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Quantification of climate change implications for water-based management: A case study of oyster suitability sites occurrence model along the Kenya coast

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ABSTRACT

To ensure long-term sustainability of the littoral marine ecosystem for water-based management and aquaculture potential, it is necessary to quantify and project the effect of sea warming on the resident biota. This study evaluated the potential of an oyster Suitability Sites Occurrence Model (SSOM) to predict the status of littoral areas in the future due to sea warming. Data sources comprised Moderate Resolution Imaging Spectroradiometer (MODIS) and Landsat 7 ETM+. The suitable sites were ranked on a scale of 1 (least suitable) to 5 (most suitable). In the suitability model, score 5 had the highest proportion (35.8%) of oyster suitability which shrank to 16.2% with a 4 °C increase in sea temperature. Future increases in sea temperature are likely to cause shrinkage in the spatial extent of most suitable and suitable oyster sites. Thus changes in marine oyster suitability in littoral zones are predicted to worsen gradually as sea temperatures increase in the future. Differences in the recorded sea temperature of ≤6 °C within and between sites may influence spatial variations in oyster habitat due to future sea warming. Such concepts could form an alternative scientific basis for quantification of potential global climate change effects on biodiversity for marine systems policy adaptation analysis, aquaculture potential, and management.

1. Introduction

Elevated demands for freshwater, population growth, and increased industrial discharge, have great implications on coastal ecosystems and estuaries, and therefore associated policy formulation and management (Alber, 2002; Flemer and Champ, 2006). Coastal littoral zones bear the brunt of such synergistic effects of multiple anthropogenic activities due to their proximity to land. Therefore, there is an increasing awareness that water resource management is needed to mitigate human impacts on such sensitive ecosystems. One such environmental threat is climate change (Johanna and Welch, 2016). Water resource ecosystems are likely to be manifested directly in changes to fisheries stock structure, phenology, distribution, and indirectly through habitat changes, and suspended sediments in the water column, potentially influencing the accessibility of target species, reducing fisheries sustainability and food security (Kjelland et al., 2015; Johanna and Welch, 2016). For example, studies have shown that globally, marine systems are likely to be sensitive to climate change (Lassalle and Rochard, 2009). According to Cheung et al. (2010), the occurrence of sessile marine fisheries, especially oysters (Family Ostreidae), are vulnerable to temperature change.

Oysters are considered a major fishery, with their abundance at an all-time low, estimated at 15% of historic levels worldwide. The resource is considered to be near functional extinction (Beck et al., 2011). Their recovery has been hindered by interaction of factors such as eutrophication, disease and habitat loss, exacerbated by climate change effects. Current production is heavily dependent on aquaculture (Jackson, 2008). In the near future, wild oyster restoration may emerge as a major focus to maximize environmental benefits, or to maximize the yield from the fishery. For progress to be met, different issues on ecological perspectives and climate changes have to be addressed. Important ecological perspectives may include variables considered for oyster growth, survival, quality and quantity. Changes in parameters for optimal growth of oysters, including sea temperature, depth, Chlorophyll-*a* and suspended sediment concentration (SSC), may affect their distribution if altered (Leffler and Greer, 1991; Tack et al., 1992; FAO, 1997; Kjelland et al., 2015).

The challenge is to provide policy-makers with reliable information for oyster resource management and aquaculture potential, based on

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integrated data and tools derived from both earth observations and scientific models (Lehmann et al., 2014). This is because other than for biodiversity conservation in itself, bivalves (among them oysters) have been recognised as sources of animal protein with high nutritional value. Collected from oceanic habitats or aquaculture platforms, bivalves are widely exploited at subsistence and commercial levels (Radiarta et al., 2011). However, in most developing countries such as Kenya, historical yields and management tools of oysters are poorly known, but isolated and invalidated records do exist (Ruesink et al., 2005; Kimani et al., 2008). Nevertheless, trials on oysters culture were set up in Gazi, Kenya under a Kenya-Belgium project in 1986 (Kofi, 1986), and provide some historic information.

Several authors have developed tools and models to assess the impacts of climate change on water resources (e.g., Wakelin et al., 2015; Aura et al., 2016; Johanna and Welch, 2016). Due to the vast extent of oceanic waters, there is growing importance of satellite data for marine climatology (Winterfeldt et al., 2011). Analyses of climate variability using satellites is useful in quantifying and predicting climate signals that may have an effect on habitat suitability of biota (Schmelzer and Holfort, 2011; Walczowski and Piechura, 2011; Wolter and Timlin, 2011; Yamaguchi and Kawamura, 2005). Adequate water-based management tools that could quantify possible climate change implications, delineate suitable sites for biota, and give future projections of climate changes based on satellite data are lacking, but are critical to mitigate such impacts. This is because to ensure adaptation to changing climate, future monitoring and research must be closely linked to responsive, flexible and reflexive marine management systems (Brander, 2010).

Oysters provide an excellent indicator of freshwater inflow, tidal pattern and salinity distributions in many estuaries as well as littoral areas (Petes et al., 2012; Soniat et al., 2013). They offer good candidates for research in estuaries and littoral areas for water-based management through water quality improvements (Kellogg et al., 2013), storm surge protection (Piazza et al., 2005) and landscape diversity (Eggleston, 1999). Oysters have been used, for example, as indicators in Gulf of Mexico estuaries and littoral zones with historically productive oyster fisheries (Buzan et al., 2009; Pollack et al., 2011). In the Western Indian Ocean region (WIO), from the Seychelles, Aldabra, Tanzania, Somalia and Kenya, *Crassostrea* spp. (*Crassostrea cucullata*, Born; *Crassostrea*

