); habitat occupation; and trophic guild. The indicators used to quantify the regulation and maintenance ES provided by MMIs were developed using an independent approach applied to the data set analysis; the process behind it is explained in more detail below.

The first step involved the assessment of the different functions performed by every MMI trophic guild (e.g. deposit feeder, suspension feeder, scavenger), which were then linked to different classes of regulation and maintenance ES following Lam-Gordillo et al. (2020) and the CICES classification adapted to a marine context (a guideline of these interactions is presented in Tables S3 & S4). Since the data set consists of species occurrence data from a variety of different sources, species richness (SR) was used as a proxy to reduce bias and data limitations (e.g. abundance); all data entries were standardized to the species level, and no data with higher taxa levels were present. Considering that SR is affected by sampling effort, we aggregated SR data into decades because species accumulation through time reflects non-random distributions rather than sampling efforts and techniques (White et al. 2006, Magurran et al. 2010). To assess MMI functions, the data set was also divided into decades, and all of the existing species were considered once (SR) for each decade. Due to the inherent uncertainty regarding whether the contribution of a species' traits to different functional groups is variable or uniform, we adopted the methodology suggested by Pakeman (2004) and de Bello et al. (2005) which is based on fuzzy coding. This approach accommodates the variability of species in performing multiple functions when their precise ecological roles are unknown. In this sense, marine macroinvertebrate traits were systematically categorised using fuzzy coding to address interspecific variability within a given trait and the functional traits associated with distinct functional groups. Thus, when a species exhibited functional traits linked to different functional groups, we estimated its contribution to each functional group by equally dividing the total contribution (equal to 1) across the number of functional groups it contributed to. Subsequently, a matrix consisting of the number of species under each functional group (species as rows × trophic guild functional groups as columns) per decade was constructed. The contribution of each functional group to an ES was calculated through the equation developed by Asante et al. (2023): $C_{fi} = 1/N_f \times S_{fi}$, where C_{fi} is the contribution of the i^{th} functional group; N_f is the total number of functional groups contributing to a particular ES; and S_{fi} is the number of species in the i^{th} functional group considered. A score level for each regulation ES was then calculated by summating all the functional contributions linked to that ES.

The evaluation of MMI cultural services included the estimation of SR per decade from the analysis of the MB data set (https://doi.org/10.5281/zenodo.7074686), and the number of recreational and sport fisheries licences retrieved from António et al. (2017). Recreational and sport fishing share the common feature of fishing for leisure. For this reason, both fishing types were considered only cultural interactions, although occasionally, catches can add to the family's food security.

The trends of provisioning; regulation and maintenance; and cultural ES provided by MMIs of MB were assessed based on the indicators evaluated, considering the last 2 decades, i.e. 2010–2019 in relation to 2000–2009. This time-series corresponds to the post-civil war period, representing an increasing effort to collect data. The trends of regulation and maintenance ES, and cultural ES based on SR must be interpreted cautiously due to the limitation and scattered nature of the available data. Nevertheless, temporally aggregated SR is considered a reliable measure that accounts for sampling effects and can be used to explore temporal trends (Magurran et al. 2010).

2.2.3. ESCM

To create a robust ESCM, a few fundamental steps were taken based on Olander et al. (2018). Firstly, a specific outcome was established by adapting the model to an exact site and context, i.e. to understand the role of MMIs in mangroves and seagrasses, ultimately considering the food security of the local communities as an outcome. Secondly, the kind of model to develop was chosen considering that this study was based on linking existing scattered information and data; and that all the understanding of the study area and its systems was attained remotely. Engaging with local stakeholders was outside of the scope of this study. Therefore, the exploratory conceptual model (sensu Olander et al. 2018: ESCM connotation, i.e. exploratory, general, or specific) was considered the most adequate to provide baseline information for decision-making. Thirdly, model assumptions entailed the clarification of hypotheses and the refining of the model, leading to a process of adding missing nodes and removing extraneous ones. This was followed by a fourth step, the search for corroborating evidence (for each assumption), which consisted of assessing and documenting what is generally known about the relationships in the model, providing an initial indication of the magnitude and direction of change where it is known, and refining model relationships (add/drop nodes and arrows as needed to represent what has been learned). The fifth step was based on evidence assessment and the confidence behind each relationship described in the model; at this stage, an expert-based discussion in an Ecosystem Services Workshop-specific case study (led by Melanie Austen and Stefanie Broszeit and organised within the scope of the Portugal Twinning for Innovation and Excellence in Marine Science and Earth Observation [PORTWIMS] Project), and all results obtained during the course of this study were integrated to further enhance the model, which further specified gaps that should be prioritized in the research agenda. Finally, the visualization of the model and the discussion of the confidence in the existing evidence and the concerns about the gaps identified were discussed. This contributed to an understanding of the benefits and risks behind the results. The first sketches of the conceptual model were developed through 2 online meetings between the co-authors.

3. RESULTS

3.1. Ecosystem condition and pressures

The condition indicator, expressed as the ratio between the total marine area of Maputo Province (110 878 km^2) and the integrated MPA (678 km^2), was 0.661 %, which is much lower than the 10 % considered by the Aichi Target 11.

At the beginning of the century, the mean SST was close to 14.8°C, and since then, albeit with several oscillations, it increased to approximately 15.9°C in 2017 (Fig. 2A). According to the line of best fit, there has been a mean SST increase of 0.4°C in MB over the last 20 yr. The mean SL in MB was approximately 6.95 m in the 1960s and increased to approximately 7.15 m at the beginning of the 21st century (Fig. 2B). The SL line of best fit indicated a slight SL rise in 40 yr, but if the SL registered in 2002 represents the actual SL trend in the last 18 yr (there was no available data on SL in MB after 2002), the SL rise may be higher than presented here.