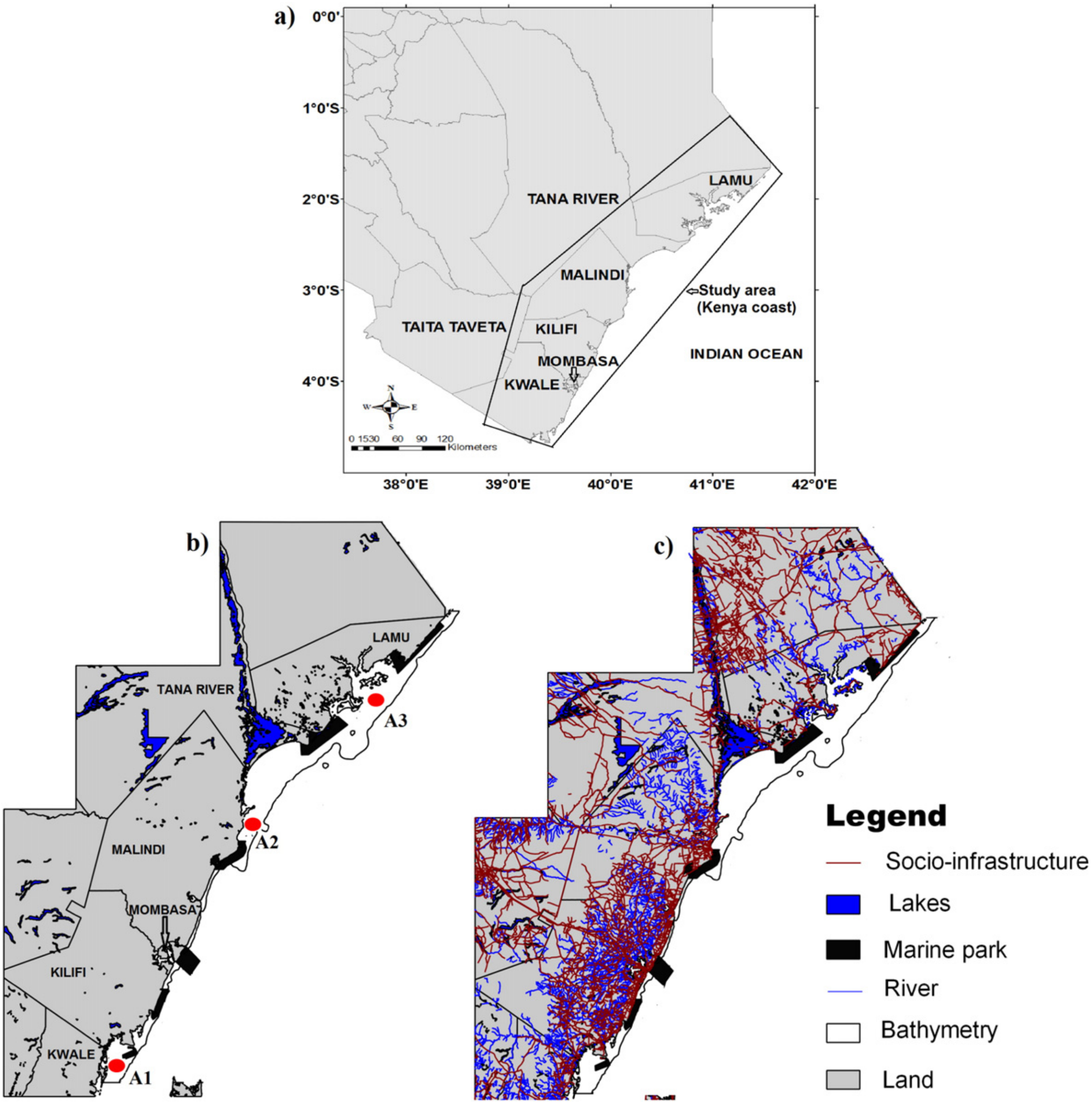

Fig. 1. Study area of potential littoral oyster areal extent along the Kenya coast indicating a) Kenyan coastline on the Kenya map, b) county/district boundaries along the Kenyan coastline with red markings (A1, A2, A3) where mean MODIS values for Chl-*a*, SST and SSC were obtained, and c) socio-infrastructure, marine parks, lakes and rivers distribution along the Kenyan coastline. The bathymetry threshold used in this study was up to spring high water mark level of about 3.5 m.

forskali, Gmelin; *Crassostrea pulmura*, Carpenter) are abundant in the upper eulittoral zone (Okemwa et al., 1986; Tack et al., 1992). In some cases the upper distribution limit is known to be slightly (0.3–0.5 m) above the mean high water spring tide level, and probably changing with wave action (Chelazzi and Vannini, 1980).

Changes in sea surface temperature (SST) is widely considered as a significant consequence of climate change (IPCC, 2014). Evidence shows that increasing temperatures has contributed to sea-level rise (SLR) in recent decades (IPCC, 2007). Estimates of future SST vary for different regions, but global SST for the next century is expected to increase at a greater rate than during the past 50 years (IPCC, 2014). Local, regional, and global factors will influence future relative SST and SLR for specific coastlines around the world. Assuming that these SST trends continue, the IPCC has projected future changes in surface temperature until the middle of the 22nd century (2000–2150), and that these changes will range from 1.0 °C (the best estimate for low scenario-RCP2.6) to 4.0 °C (the best estimate for high scenario-RCP8.5) in the world oceans (IPCC, 2014).

Sea temperature has been regarded as the most important parameter for growth and survival of oysters relative to other factors (FAO, 1997; Chelazzi and Vannini, 1980). Furthermore, changes in water temperature will affect the timing and levels of productivity across coastal and marine systems (Olonscheck et al., 2013). Sea temperature at the Kenya coast have been reported to range between 25 and 32 °C with a thermal stress threshold which occurs at 29.3 °C (Obura, 2001; Grimsditch et al., 2010). There have been reports of sea surface temperature (SST) anomalies that rose to 1–2 °C above seasonal maxima, and caused 50–90% coral mortality in the studied areas of Kenya in March–April 1997/1998 (Wilkinson et al., 1999; Goreau et al., 2000; Obura, 2001) in March–April 1997/1998. Such sea warming may pose potential negative impacts on habitat suitability for oyster occurrence. Quantifying and projecting the effects of climate change on oyster habitat suitability could contribute greatly towards understanding how climate change influences areal extent of biota and water resources such as those in the littoral zones. Globally, aquaculture suitability models have been used to demonstrate the impact of climate change on aquaculture activities (Aura et al., 2016; Liu et al., 2014; Saitoh et al., 2011). Yet limited information is available on suitable sites for uncultured species, and ecosystem modelling in relation to climate change and habitat suitability. The aim of this study was to quantify and project the effects of sea warming on the spatial distribution of oysters in the littoral zones of the Kenya coast.

2. Materials and methods

2.1. Study area

The littoral oysters *Crassostrea* spp. of the WIO region are found on the trunks, stilt roots and pneumatophores of mangrove plants and rocky substrata in the wave-affected brackish-marine environments of the Kenyan coast (Okemwa et al., 1986). The ecological studies of this species indicate that it is abundantly found in the upper eulittoral zone following the shore terminology of Hartnoll (1976). The tides on which the oysters depend for their filter feeding (Morton, 1977; Tack et al., 1992) exhibit a large range in this portion of the WIO region and are semi-diurnal. The study selected the littoral areas (up to spring high water mark level of about 3.5 m) of the Kenya coast (−2–−4°S, 39.4–41.5°E) which is approximately 600 km long, along the littoral areas of the Indian Ocean as potentially suitable sites for the occurrence of littoral oyster (Fig. 1). Various studies on the vertical distribution of mollusks (such as oysters) on the Kenya coast have demonstrated that they may be size-related both interspecifically and intraspecifically (Ruwa and Brakel, 1981). However, scanty published information on the ecological characteristics, habitats and distribution exist for the Kenya coast, prompting the need for the current study. Existing literature mainly focuses on current regimes and tidal measurements. The Kenya coast is under the influence of the dominant offshore current regimes. During the South East Monsoon (SEM), which occurs between April and October, the current circulation is dominated by the northward flow of the East African Coastal Current (EACC). In this season, the ocean also receives the heaviest inflow of river discharge from the rivers Tana and Sabaki. During the North East Monsoon (NEM), between November and March, the northward flowing EACC meets the southward flowing Somali Current (SC) to form the Equatorial Counter