The comparison between the LULC of Maputo province in 1992 and 2015 (Fig. 3) shows the changes that occurred in the area over time. In both cases, the majority of the land had a (semi)natural cover, although there was a decrease from 1992 to 2015; the agricultural cover was the second most common type,

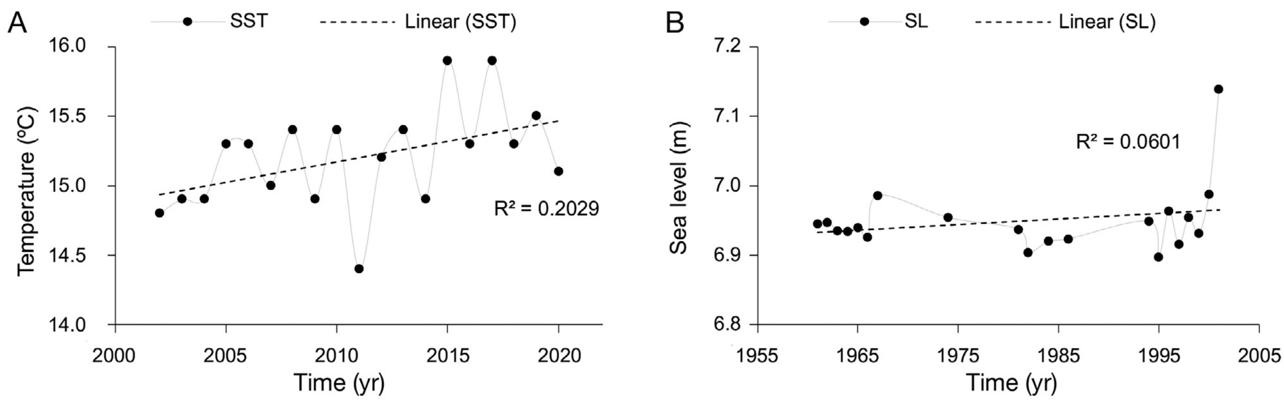

Fig. 2. (A) Maputo Bay (MB) mean sea surface temperature (SST) over time; source data: NEO (2020). (B) MB mean sea level (SL) over time; source data: PSMSL (2005). Dashed lines represent the linear trends

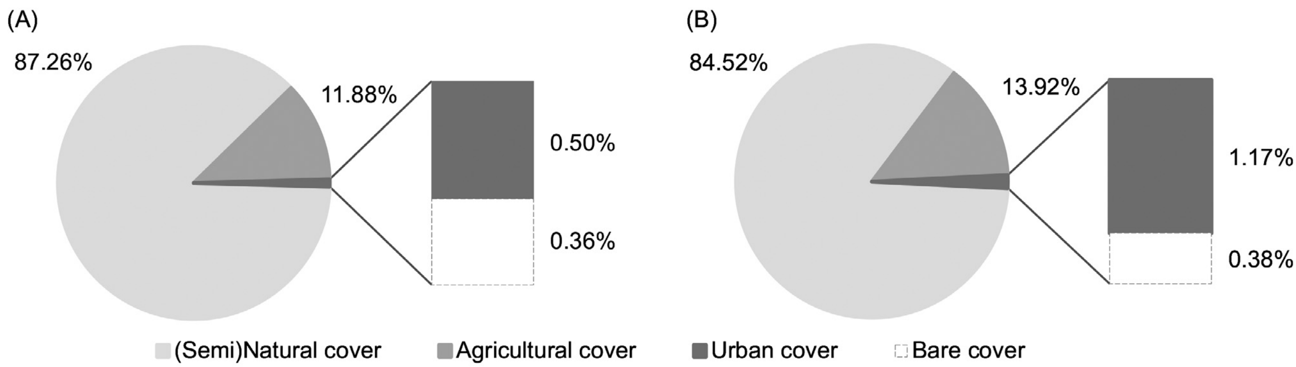

Fig. 3. Land use/land cover (LULC) in the Maputo district in (A) 1992 and (B) 2015. Source data: ESA (2017)

followed by urban, both with an increase; the bare area did not change in the study period.

The total area of changes in mangrove forest cover at MB did not follow a consistent trend (Fig. 4). However, there was a clear area drop, from 80.5 km^2 in 1996 to 76 km^2 in 2016. In sum, approximately 5% (ca. 4 km^2) of the mangrove forest was lost in MB over the course of 20 yr.

The number of fishing licences attributed to the artisanal fishery was used as a proxy to measure overfishing (Fig. 5). At the national level, the highest number of licences was issued in 2015. The decrease (ca. 5000) of licences from 2015 to 2016 was followed by an increase in 2017. A similar pattern was observed in MB, with a maximum of licences in 2015. Overall, in MB there was a tendency for an increase in the number of artisanal fishery licences.

Table 1 presents the trends of all pressures affecting the bay, its mangrove forests and seagrass meadows, as well as MMI stocks, based on the analysis of the indicators applied during this study. If current trends

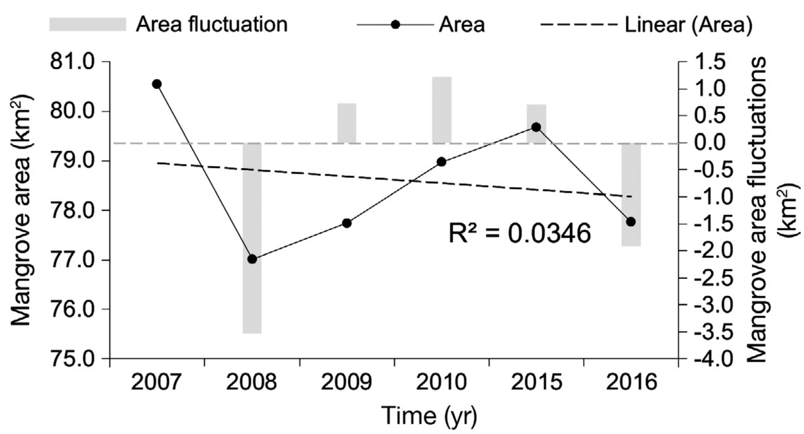

Fig. 4. Area of mangroves in Maputo Bay over time. The black dashed line represents the linear trend. The columns illustrate the variation in the mangrove area between consecutive years. The grey dashed line marks the 0 relative to the area fluctuation scale (grey axis) for visual reference. Adapted from Worthington et al. (2020)