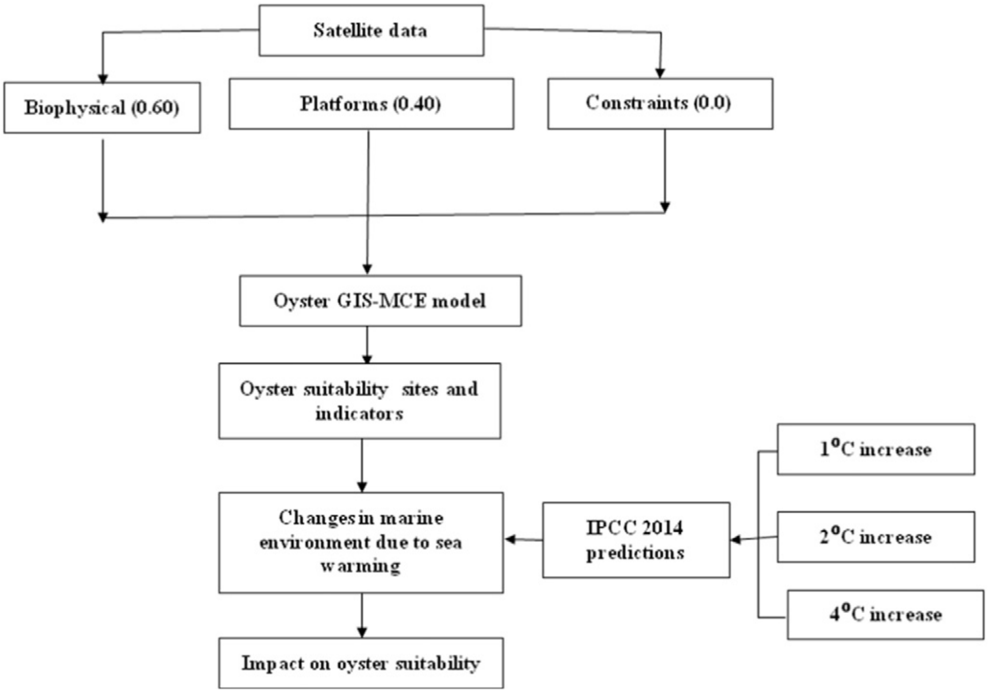

Fig. 2. Schematic diagram for the development of littoral oyster Suitable Sites Occurrence Model (SSOM) for coastal Kenya. Weights for biophysical (0.60) and platform (0.40) sub-models were assigned using the Analytical Hierarchical Process (AHP).

Table 1
Sources of data used in the study. The sourcing was based on existing literature for essential parameters for littoral oyster growth, survival and occurrence. Analytical Hierarchical Process (AHP) weights developed for individual parameters are shown in parentheses. MODIS data were for the years 2011–2014.

Sub-model	Indicator (AHP weights)	Source of data (resolution)
Biophysical	Chlorophyll-*a* (0.40)	MODIS*/Aqua (1 km)
	Sea surface temperature (0.30)	MODIS*/Aqua (1 km)
	Suspended sediment concentration (0.20)	Kd490 MODIS*/Aqua (1 km)
	Bathymetry (0.10)	UNEP* (150 m)
Platforms	Distance to mangroves/trunks/rocks (0.57)	LANDSAT* 7 ETM+ (15 m)
	Distance to socio-infrastructure (0.43)	LANDSAT 7 ETM+ (15 m)
Constraints	River mouth	LANDSAT 7 ETM+ (15 m)
	Lake	LANDSAT 7 ETM+ (15 m)
	Township/industrial area	LANDSAT 7 ETM+ (15 m)
	Marine park	LANDSAT 7 ETM+ (15 m)

MODIS*-sourced from NASA (http://oceancolor.gsfc.nasa.gov/cgi/browse.pl); UNEP*-United Nations Environment Program; LANDSAT*- Sourced from GLOVIS (glovis.usgs.gov).

Current (Aura et al., 2014). The littoral areas are shallow with a wide continental shelf whose extent ranges between 15 and 60 km. The mean depth at high spring tide is 12 m at 1.5 nautical miles (nm) and 18.0 m at 6.0 nm. The depth increases rapidly to 100 m beyond 7 nm and generally decreases northwards. Terrigenous sediments from the rivers dominate the bottom surface in the bay areas (Aura et al., 2014).

2.2. Approach to quantifying the implications of sea warming on oyster occurrence

Several steps were involved towards quantifying the implications of sea warming on littoral oyster habitat suitability (Fig. 2). Oyster Suitable Sites Occurrence Model (SSOM) for the Kenya coast was developed in the initial stages that involved use of satellite data in the GIS-based Multi-Criteria Evaluation (MCE) approach. The satellite data consisted of biophysical, platforms and constraints factors. The final stage of developing the model involved relating performance of oyster suitability sites developed with the latest Intergovernmental Panel on Climate Change (IPCC, 2014) projections, to assess future changes of spatial extent of suitability sites for oysters in the littoral areas of the Kenya coast.

2.2.1. Biophysical factors

Oysters are bivalves (inequivalve) with solid shells and have a sedentary existence, preferring firm bottom substrates. However, they can also be found on mud and sand-mud bottoms. Oysters can survive broad range of salinity gradients in excess of 35%, where they are unlikely to breed. Oysters have a broad temperature tolerance of −1.8 to 35 °C but spawning generally occurs at temperatures >20 °C and rarely at 15–18 °C. Growth of oyster larvae is very rapid in good conditions which include the lower sub-tidal depths of up to 40 m (FAO, 1997), natural phytoplankton as food supply, sea temperature for metabolic activities for provision of energy (Leffler and Greer, 1991; FAO, 1997; Ruesink et al., 2005), and a moderately transparent water column to prevent clogging their filter feeding ability (Morton, 1977; Everett et al., 1995). Under these conditions oysters should reach a market size of about 70–100 g within 18–30 months (FAO, 1997).

Based on these requirements, important biophysical data which include sea surface temperature (SST), Chlorophyll-*a* (Chl-*a*), suspended sediment concentration (SSC), and bathymetry (Silva et al., 2011, 2012; Cho et al., 2012) were used in the present study. The Chl-*a*, SST and Kd490 (for SSC) were derived from the Moderate Resolution Imaging Spectroradiometer (MODIS)-Aqua sensor as daily level-2 data at 1 km resolution (Table 1). To reduce the effect of cloud cover, all MODIS data images were computed as monthly composite imagery which was used to generate average biophysical values.

We extracted Kd490 from MODIS to calculate SSC based on Wang et al. (2005) algorithm:

$$\mathrm{SSC} = 1.43 \times (\mathrm{Kd490})^{-0.89} \quad (1)$$

where Kd490 is the diffuse attenuation coefficient at 490 nm as an indicator of water turbidity.

Bathymetric data were sourced from United Nations Environmental Program (UNEP: http://gridnairobi.unep.org/). The Remote Sensing software used to process, analyse and display the data in this study were SeaDAS 6.3 (GSFC/NASA, USA) and ERDAS Imagine version 9.3 (ERDAS Atlanta, GA, USA).

2.2.2. Platforms and constraints factors

The study employed the use of platforms as factors that positively affect the quality and quantity of oysters. Littoral oysters such as *Crassostrea* spp. are found on trunks, stilt roots, rocks, pneumatophores of mangrove plants, and socio-infrastructural facilities (Okemwa et al., 1986). A reconnaissance survey to identify possible oyster platforms was carried out in the preliminary stages of the study that involved observation, identification and recording of oyster samples and habitats. Constraints consisted of marine parks, lakes, river mouths, marine parks and township or industrial area. Constraints were defined as areas that were excluded from analyses of the present study. This is because the constraint area may limit the potential of suitable site for oyster culture in the future.

2.2.3. Development of Suitable Sites Occurrence Model (SSOM) for oysters

The SSOM comprised a combination of a biophysical sub-model (monthly images of Chl-*a*, SSC, SST and bathymetry), a platform sub-model (distance to trees/trunks, distance to socio-infrastructural facilities) and a constraints sub-model (distance to lakes, river mouths, marine park and township or industrial area). All data was integrated into a 1 km resolution spatial database and reclassified in the spatial analyst tools to create a standard scoring system. The distance analysis method was used to convert platforms data that were provided in vector formats, into raster formats. Each indicator layer was scored on a scale of 1 (least suitable) to 5 (most suitable) for the indicator suitability criterion for oyster suitability (Table 2). In this case, an s-curve relationship was used for ranking parameter values between scores 1 and 5. The next step was to provide a weighting for each criteria and factor.

Table 2
Biophysical and platform (attachment) requirement and suitability scores for oyster along the Kenyan coast. The scale units are represented by scores of 1 (least suitable) to 5 (most suitable).