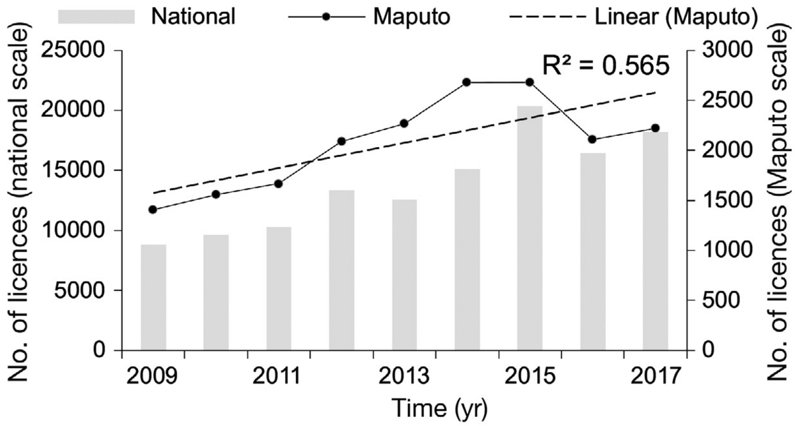

Fig. 5. Number of licences attributed to artisanal fishery over time at the national scale and for Maputo Province (dashed line represents the linear trend). Source data: António et al. (2017)

Table 1. Trends (up- or downward arrowhead) of the major pressures, i.e. climate change, land use/land cover (LULC), and overexploitation, affecting Maputo Bay, its mangroves, seagrasses, and marine macroinvertebrates

Pressure	Indicator	Trend
Climate change	Sea surface temperature	▲
	Sea level rise	▲
LULC	(Semi) natural cover	▼
	Agricultural cover	▲
	Urban cover	▲
Overexploitation	Mangrove deforestation	▲
	No. of licences for artisanal fishery	▲

continue, then both SST and SL are likely to rise; the agricultural and urban cover of Maputo Province are likely to increase to the detriment of the (semi)natural cover; and lastly, mangrove deforestation and artisanal fishing production are also going to rise.

3.2. Assessment of MMI ES

3.2.1. ES identification and classification

The identification and classification of MMI ES assessed in this study, both in mangrove forests and seagrass meadows, are summarised in Table 2.

3.2.2. ES quantification and trends

Provisioning ES. In 2017, more than 23 000 artisanal fishery boats were working in Mozambique, and more than 2000 of them operated in MB, mostly 7 d wk^{-1}, in shallow waters on sandbanks, representing 5% of all the country's artisanal fishery production (data retrieved from António et al. 2017). Overall, artisanal fishery production increased over time both nationally and in MB (Fig. 6A).

In Maputo province, MMIs had an important contribution to the artisanal fisheries (639 t), particularly shrimp captures (Fig. 6B). Considering shrimp semi-industrial fisheries, the main trawling areas in 2014 were located in 4 distinct zones: Area A, near Maputo, is the largest of the 4; Area B, where mostly *Fenneropenaeus indicus* was captured; Area C, which enters the POPMR; and Area D, which is the smallest area and located furthest from the shore (Fig. 6C).

Regulation and maintenance ES. The supply of all 5 ES classes analysed presented visible oscillations through time (Table 3). Considering the whole bay, the highest supply of 'Maintaining nursery populations and habitats' occurred in the 2010s; 'Decomposition and fixing processes and their effect on sediment quality', 'Hydrological cycle and water flow regulation', and 'Filtration/sequestration/storage/accumulation by micro-organisms, algae, plants, and animals' in the 1980s (but always with a low supply); and 'Regulation of the chemical condition of salt waters by living processes' in the 1960s. The MMI ES related to 'Maintaining nursery populations and habitats' attained the highest values, followed by 'Regulation of the chemical condition of salt waters by living processes'. Except for the decades of 1910 and 2000, when seagrass meadows had the highest ES supply, and for the 2010 decade, when the supply was very similar between both ecosystems, mangrove forests presented the highest values of MMI regulation and maintenance ES.

Cultural ES. SR has been rising over the last 10 yr in all MB mangroves and seagrasses. The highest SR was observed in the 1960s and 2010s, in mangroves and seagrasses, respectively (Fig. 7). A substantial decrease in SR was observed from the 1970s to the 2000s. Also worth noticing is the fact that SR reached higher values in mangrove forests than in seagrass meadows, although when in decline, both reached values around zero.

Overall, the number of licences for recreational and sport fishing increased over the last decade, illustrating the cultural importance that this activity can represent for promoting health, recuperation, or enjoyment through active or immersive interactions (Fig. 8).

Table 2. Identification and classification (Common International Classification of Ecosystem Services [CICES] and its Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services [IPBES] equivalence) of the ecosystem services (ES) provided by marine macroinvertebrates (MMIs) in mangroves and seagrasses of Maputo Bay

Section	CICES		IPBES	MMI ES
	Group	Class	Code	
Provisioning	Wild animals (terrestrial and aquatic) for nutrition, materials, or energy	Wild animals used for nutritional purposes	12	Edible MMIs (shrimps, prawns, crabs, lobsters, cephalopods) through artisanal and semi-industrial fisheries
Regulation and maintenance	Lifecycle maintenance, habitat, and gene pool protection	Maintaining nursery populations and habitats (including gene pool protection)	1	Food web stability Habitat modification Nutrient cycle
	Regulation of sediment quality	Decomposition and fixing processes and their effect on sediment quality	8	Sediment quality
	Regulation of baseline flows and extreme events	Hydrological cycle and water flow regulation	6	Hydrological flux
	Water conditions	Regulation of the chemical condition of salt waters by living processes	7	Water quality
	Mediation of wastes or toxic substances of anthropogenic origin by living processes	Filtration/sequestration/storage/accumulation by micro-organisms, algae, plants, and animals	3	Waste filtration
Cultural	Intellectual and representative interactions with natural environment	Characteristics of living systems that enable scientific investigation or the creation of traditional ecological knowledge	15	Scientific or traditional knowledge about MMI diversity in the environment (nature)
		Characteristics of living systems that enable education and training	15	Skills or communication about MMI diversity in the environment (nature)
	Physical and experiential interactions with natural environment	Characteristics of living systems that enable activities promoting health, recuperation, or enjoyment through active or immersive interactions	16	Recreational and sport fishing

Table 4 presents the trends of provisioning; regulation and maintenance; and cultural ES provided by MMIs in MB, based on the indicators applied here considering the last 2 decades, i.e. 2010–2019 in relation to 2000–2009. In terms of provisioning, all ES identified were related to food security and the fact that MMIs could be used for nutritional purposes. In general, MMI production seems to be increasing. However, upon closer examination, shrimp production, the main target species of both fisheries (artisanal, but mainly semi-industrial), is decreasing. MMI regulation and maintenance ES, related to 'Maintaining nursery populations and habitats' and 'Regulation of the chemical condition of salt waters by living processes' seem to be increasing, whereas the trends of the other services are decreasing. With regards to MMI cultural ES, the increasing SR contributes to the opportunity for scientific investigation or the creation of traditional ecological knowledge; at the same time, MMIs may also represent an increasing target for recreation and sport fishing.