Indicator	Suitability score and ratings				
	5	4	3	2	1
Chlorophyll-*a* (mg m^{-3})	0.10–0.08	0.08–0.06	0.06–0.04	0.04–0.02	<0.02; >0.10
Sea surface temperature (SST, °C)	24.0–26.0	22.0–24.0; 26.0–28.0	20.0–22.0; 28.0–30.0	18.0–20.0; 30.0–32.0	<20.0; >32.0
Suspended sediment concentration (SSC, mg m^{-3})	>3.5	3.5–3.0	3.0–2.5	2.5–2.0	<2.0
Bathymetry (m)	5.0–10.0	10.0–15.0	15.0–20.0	20.0–25.0	<5.0; >25.0
Distance to mangrove/trunks/rocks (km)	<0.1	0.1–0.2	0.2–0.3	0.3–0.4	>0.4
Distance to socio-infrastructural facility (km)	<0.5	0.5–0.6	0.6–0.7	0.7–0.8	>0.8

Parameter weights were determined by pair-wise comparisons in relation to relative importance to growth and survival (biophysical) and quality and quantity (platforms) of oysters. The comparisons were done according to the analytical hierarchy process (AHP) for decision-making (Malczewski, 1999). The AHP demands that each criterion should be paired against each other (Saaty, 2008) in order to develop a set of relative weights for each parameter in the multi-criteria evaluation (MCE) function (Saaty, 1997, 2008; Malczewski, 2006).

In the AHP method, the relative importance of one of the criterion to the other was scored on a scale of 1 to 4 and 1 to 2 for biophysical and platform factors, respectively. Therefore, the least important was 1 and the reciprocal of the value chosen was assigned to the reverse relationship. The parameter values in each column of the matrix were summed, each value in the matrix divided by the column sum, resulting in a normalized matrix. The values in each row of the normalized matrix were averaged to form weights of each parameter (Table 2). After comparisons were made, the principal eigenvector of the pair-wise comparison matrix was computed to give the best fit for a total weight of 1.0. A consistency ratio (C.R.) of 0.1 or less was acceptable and showed good consistency in judgement of weights criteria (Saaty, 2008). Consistency ratio (C.R.) is a single numerical value which measures the level of inconsistency of the pair-wise comparison matrix (i.e. the likelihood whether factor weights were randomly assigned in the study) (Saaty, 2008).

The next step was GIS analysis using ArcGIS 10.0 (Environmental System Research Institute, ESRI, USA) for MCE function (Saaty, 1997, 2008; Malczewski, 2006). To create the model, a new toolbox under the name "biophysical" was created. All the biophysical data were added into the sub-model screen using weighted overlay in the spatial analysis tools. Similar steps for the platform and constraints sub-models of weighted overlay were done. All the steps were combined into the SSOM model with a 1 km resolution model output. Similar to parameter raster cell ranking, the model output suitability scores were ranked on a scale of 1 (least suitable) to 5 (most suitable). All spatial data used in the GIS models was built on the WGS 1984 Universal Transverse Mercator (UTM) coordinate system.

2.2.4. Assessing implications of sea warming on oyster distribution

The final stage involved determining the relationship between the performances of oyster suitability scores developed, and the latest IPCC (2014) predictions. The relationship was used to demonstrate the application of oyster suitability sites in exploring the extent of future perspectives of the impact of climate change on coastal biota. After SSOM construction, the effect of SST warming was modelled using temperature increases of 1 °C, 2 °C or 4 °C as case-studies for model inputs due to possible future SST variations. These three SST values were selected based on the fifth assessment report of the IPCC (2014).

In order to assess the extent of oyster suitability differences due to climate change, suitability models for increases (positive extent, i.e. increase in habitat suitability classification), decreases (negative extent, i.e. decrease in habitat suitability classification) and no change (no extent, i.e. lack of habitat suitability difference) in the suitable areas were developed. This was done by subtracting the resultant model score after sea temperature increase, from the original model score.

3. Results

Prevalence of platforms appeared to decrease northwards from Kwale (A1) to Lamu (A3) (Fig. 1c). The Chl-*a* concentration was the highest in the March–May (0.06–0.09 mg m^{-3}) and October–November (0.06–0.10 mg m^{-3}) periods (Fig. 3a). The lowest concentrations (0.02–0.06 mg m^{-3}) were recorded in June–July and December–February of every year. Region A3 emerged with the highest Chl-*a* concentrations (≈0.10 mg m^{-3} in March–May and October–November), while the least was at A1. SSC were positively correlated with Chl-*a* (Fig. 3b). The annual peaks in SSC occurred in March–May (4.0–4.9 g m^{-3}) and October–November (3.5–4.9 g m^{-3}). The lowest SSC were found in June–July and December–February of every year with a minimum in A1 (2.0 g m^{-3}). The time series of SST exhibited a biomodal peak with the warmest months occurring in June–July and December–February of every year (Fig. 3c). The SST range was 25–31 °C.

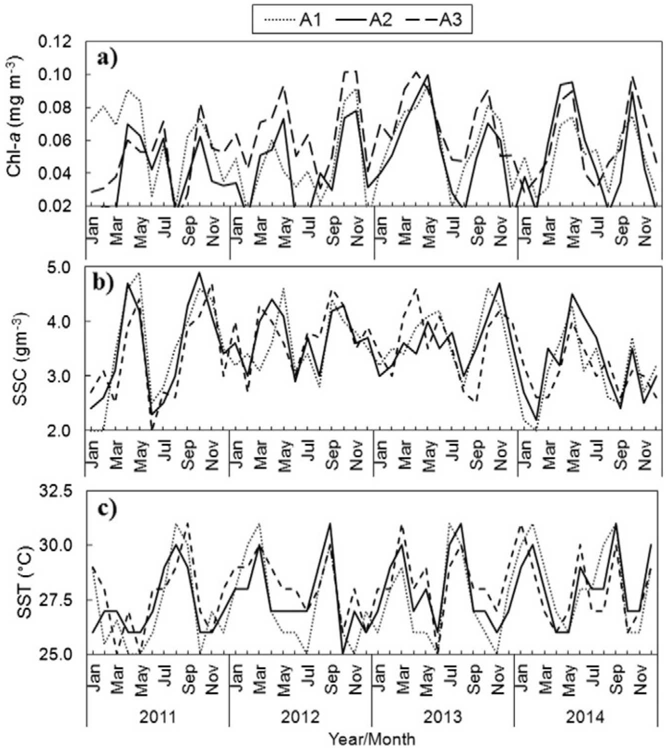

Fig. 3. Time series of monthly a) chlorophyll-*a* (Chl-*a*) concentration, b) suspended sediment concentration (SSC), and c) sea surface temperature (SST) for the three marine zones (A1, A2, and A3) along Kenyan coastal area from 2011 to 2014.

Results of the biophysical parameters' contribution based on the model output scenarios are shown in Table 3. In the original model, SST emerged as the best indicator (most suitable score of 51%) of the

Table 3
Proportional model output (%) of biophysical parameters contribution in oyster habitat suitability classifications, resulting from projections using three scenarios of SST increase. Values are in percentage of the total potential area (4200 km^2; up to spring high water mark of about 3.5 m).

Parameter	Model	Suitability scores				
		1	2	3	4	5
SST	Original	7.0	5.0	10.0	27.0	51.0
	+1 °C	7.5	6.0	9.0	30.2	47.3
	+2 °C	9.0	7.1	13.0	37.0	33.9
	+4 °C	15.0	21.0	17.0	20.3	26.7
Chl-*a*	Original	9.0	6.0	10.0	32.0	43.0
	+1 °C	10.1	7.3	11.5	33.9	37.2
	+2 °C	9.7	8.2	19.5	31.1	31.5
	+4 °C	18.3	17.2	20.1	23.7	20.7
SSC	Original	7.3	8.2	11.2	32.1	41.2
	+1 °C	9.0	7.3	17.8	30.0	35.9
	+2 °C	9.7	8.2	19.5	31.1	31.5
	+4 °C	16.0	12.8	23.4	29.5	18.3
Bathymetry	Original	5.1	6.2	10.7	30.1	48.0
	+1 °C	5.1	6.2	10.7	30.1	48.0
	+2 °C	5.1	6.2	10.7	30.1	48.0
	+4 °C	5.1	6.2	10.7	30.1	48.0
Overall model	Original	16.5	21.4	12.2	14.1	35.8
	+1 °C	10.0	20.2	13.7	16.5	32.3
	+2 °C	17.8	27.6	15.7	19.9	19.0
	+4 °C	18.1	28.4	16.5	20.8	16.2

potential area for oyster suitability, followed by bathymetry (48.0%), Chl-*a* (43.0%), and SSC (41.2%). Further additions of SST at 1 °C, 2 °C, and 4 °C, kept the same trend of parameters' importance. Sea warming favoured increased contributions in the lower scores (scores 1, 2 and 3) for all the biophysical parameters, with further reduction of proportional contributions in the higher scores of 4 and 5.

Fig. 4 shows the suitability map (SSOM) of oyster habitat suitability along the Kenya coast, together with predicted suitability models for the changes in oyster habitat suitability based on sea warming projections due to three scenarios of SST increases. Spatial extent for oysters in the littoral zone of the Kenya coast was about 4200 km^2 measured to the spring high water mark level of about 3.5 m. Sites with high scores of 4 and 5 (hence suitable and most suitable sites, respectively) were found in areas around Kwale, Mombasa, Tana River and Lamu. Lower scores of 1–3 occurred in areas that were away from the littoral zones. In the suitability model, score 5 had the highest proportion (35.8%) of oyster habitat suitability which decreased to 16.2% with increases in sea temperature from 1 °C to 4 °C (Figs. 4 and 5, Table 3). In the original model, the least suitable sites had the least proportion of 16.5% but recorded slight proportional increases with increase in sea warming from 1 °C to 4 °C. Moderate suitability score of 3 and suitability score of 4 recorded minimal increases in proportional habitat suitability of

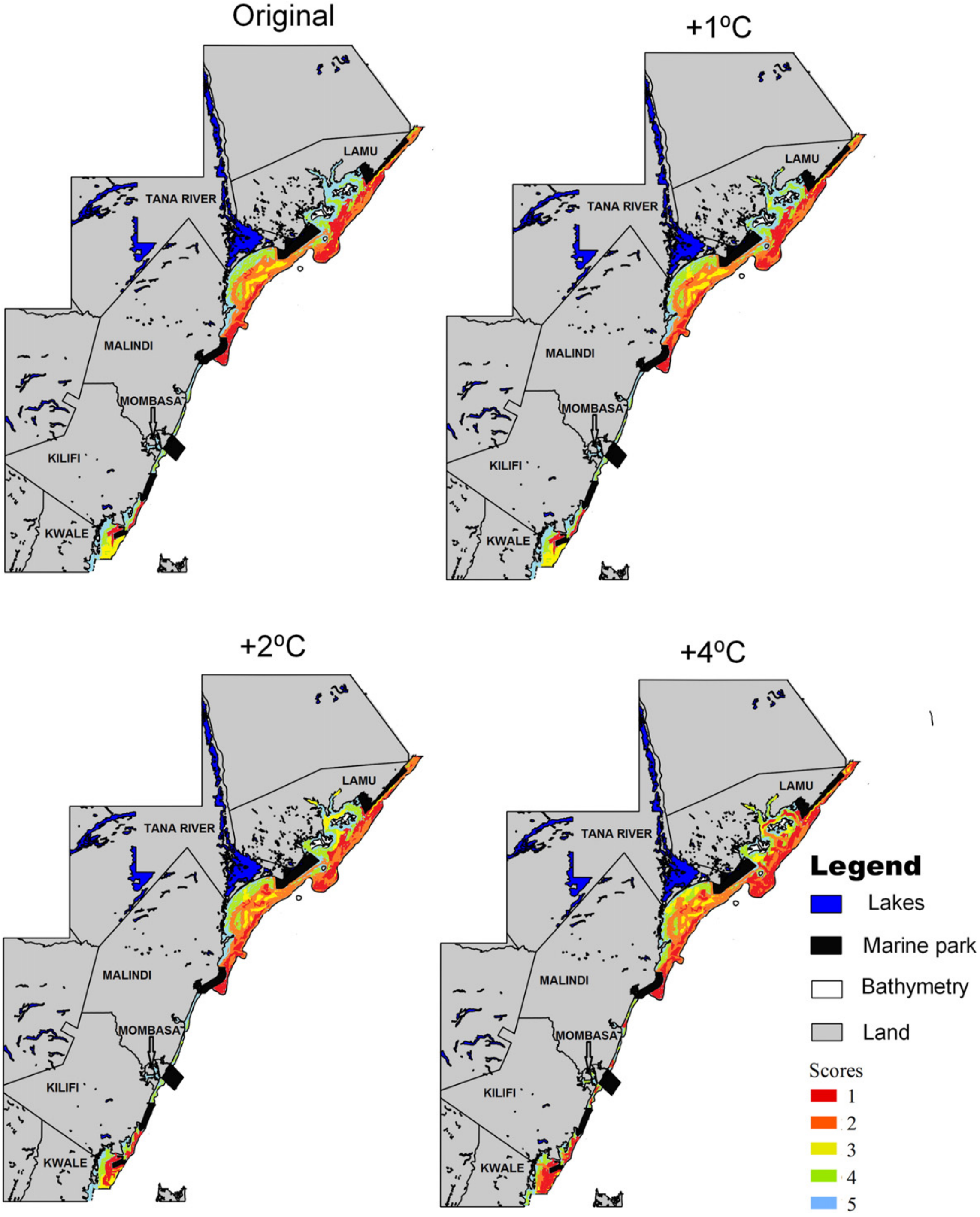

Fig. 4. Littoral oyster Suitable Sites Occurrence Model (SSOM) together with predicted suitability models for the changes in oyster habitat extent for sea warming projection scenarios of SST increases for coastal Kenya waters. The scale units are represented by scores of 1 (least suitable) to 5 (most suitable) for the potentiality of oyster distribution.

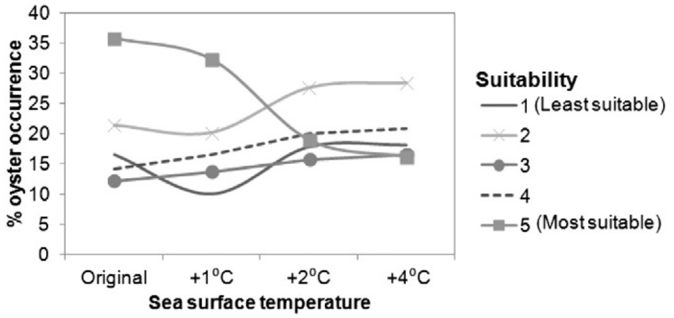

Fig. 5. Predicted modelled changes in suitability scores due to sea warming that are given as percentage of the total potential area (4200 km^2) for inshore oyster habitat suitability (up to spring high water mark level of about 3.5 m), resulting from projections using three scenarios of SST increase.

oyster with increased sea temperatures. The suitability score of 2 showed a decrease in the proportion of oyster habitat suitability with additional of 1 °C, but increased proportionally with increase in sea temperatures of 2 °C and 4 °C.