3.3. ESCM

The exploratory ESCM applied to MMIs from MB, taking into consideration all of the factors analysed during this study, is presented in Fig. 9. This model links the pressures analysed (where habitat loss summarises the consequences of LULC changes and deforestation) as well as invasive species and pollution (which were not evaluated here due to the lack of data but are also important pressures to consider in management options), condition features of both

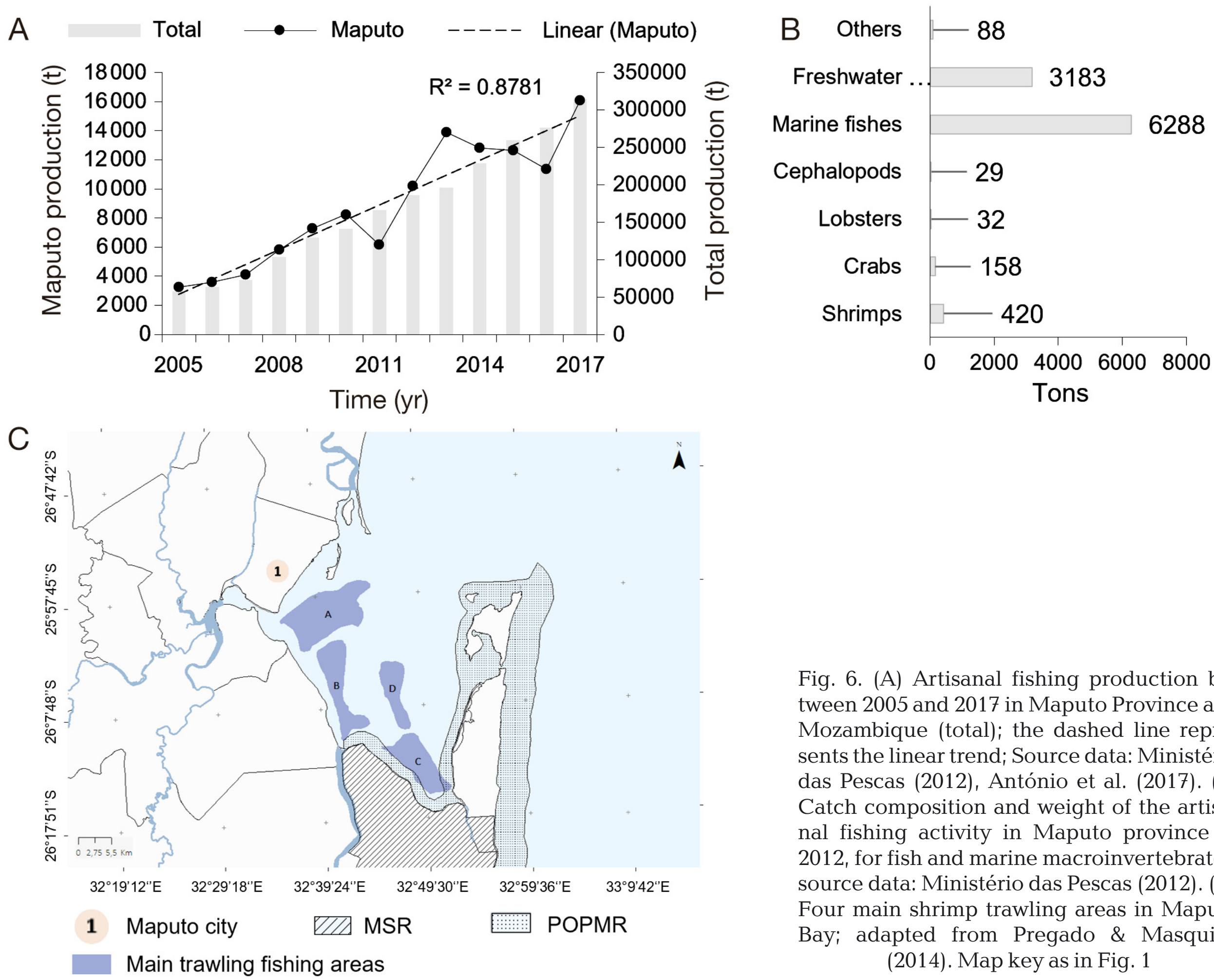

Fig. 6. (A) Artisanal fishing production between 2005 and 2017 in Maputo Province and Mozambique (total); the dashed line represents the linear trend; Source data: Ministério das Pescas (2012), António et al. (2017). (B) Catch composition and weight of the artisanal fishing activity in Maputo province in 2012, for fish and marine macroinvertebrates; source data: Ministério das Pescas (2012). (C) Four main shrimp trawling areas in Maputo Bay; adapted from Pregado & Masquine (2014). Map key as in Fig. 1

mangrove forests and seagrass meadows, the assessed MMI ES, and critical management goals in MB. Invasive species, climate change, habitat loss, overfishing, and pollution affect biodiversity and the state of MMI stocks. The MMI ES supply mainly depends on the maintenance of biodiversity and water quality through their sustainable use and management. These goals are also reinforced by MPAs that will function as fishing deterrents and provide high-quality nursery areas. Managing MB for the sustainable supply of MMI ES and good ecological status will ensure food security, biodiversity protection, and increased sustainable recreational and educational opportunities.