Fig. 6 shows modelled suitability maps of predicted littoral oyster habitat suitability differences due to possible future sea warming in coastal Kenya. Oyster suitability classification near Kwale showed minimal increase in oyster suitability extent due to future increases in sea temperature. Future increases in sea temperature were associated with the shrinkage of the extent of most suitable (score 5) and suitable (score 4) oyster sites near Tana River. Sites near Lamu had a mixture of decreases and no change of suitability classification due to future sea warming.

Highest proportions of suitability classification were recorded in areas with no oyster habitat suitability differences with increases in sea temperature. But the proportional extent decreased with increase in sea warming (Table 4). At both large-scale increase (−2) and small-scale increase (−1) in oyster suitability classification, minimal expansions in proportions of oyster sites were recorded with future increases in sea temperature. At small-scale decreases (+1) in oyster suitability classification, there was a minimal expansion in proportions of oyster sites with future increases in sea temperature. At large-scale decreases (+2) in oyster suitability classification, slight increases in sea temperatures had no effect on oyster proportional suitability, but slightly increased with increase in further sea warming.

4. Discussion

Marine waters satellite observations in the visible and near-infrared bands make it possible to obtain measurements on several variables related to ocean colour, primarily Chl-*a* concentration, SSC, and SST. However, for coastal Case-2 waters containing more yellow substances and increased suspended matter, non-phytoplankton matter plays an important role.

in the determination of the optical properties of the water body. Since there are no studies in the region linking satellite data and in situ data with high precision of similar geographical sites, the current study could not determine the consistency of MODIS Chl-*a*, SST and SSC data with in situ data. However, a few studies conducted on the Kenya coast, have presented a similar range of results (e.g. KCDP, 2015; Obura, 2001). Driven by seasonal changes, Chl-*a* concentrations have been recorded to range between 0.04 and 0.10 mg m^{-3}, with the highest ranges in the rainy season. The wet season has been associated with increased water levels in coastal rivers with high Chl-*a* likely due to increased discharges of freshwater containing abundant nutrient matter along the coastal shore, which enhances phytoplankton growth (Liu et al., 2010).

Similar to Chl-*a*, SSC concentrations have been shown to range between 3.5 and 5.0 g m^{-3} (KCDP, 2015). Suspended sediment concentration can be affected by Chl-*a* concentration, water pollution, sea level rise and tide regimes which can vary among coastal regions that experience different environmental conditions (Wang et al., 2005). Such a relationship is likely to be linked with SSC concentrations that positively correlated with Chl-*a*. The SST ranges for the Kenya coast have been associated with rainy and dry seasons with a range of 25–32 °C (Obura, 2001). Thus, biophysical parameters on this coast appear to be influenced by seasonal variations, in this case, dry and wet seasons, an indication that such parameters are climate-driven. Based on the model analysis, the order of importance of the biophysical parameters affecting the model were as follows: SST > bathymetry > Chl-a > SSC (Table 3). This was an indication that sea temperature (SST) could be ranked as a priority preference variable in the determination of oyster habitat suitability as opposed to SSC. The ranking of parameter contributions to the model could signal the likelihood of sea warming to have significant impacts on the oyster habitat suitability. However, since there were significant seasonal variations in the biophysical parameters, the temporal extent of the model could be investigated further in order to ascertain seasonal contributions.

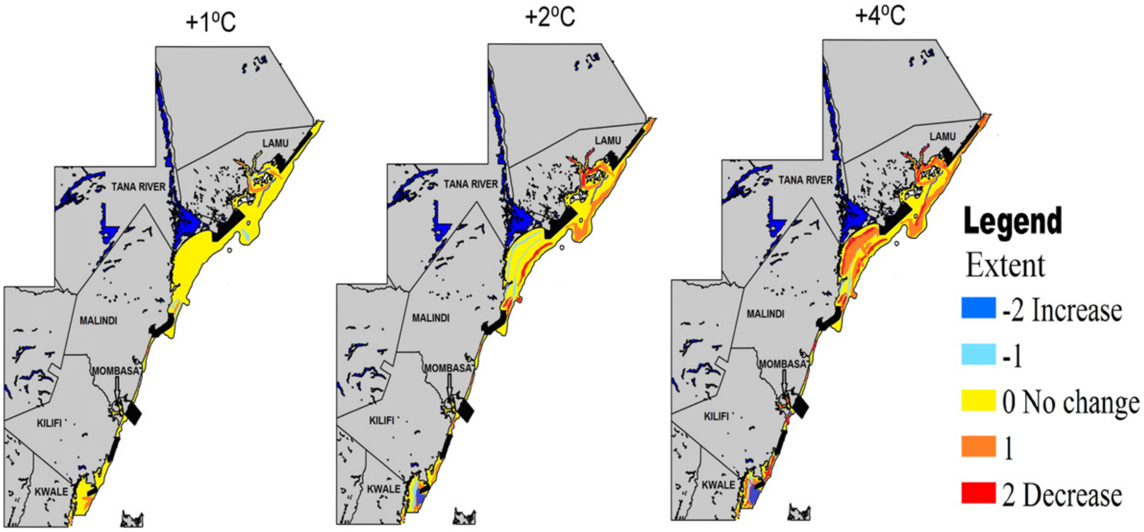

Fig. 6. Modelled suitability maps showing predicted habitat suitability differences in littoral oyster areal extent due to sea warming in coastal Kenya.

Table 4
Predicted modelled change in littoral oyster areal extent due to sea warming, resulting from projections using three scenarios of SST increase. Values are in percentage of the total potential area (4200 km^2; up to spring high water mark of about 3.5 m).

Extent	Increase (e.g., 5–4, 4–3…, 3–5, 2–4…)		No change (e.g., 5–5, 4–4…)	Decrease (e.g., 5–4, 4–3…, 5–3, 4–2…)	
Model/Score	−2	−1	0	+1	+2
+1 °C	0	1.6	94.3	4.1	0
+2 °C	2.1	1.4	78.7	12.5	5.3
+4 °C	2.5	1.8	71.5	15.3	8.9

The present study employed a GIS-based model and used satellite remote sensing data to develop a SSOM for oysters along the Kenya coast. Biophysical factors, such as SST, SSC and bathymetry, and platform factors that were relevant to the coastal areas of Kenya were incorporated into the model. Though in situ data may provide robust accuracy to the model, sampling on such a large extent of the approximately 600 km Kenyan coast would prove to be cumbersome and costly. The GIS and satellite data for the model construction in this study could therefore offer a better alternative. However, accuracy of the SSOM could be improved further. In the biophysical sub-model, additional factors that influence oyster growth and survival, such as salinity, dissolved oxygen, feedbacks of temperature increases to phytoplankton and other biophysical responses, and hydrodynamics could be included in the SSOM. Despite the absence of active fishery and an overall dearth of historical data, the abundance and status of oysters in the littoral zones are known to fluctuate with variable salinity (Barnes et al., 2007). Additionally, sea level rise (hydrodynamics), though affecting sea temperature changes, has been noted to affect salinity variations and oyster growth (Huang et al., 2015).

Climate change is a complex phenomenon which could be influenced by many factors (IPCC, 2007). Apart from the rainy and wet seasons, the Kenyan coast is under the influence of the dominant offshore current regimes which influence littoral zones. In the NEM season, occurring between November and March, the northward flowing East African Coastal Current meets the southward flowing Somali current to form the Equatorial Counter Current. During the SEM season, which occurs between April and October, the current circulation is dominated by northward flow of the EACC (Aura et al., 2016). Global climate events, among them El Niño, have been implicated as major factors controlling the climate of the oceans (Liu et al., 2014; Zhang et al., 1996). Thus, projections of biota habitat suitability in the future under changing climate conditions are of importance in advising relevant authorities on the management of littoral zones.