4. DISCUSSION

4.1. Ecosystem condition and pressures

The ratio between the area of POPMR and the total marine area in Maputo province was low when compared to the standard value proposed by Aichi Target 11 (10%), which reflects the struggle of most developing countries to meet this goal (Failler et al. 2019). The poor coverage of MPAs in low- and medium-income countries, such as Mozambique, reflects the context in which conservation is implemented: institutions are too weak to meet their international commitments while economic development is the main public policy concern. In addition, the lack of funding and the political instability add to the difficulties of implementing measures to protect the environment (Failler et al. 2019). Overall, regarding the assessment of the MB ecosystem condition, it is safe to say that the application of only one indicator is insufficient. However, there were no data that could be fitted into deep and detailed assays, such as physical, chemical, and biological analyses, to achieve a holistic evaluation of both mangrove and seagrass condition in MB through the application of different indicators. While attempting to understand the real condition of the MB marine ecosystems, many aspects can be rea-

Table 3. Quantification of marine macroinvertebrate (MMI) regulation and maintenance ecosystem services (ES) over time (by decades) in Maputo Bay (MB, entire bay), mangroves (MG), and seagrasses (SG). Green entries represent ES potential increases; red entries represent ES potential decreases; white entries represent no variation in ES

MMI ES	Maintaining nursery population and habitats			Decomposition and fixing processes and their effect on sediments			Hydrological cycle and water flow regulation			Regulation of the chemical condition of salt water by living processes			Filtration/sequestration/storage/accumulation by microorganisms, algae, plants, and animals		
Time (decades)	MB	MG	SG	MB	MG	SG	MB	MG	SG	MB	MG	SG	MB	MG	SG
1870–79	0.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.00	0.00	0.00	0.00	0.00
1880–89	0.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.00	0.00	0.00	0.00	0.00
1890–99	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1900–09	1.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.00	0.00	0.00	0.00	0.00
1910–19	4.09	0.00	4.09	0.14	0.00	0.14	0.14	0.00	0.14	1.48	0.00	1.48	0.14	0.00	0.14
1920–29	0.67	0.00	0.67	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.00	0.33	0.00	0.00	0.00
1930–39	7.33	1.33	4.00	0.00	0.00	0.00	0.00	0.00	0.00	0.67	0.67	0.00	0.00	0.00	0.00
1940–49	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1950–59	42.85	34.66	3.00	0.29	0.00	0.00	0.29	0.00	0.00	2.28	1.33	0.00	0.29	0.00	0.00
1960–69	85.71	64.72	7.67	0.14	0.14	0.00	0.14	0.14	0.00	24.79	21.79	0.33	0.14	0.14	0.00
1970–79	76.31	34.99	14.67	0.00	0.00	0.00	0.00	0.00	0.00	9.66	5.99	0.33	0.00	0.00	0.00
1980–89	20.00	17.00	3.00	1.00	1.00	0.00	1.00	1.00	0.00	1.00	1.00	0.00	1.00	1.00	0.00
1990–99	13.66	9.33	3.00	0.00	0.00	0.00	0.00	0.00	0.00	1.33	0.67	0.00	0.00	0.00	0.00
2000–09	38.23	4.00	34.23	0.86	0.00	0.86	0.86	0.00	0.86	8.18	1.00	7.19	0.86	0.00	0.86
2010–19	129.65	49.99	49.33	0.00	0.00	0.00	0.00	0.00	0.00	8.33	4.00	3.66	0.00	0.00	0.00

soned. Yet what is truly key for tackling this type of approach is the existence of reliable data and standard points of reference. In essence, a well-established monitoring programme is needed to acquire new data and to establish an adequate classification system that can be used as a reference state. This information is key to objectively determine the quality of the ecosystems under study and to develop and apply appropriate indicators.

Overall, SL and SST showed an increase through time. Schumann et al. (1995) and Rouault et al. (2009) described the phenomenon of rising SST surrounding southeast Africa. The rising SL is supported by Mahongo (2009), who found that it has been rising at a rate of 0.73 mm yr^{-1}, also consistent with recent global SL rise trends (IPCC 2022). There is a growing concern about the effects of climate change on developing countries because they are the most vulnerable to the rising frequency and severity of extreme weather events and climate variability (Mirza 2003). At the beginning of the 21st century, there was an intensification in sedimentation levels, which led to the degradation of seagrass meadows in Mozambique, highlighting the connection between seagrass dieback and climate change (Christie & Hanlon 2001). During that time, coastal erosion also occurred at some points of MB. A distressing example is Xefina Grande Island, where coastal erosion is often reported, and which was bisected in the year 2000 as a direct consequence of floods (Bandeira & Gell 2003). Portuguese Island also lost a large area over time, which affects the tidal recharge of the mangrove and causes its dieback (Hatton & Couto 1992). Climate change is a driver with potential for more complex analysis, and although only SL and SST were assessed, other phenomena, such as ocean acidity and hypoxia, would have been interesting to consider if data were available. SST was the only indicator with a good amount of accessible data. The SL records were relatively poor, and side effects such as coastal erosion in MB are still not comprehensively studied. Monitoring SST, SL, rainfall, climatic variability, and extreme events are needed to develop local models. Robust models based on solid data will allow forecasting and further understanding the consequences of climate change at MB, and thus its ES. This knowledge will contribute to informed options for climate adaptation and to implement mitigation measures to face detrimental impacts (Paula & Ban-

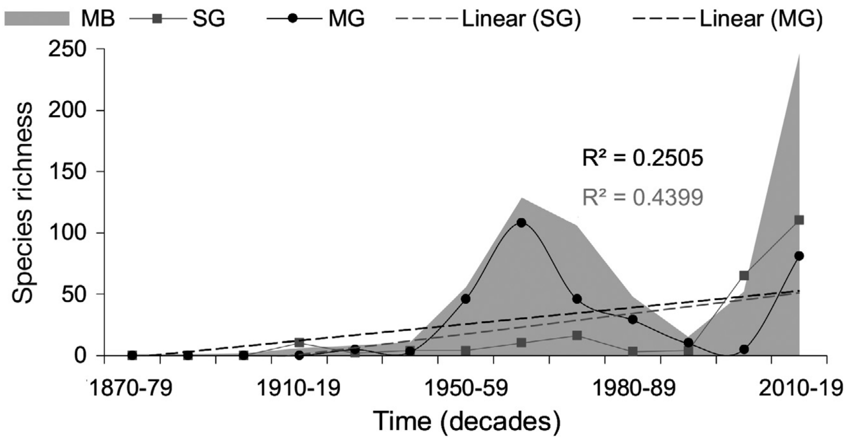

Fig. 7. Species richness over time (in decades) in Maputo Bay (MB, entire bay), mangroves (MG) and seagrasses (SG). Dashed lines represent linear trends