The spatial extent of oyster suitability was confined in the littoral zone mainly in Kwale, Mombasa, Tana River and Lamu. This is attributed to the presence of mangroves, trunks, and land-based buildings for oyster attachment. The prevalence of socio-infrastructural platforms appeared to decrease northwards from Kwale to Lamu (Fig. 1c) which most likely affected the model performance in favour of Lamu. In the suitability model, score 5 had the highest proportion (35.8%) of oyster suitability which decreased to 16.2% with a 4 °C increase in sea temperature. Most suitable oyster sites showed high levels of habitat suitability differences due to increased sea warming (Fig. 5). This would imply that such areas may experience proportional loss of littoral niches in the future due to increased sea warming. Moderately suitable sites (suitability of 2, 3, and 4) recorded proportional increases in oyster habitat suitability based on future sea warming. Such findings would be due to loss of most suitable sites that tended to accumulate in areas with moderate conditions for oyster occurrence. Thus future global warming effects (IPCC, 2007, 2014) are likely to gradually decrease the extent of the most suitable oyster sites along the Kenyan coast, impacting negatively on their abundance and distribution.

Slight differences in SST within and between sites recorded would influence spatial variations in oyster suitability sites (Fig. 6). For example, oyster habitat suitability near Kwale (A1, see Fig. 3) showed minimal increase in oyster suitability classification due to future increases in sea temperature. Furthermore, future increases in sea temperature were associated with shrinkage of oyster suitability classification near Tana River and a mixture of decreases and no change of suitability classification near Lamu (A3). The model generally predicted a decrease of the most suitable areas for oyster occurrence under future scenarios of sea warming due to climate change. Such concepts should be considered by management authorities in establishing policies and programmes to address future climate induced changes in the littoral zone.

5. Conclusion

Future increases in sea temperature are likely to cause shrinkage in the spatial extent of 'most suitable' and 'suitable' oyster sites. This is predicted to worsen in the future due to predicted increases in sea temperatures. Differences of ≤6 °C recorded within and between sites may have an influence on spatial variations in oyster habitat suitability due to future sea warming. Application and determination of the changes in the marine environment on oyster distribution involved the use of dominant indicators for ecological feedback (biophysical and platform factors) and projections (latest climate change predictions). The order of oyster biophysical parameters preference from most preferred to the least preferred was SST > bathymetry > Chl-*a* > SSC. However, considerable seasonal variability in the biophysical parameters in the present study may require further investigations to determine the temporal extent of the oyster suitability model. Such concepts could form alternative baseline information in marine ecosystem models on how to quantify and predict global change effects for biodiversity and aquatic resource management.

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References

Alber, M., 2002. A conceptual model of estuarine freshwater inflow management. Estuaries 25, 1246–1261.

Aura, M.C., Anam, R.O., Musa, S., Kimani, E.N., 2014. Length-weight relationship and condition factor (K constant) of *Dentex Marocannus* Valenciennes 1830 (family Sparidae) at Malindi, Kenya. West. Indian Ocean J. Mar. Sci. 12 (1), 79–83.

Aura, C.M., Saitoh, S.-I., Liu, Y., Hirawake, T., Baba, K., Yoshida, T., 2016. Implications of marine environment change on Japanese scallop (*Mizuhopecten yessoensis*) aquaculture suitability: comparative study in Funka and Mutsu Bays, Japan. Aquac. Res. 47, 2164–2182.

Barnes, T.K., Volety, A.K., Chartier, K., Mazzotti, F.J., Pearlstine, L., 2007. A habitat suitability index model for the eastern oyster (*Crassostrea virginica*), a toll for restoration of the Caloosahatchee Estuary, Florida. J. Shellfish Res. 26 (4), 949–959.

Beck, M.W., Brumbaugh, R.D., Airoldi, L., Carranza, A., Coen, L.D., Crawford, C., Defeo, O., Edgar, G.J., Hancock, B., Kay, M.C., Lenihan, H.S., Luckenbach, M.W., Toropova, C.L., Zhang, G.F., Guo, X.M., 2011. Oyster reefs at risk and recommendations for conservation, restoration, and management. Bioscience 61, 107–116.

Brander, K., 2010. Impact of climate variability on marine ecosystems: a comparative approach. J. Mar. Syst. 79 (3–4), 389–402.

Buzan, D., Lee, W., Culbertson, J., Kuhn, N., Robison, L., 2009. Positive relationship between freshwater inflow and oyster abundance in Galveston Bay, Texas. Estuar. Coasts 32, 206–2012.

Chelazzi, G., Vannini, M., 1980. Zonation of intertidal molluscs on rocky shores of southern Somali. Estuar. Coast. Mar. Sci. 10, 569–583.

Cheung, W.W.L., Lam, V.W.Y., Sarmiento, J.L., Kearney, K., Watson, R., Zeller, D., Pauly, D., 2010. Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. Glob. Chang. Biol. 16, 24–35.

Cho, Y., Lee, W.C., Hong, S., Kim, H.C., Kim, J.B., 2012. GIS-based suitable site selection using habitat suitability index for oyster farms in Geoje-Hansan Bay, Korea. Ocean Coast. Manag. 56, 10–16.

Eggleston, D.B., 1999. Application of landscape ecological principles to oyster reef habitat restoration. In: Luckenbach, M.W., Mann, R., Weston, J.A. (Eds.), Oyster Reef Habitat Restoration: A Synopsis and Synthesis of Approaches. Virginia Institute of Marine Science Press, Gloucester Point, Virginia, pp. 213–227.

Everett, R.A., Ruiz, G.M., Carlton, J.T., 1995. Effect of oyster mariculture on submerged aquatic vegetation: an experimental test in a Pacific northwest estuary. Mar. Ecol. Prog. Ser. 125, 205–2017.

FAO, 1997. Aquaculture development. FAO Technical Guidelines for Responsible Fisheries No. 5. FAO, Rome, Italy.

Flemer, D.A., Champ, M.A., 2006. What is the future fate of estuaries given nutrient overenrichment, freshwater diversion, and low flows? Mar. Pollut. Bull. 52, 247–258.

Goreau, T., McClanahan, T.R., Hayes, R., Strong, A., 2000. Conservation of coral reefs after the 1998 global bleaching event. Conserv. Biol. 14, 5–15.

Grimsditch, G., Mwaura, J.M., Kilonzo, J., Amiyo, N., 2010. 2010. The effects of habitat on coral bleaching responses in Kenya. Ambio 39 (4), 295–304.

Hartnoll, R.G., 1976. The ecology of some rocky shore in tropical East Africa. Estuar. Coast. Mar. Sci. 4, 1–21.

Huang, W., Hagen, S., Bacopoulos, P., Wang, D., 2015. Hydrodynamic modeling and analysis of sea-level rise impacts on salinity for oyster growth in Apalachicola, Florida. Estuar. Coast. Shelf Sci. 156, 7–18.

IPCC (Intergovernmental Panel on Climate Change), 2007. Climate change 2007: impacts, adaptation and vulnerability. In: Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E. (Eds.), Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel of Climate Change. Cambridge University Press, Cambridge, UK, p. 976.

IPCC (Intergovernmental Panel on Climate Change), 2014. Chapter 12: long-term climate change: projections, commitments and irreversibility. In: Stocker, T.F., Qin, D., Plattner, G.K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, B., Midgley, B.M. (Eds.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change. Cambridge University Press, Cambridge, UK., pp. 1–18 1008pp.