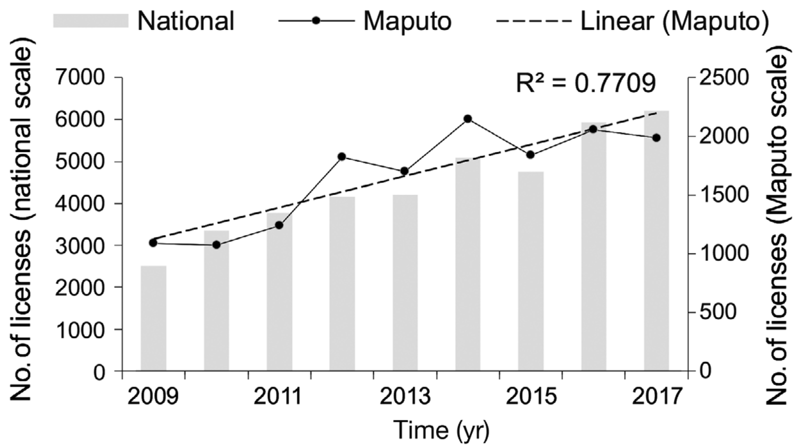

Fig. 8. Number of licences attributed to recreational and sport fishery over time at the national scale and for Maputo Bay (dashed line represents the linear trend). Source data: Ministério das Pescas (2012), António et al. (2017)

deira 2014) and to promote a sustainable use of ES provided by the MB marine ecosystems.

LULC variations were key for understanding the growing urbanization and agricultural intensification, sometimes occurring to the detriment of mangrove cover. This is a concerning situation, making soil reclamation a big threat to the study area, with rising urbanization. A disturbing example of urban and peri-urban extension is Costa do Sol, where reclamation for housing is aggressive; in Matola City, this problem was also aggravated by land conversion to saltpans and shrimp aquaculture farms, although the latter are now abandoned (Brouwer & Falcão 2004). LULC changes are directly linked to urban expansion and agriculture intensification due to overpopulation and are possibly very complex to avoid. Negative LULC changes may perhaps be contained through better administrative and spatial management, where the integrity of coastal ecosystems must be prioritized. Finally, as the assessment of this driver was mainly carried out through mapping tools, it would benefit from imagery with better resolution and a greater timespan. Mangrove deforestation, besides being directly connected to urban development, can also be related to the exploitation of wood. According to Brouwer & Falcão (2004), deforestation in MB is strongly linked to the use of fuelwood, which, along with charcoal, is a prime source of domestic fuel for peri-urban populations. Furthermore, wood is widely collected both for domestic consumption and commercial purposes, being a useful material not only for boat and house construction but also for the production of various household utensils. Macamo et al. (2015) reported the Incomati estuary as probably one of the most impacted mangrove forests of the bay, resulting from pollution and freshwater abstraction, as well as deforestation. Peri-urban mangroves are particularly vulnerable to degradation, as the population density is high and local communities still have a high level of dependency on coastal natural resources (Macamo et al. 2015). There are clear knowledge gaps on deforestation, as the data did not include the mangrove forests of the Espírito Santo estuary, and according to Paula & Bandeira (2014), the forests in the south and south-east of the bay are poorly known in comparison to those in north and north-west. Future steps need to encompass a more thorough assessment of mangrove forests in south MB and Machangulo Peninsula, as well as more detailed shape or raster files of the study area with mangrove ecosystems well discriminated. Operations to strengthen conservation and strategic reforestation of mangroves in the bay would also be beneficial.

Another form of overexploitation found in MB was overfishing. On a national scale, fisheries are an important source of income and the main source of protein for the population (Macia 2004). The same can be stated for MB, as it is the second-largest fishing zone

Table 4. Trends (up- or downward arrowheads) of provision; regulation and maintenance; and cultural ecosystem services (ES) provided by marine macroinvertebrates (MMIs) in Maputo Bay, considering the last 2 decades (i.e. 2010–2019 in relation to 2000–2009)

ES section	CICES	Indicator	Trend
Provision	Wild animals used for nutritional purposes	Artisanal fishery (MMI) production	▲
		Semi-industrial fishery (shrimp) production	▼
Regulation and maintenance	Maintaining nursery populations and habitats (Including gene pool protection)	Score calculated through MMI functional traits and SR	▲
	Decomposition and fixing processes and their effect on substrate quality	Score calculated through MMI functional traits and SR	▼
	Hydrological cycle and water flow regulation	Score calculated through MMI functional traits and SR	▼
	Regulation of the chemical condition of salt water by living processes	Score calculated through MMI functional traits and SR	▲
	Filtration/sequestration/storage/accumulation by micro-organisms, algae, plants, and animals	Score calculated through MMI functional traits and SR	▼
Cultural	Characteristics of living systems that enable scientific investigation or the creation of traditional ecological knowledge	MMI SR	▲
	Characteristics of living systems that enable education and training	MMI SR	▲
	Characteristics of living systems that enable activities promoting health, recuperation, or enjoyment through active or immersive interactions	Number of licences for recreation and sport fishing	▲

in the country. While consistent data on annual maximum sustainable yields were not available, it is generally recognized that fishing stocks are overexploited and need better management to achieve sustainability (de Freitas & Araujo 1974, Ulltang 1980, Sousa & Gjøsaeter 1987, Macia 1990, Dengo & Govender 1998, Chaúca et al. 2007).

The number of artisanal fishing licences has also increased over time, indicating an increase in fisheries exploitation over the years. Further, information regarding bycatch (Machava et al. 2014) linked to shrimp fisheries (both artisanal and semi-industrial) indicates that semi-industrial fisheries represent a significant pressure. The bycatch of shrimp species consists of a high diversity of organisms that are often discarded (Carvalho et al. 2020). Both artisanal and semi-industrial fishing result in approximately 3 and 4 kg of bycatch (respectively) for each kilogram of shrimp produced. Bycatch is often discarded. In MB, while 2.5 kg of bycatch produced by artisanal fishery are consumed, only 1.6 kg are utilized in the semi-industrial fishery (Machava et al. 2014). The mechanized fishing gears used in semi-industrial fishing (bottom trawls and more recently bottom gill nets) have low selectivity, resulting in increased bycatch (Komoroske & Lewison 2015). Additionally, this gear has a significant impact on the seabed (Freese et al. 1999), leading to the degradation of ecosystems such as seagrass meadows. In semi-industrial fisheries, bycatch has no commercial value, or the individuals are not of marketable size (Komoroske & Lewison 2015, Carvalho et al. 2020). Apart from endangering the populations and biodiversity of the bay, the generated bycatch also represents an important protein source that could contribute to food security (Silva & Masquine 2014). Hence, it can be argued that artisanal fishermen make better use of the species they catch by consuming them and discarding only a small portion of the bycatch (Machava et al. 2014). In addition, China has been investing in a variety of economic sectors and infrastructures of Mozambique, in exchange for fishing licences, leading to the continuous arrival of Chinese fleets to the country (some for deep-sea fishing of shrimp). Local fishermen have already voiced their concern about the well-being of ecosystems and the preservation of their livelihoods, as they face uncertainty due to the excessive exploration brought by the Chinese fleets (Mosse 2018, Baker 2019). Given the economical and food security relevance of MMIs

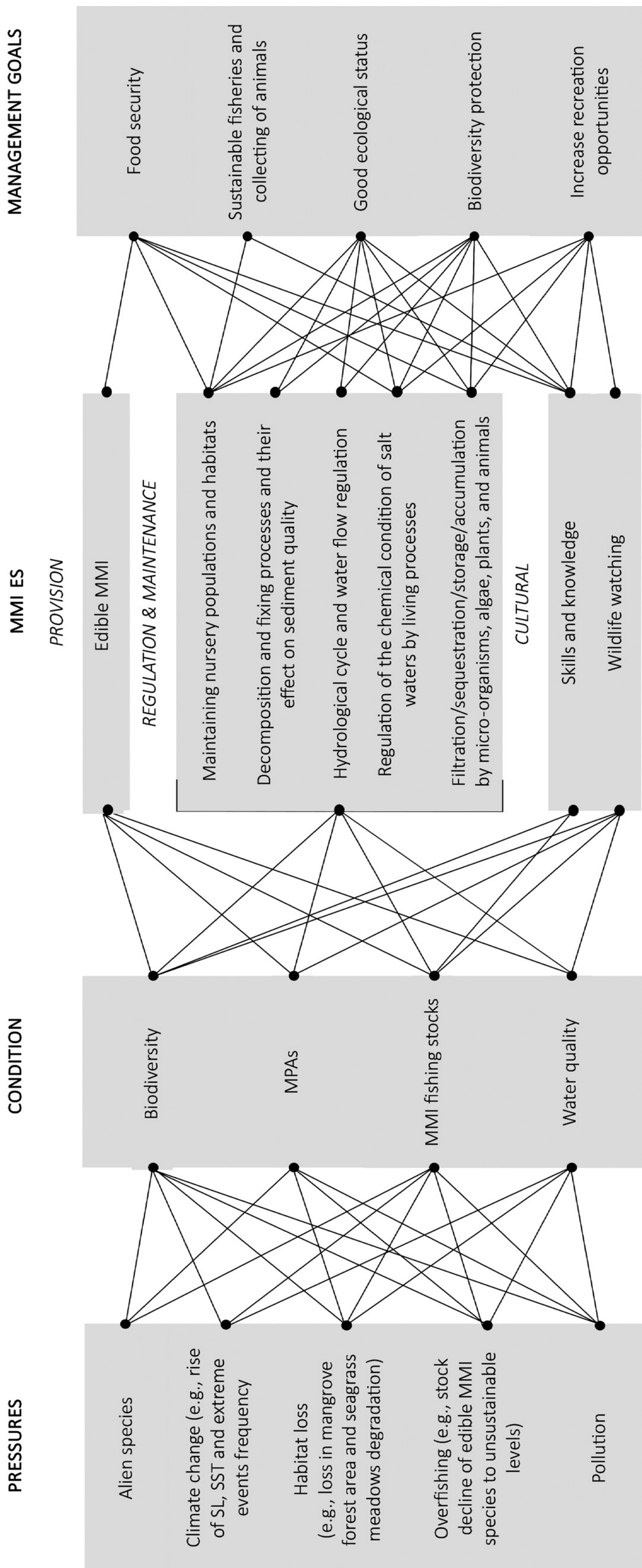

Fig. 9. Exploratory conceptual model developed to address the sustainable use of marine macroinvertebrate (MMI) ecosystem services (ES) in Maputo Bay. The model links pressures, key ecosystem condition features, specific MMI ES, and the proposed management goals to ensure a healthy supply of MMI ES. MPA: marine protected area; SL: sea level; SST: sea surface temperature

in MB, overfishing and the unknown state of their stocks is very concerning. Thus, monitoring MMI stocks, aiming to obtain long data series and reliable bio-ecological data related to industrial, semi-industrial, and artisanal fisheries is of particular importance. This will support the proper management of stocks, which should be reinforced through up-to-date legislation (Paula & Bandeira 2014). Simultaneously, monitoring excessive bycatch and exploring potentially new technologies pave the way to reduce fishing pressure (Paula & Bandeira 2014) and achieve sustainable fisheries.

There are other pressures on MB for which no data could be obtained. One example is the introduction of alien species, namely marine invertebrates. The penaeid shrimp *Metapenaeus dobsoni*, detected in 2007 (Simbine et al. 2018), was the only recorded marine invertebrate invasive species found in MB during our literature search. Another example of deficient information is the pressure related to the sources of pollution affecting MB. According to Scarlet & Bandeira (2014), there are 2 major sources of pollution in MB, namely land-based and port-based, but we were not able to obtain further data. Both types of pollution have the potential to interfere with the good ecological status of the MB marine ecosystems, endangering biodiversity and MMI populations, ultimately putting MMI ES and even food security at risk. Furthermore, pollution from e.g. agriculture and other sources such as industrial or urban wastewater discharges, affects water quality and generates solid waste (mainly plastic), ultimately impacting recreational opportunities.

4.2. Assessment of MMI ES

MB represents 5% of MMI artisanal fisheries at a national level, with more than half consisting of shrimp species.

The semi-industrial fishery is also an important sector of MB's economy that relies mostly on shrimp capture by trawling. Shrimp species, namely *Fenneropenaeus indicus* (white shrimp) and *Metapenaeus monoceros* (brown shrimp) are a very important source of protein and income (FAO 2022) in the bay. Contrasting with the artisanal fisheries, semi-industrial production of shrimp has been declining (de Freitas & Araujo 1974, Ulltang 1980, Sousa & Gjøsaeter 1987, Macia 1990, Dengo & Govender 1998, Chaúca et al. 2007). Despite this, the demand for shrimp is increasing (de Freitas & Araujo 1974, Ulltang 1980, Sousa & Gjøsaeter 1987, Macia 1990, Dengo & Govender 1998, Chaúca et al. 2007), leading to the expansion of fishing areas into protected areas (POPMR near Machangulo Peninsula).

The study of MMI regulation and maintenance ES was limited by the availability of information and scattered data, resulting in knowledge gaps related to species representation and abundance in our data set. For example, the high number of MMI records in the 1960s or the 2010s probably corresponded to more intensive fieldwork. Further steps need to be taken to correctly assess MMIs, including the implementation of a well thought out methodology for monitoring MMI biodiversity. The obtained information can be integrated into the MB data set to provide new knowledge. Nevertheless, this study made the best use of the currently available data, contributing to baseline information that can be further applied in research on MMI regulation and maintenance ES. Overall, MMIs play an important role in the regulation and maintenance of the surrounding environment, fostering the preservation of nursery populations, sediment and water quality, and water flow regulation, and thereby enhancing the ecological status of mangroves and seagrasses.

Regarding cultural ES, the conservation and understanding of MMI biodiversity offer excellent opportunities and prospects for scientific research and the integration of traditional ecological knowledge. In fact, there is an urgent need for new data and information in this field. Moreover, MMIs have the potential to become an increasingly popular target for recreation and sport fishing, evidenced by the rising number of licences issued, which indicates a growing demand for this particular ES.

4.3. ESCM

The ESCM represents a simplified instrument for describing the nodes linking the effects of alien species, climate change, habitat loss due to LULC changes, deforestation and overfishing, and pollution on mangrove and seagrass condition, and how all of these pressures negatively influence biodiversity, MMI fishing stocks, water quality, and possibly the effectiveness of MPAs. Monitoring the ecological condition of MB is of paramount importance, and this can be achieved through the selection and application of a comprehensive set of core indicators. The condition and pressures affecting MB, specifically mangroves and seagrasses, have a direct impact on the supply of MMI ES. Consequently, taking them into account is key for achieving efficient management goals related to food security, sustainable MMI fisheries, good ecological status, biodiversity conservation, and sustainable recreational and educational opportunities. Understanding such nodes is therefore vital for delineating more effective conservation, management, and mitigation practices. This exploratory ESCM has the potential to help the transition of ES considerations from a conceptual approach to actionable plans for natural resource management.

The ESCM developed here serves as a practical tool for designing a plan to accomplish established management goals. It provides a good starting point for future projects that can be applied in similar areas to MB. However, to develop more in-depth models, additional steps must be taken to generate new knowledge on key ES through a transdisciplinary approach involving scientists, decision-makers, local communities, and other stakeholders using participatory techniques.

4.4. MMIs and food security

According to Raimundo (2016), Maputo local communities interpret food security as depending on access to fisheries, rice, and maize, a perspective that includes both agricultural and fishing assets. They use fish as an important source of protein, which in fact accounts for a large portion of the fishing production. However, MMIs also play a crucial role in the food security of local communities. The decline in shrimp production, coupled with increasing demand, will be aggravated by a still-growing population. In addition to shrimp fisheries, other MMIs are also exploited, mainly bivalves, sea urchins, gastropods, and crabs. These MMIs support the livelihoods and food security of many households, creating a strong dependency of coastal communities on these resources (de la Torre-Castro & Rönnbäck 2004). For example, the mud crab *Scylla serrata*, locally known as 'Hala', is harvested as a traditional artisanal activity having a high demand as a delicacy by both tourists and local consumers (Macia et al. 2014). The sea urchin *Tripneustes gratilla* is a food item with cultural and ecological importance on Inhaca Island (Fernando & Bandeira 2014). Near Maputo city (urban setting), bivalves and gastropods are primarily collected for sale in markets and restaurants. On Inhaca Island (rural setting), bivalves and sea urchins are predominantly collected for domestic consumption, underscoring the importance of seagrass meadows for the food security of local populations (Fernando & Bandeira 2014).

Rönnbäck et al. (2002), Macia et al. (2014), and de Abreu et al. (2017) provided information about important edible MMIs of MB, and the relevance of mangroves and seagrass meadows to their preservation. For instance, in Saco and Sangala Bays (Inhaca Island), these studies have shown that MMI juveniles shift between mangrove forests and seagrass meadows in response to tidal cycles. They seek protection against predators in mangrove forests during high tide and feed in seagrass meadows during low tide (de Abreu et al. 2017). The crab *S. serrata*, for example, recruits in mangrove forests where it resides during the juvenile phase (Macia et al. 2014).

To ensure food security linked to MMIs in mangroves and seagrasses requires the development of a rigorous management plan addressing ecosystem condition and pressures to promote healthy ecosystems and the sustainable supply of MMI ES.

4.5. Future perspectives and the way forward

All of the pressures assessed during this study are increasing, which can lead to the degradation or disappearance of the mangroves and seagrasses in MB and their MMI condition if no measures are taken. This will ultimately affect the MMI ES supply. Focusing on MMIs provisioning ES, while the artisanal fishery production is increasing, the semi-industrial fishery of shrimp is decreasing. This may represent a positive development regarding food security, as artisanal fisheries tend to support the sustainable use of marine resources. However, the lack of information about MMI stocks, aggravated by limited outdated data, which mostly refer to shrimp populations, fails to provide an accurate representation of the present-day situation. The exploitation of MMI stocks at an unsustainable level may be underway, highlighting the urgent need for improved monitoring of both MMI populations and fishing practices. MMIs play an important role in the supply of regulation and maintenance ES, such as sustaining nursery populations and habitats (including gene pool protection), decomposition and fixing processes and their effect on substrate quality, hydrological cycles and water flow regulation, and the regulation of the chemical condition of salt waters by living processes. Nevertheless, future scenarios of MMI contribution to these ES remain unclear due to insufficient data, which hinders accurate quantifications. Cultural ES also face a similar level of uncertainty. Therefore, ensuring sustainable fisheries and the conservation of MMI diversity requires a holistic approach encompassing the implementation of monitoring plans to gather reliable and continuous data on pressures, ecosystems condition, and MMI ES. These, together with the establishment of more MPAs and effective protection measures, will help to guarantee the health of mangroves and seagrasses and their MMIs in the long run, thus safeguarding MMI ES and local communities.

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