Jackson, J.B.C., 2008. Colloquium paper: ecological extinction and evolution in the brave new ocean. Proc. Natl. Acad. Sci. U. S. A. 105 (1), 11458–11465.

Johanna, E.J., Welch, D.J., 2016. Climate change implications for Torres Strait fisheries: assessing vulnerability to inform adaptation. Climate Change 135, 611–624.

KCDP, 2015. Kenya Coastal Development Project (KCDP) Lamu Biodiversity and Ecosystem Health Assessment Technical Report: Research Geared towards Promoting Environmentally Sustainable Management of Kenya's Coastal and Marine Resources, Kenya Marine and Fisheries Research Institute (KMFRI) Technical Report Series, Mombasa (pp. 45).

Kellogg, M.L., Cornwell, J.C., Owens, M.S., Paynter, K.T., 2013. Denitrification and nutrient assimilation on a restored oyster reef. Mar. Ecol. Prog. Ser. 480, 1–19.

Kimani, E.N., Mavuti, K.M., Mukiama, T.K., Wambiji, N., 2008. Macrofauna settlement on pearl oyster collectors in Kenya: seasonality and abundance. West. Indian Ocean J. Mar. Sci. 7 (1), 81–94.

Kjelland, M.E., Piercy, C.D., Lackey, T., Swannack, T.M., 2015. An integrated modelling approach for elucidating the effects of different management strategies on Chesapeake Bay oyster metapopulation dynamics. Ecol. Model. 308, 45–62.

Kofi, O., 1986. Oysters Recommended as Sustenance for Africa: ‘Inexhaustible Quantities’ of Protein-Rich Mollusks Could Feed the Masses. Reuters l May 11, 1986.

Lassalle, G., Rochard, E., 2009. Impact of twenty-first century climate change on diadromousfish spread over Europe, North Africa and the Middle East. Glob. Chang. Biol. 15, 1072–1089.

Leffler, M., Greer, J.R., 1991. The Ecology of *Crassostrea gigas* in Australia, New Zealand, France and Washington. Maryland Sea Grant, College Park, Maryland (UM-SG-TS-92-07).

Lehmann, A., Giuliani, G., Ray, N., Rahman, K., Abbaspour, K.C., Nativi, S., Craglia, M., Cripe, D., Quevauviller, P., Beniston, M., 2014. Reviewing innovative Earth observation solutions for filling science-policy gaps in hydrology. J. Hydrol. 518 (Part B), 267–277.

Liu, W.L., Qian, L., Zheng, X.S., 2010. Spatial temporal variation of chlorophyll- concentration in the Bohai Sea. Lect. Notes Comput. Sci 6330, 662–670.

Liu, Y., Saitoh, S.-I., Radiarta, I.N., Igarashi, H., Hirawake, T., 2014. Spatiotemporal variations in suitable areas for Japanese scallop aquaculture in the Dalian coastal area from 2003 to 2012. Aquaculture 422-423, 172–183.

Malczewski, J., 1999. GIS and Multi-Criteria Decision Analysis. John Wiley & Sons, New York, p. 392.

Malczewski, J., 2006. Ordered weighted averaging with fuzzy quantifiers: GIS-based multicriteria evaluation for land-use suitability analysis. Int. J. Appl. Earth Obs. Geoinf. 8 (4), 270–277.

Morton, B.S., 1977. The tidal rhythm of feeding and digestion in the Pacific oyster, *Crassostrea gigas* (Thunberg). J. Exp. Mar. Biol. Ecol. 26, 135–151.

Obura, D.O., 2001. Kenya. Mar. Pollut. Bull. 42 (12), 1264–1278.

Okemwa, E., Ruwa, R.K., Polk, P., 1986. The autecology of the edible oyster Crassostrea cucullata born, 1778: size related vertical distribution at Mkomani, Mombasa. Kenya J. Sci. Ser. B 7 (2), 9–14.

Olonscheck, D., Hofmann, M., Worm, B., Schellhuner, H.J., 2013. Decomposing the effects of ocean warming on chlorophyll *a* concentrations into physically and biologically driven contributions. Environ. Res. Lett. 8, 014043. http://dx.doi.org/10.1088/1748-9326/8/1/014043.

Petes, L.E., Brown, A.J., Knight, C.R., 2012. Impacts of upstream drought and water withdrawals on the health and survival of downstream estuarine oyster populations. Ecol. Evol. 2 (7), 1712–1724.

Piazza, B.P., Banks, P.D., La Peyre, M.K., 2005. The potential for created oyster shell reefs as a sustainable shoreline protection strategy in Louisiana. Restor. Ecol. 13, 499–506.

Pollack, J.B., Kim, H.-C., Morgan, E.K., Montagna, P.A., 2011. Role of flood disturbance in natural oyster (Cassostrea virginica) population maintenance in an estuary in South Texas, USA. Estuar. Coasts 34, 187–197.

Radiarta, N., Albasri, H., Sudradjat, A., 2011. Geographic information system-based modelling and analysis for site selection of green mussel, *Perna viridis*, mariculture in Lada Bay, Pandeglang, Banten Province. Indonesian Aquac. J. 6 (1), 01–105.

Ruesink, J.L., Lenihan, H.S., Trimble, A.C., Heiman, K.W., Micheli, F., Byers, J.E., Kay, M.C., 2005. Introduction of non-native oysters: ecosystem effects and restoration implications. Annual Review of Ecology, Evolution, and Systematics http://dx.doi.org/10.1146/annurev.ecolsys.36.102003.152638.

Ruwa, R.K., Brakel, W.H., 1981. Tidal periodicity and size-related variation in the zonation of the gastropod *Nerita plicata* on an East African rocky shore. Kenya J. Sci. Technol., Ser. B2 (2), 61–67.

Saaty, T.L., 1977. A scaling method for priorities in hierarchical structures. J. Math. Psychol. 15, 234–281.

Saaty, T.L., 2008. Decision making with the analytic hierarchy process. Int. J. Serv. Sci. 1 (1), 83–98.

Saitoh, S.-I., Mugo, R., Radiarta, I.N., Asaga, S., Takahashi, F., Hirawake, T., Ishikawa, Y., Awaji, T., In, T., Shima, S., 2011. Some operational uses of satellite remote sensing and marine GIS for sustainable fisheries and aquaculture. ICES J. Mar. Sci. 68 (4), 687–695.

Schmelzer, N., Holfort, J., 2011. Ice winter severity in the western Baltic Sea in the period of 1301–1500: comparison with other relevant data. Int. J. Climatol. 31, 1094–1098. http://dx.doi.org/10.1002/joc.2337.

Silva, C., Ferreira, J.G., Bricker, S.B., DelValls, T.A., Martín-Díaz, M.L., Yáñez, E., 2011. Site selection for shellfish aquaculture by means of GIS and farm-scale models, with an emphasis on data-poor environments. Aquaculture 318, 444–457.

Silva, C., Yáñez, E., Martín-Díaz, M.L., DelValls, T.A., 2012. Assessing a bioremediation strategy in a shallow coastal system affected by a fish farm culture-application of GIS and shellfish dynamic models in the Rio San Pedro, SW Spain. Mar. Pollut. Bull. 64, 751–765.

Soniat, T.M., Conzelmann, C.P., Byrd, J.D., Roszell, D.P., Bridevaux, J.L., Suir, K.J., Colley, S.B., 2013. Predicting the effects of proposed Mississippi River diversions on oyster habitat quality: application of an oyster habitat suitability index model. J. Shellfish Res. 32 (2), 629–638.

Tack, J.F., Vanden berghe, E., Polk, P., 1992. Ecomorphology of *Crassostrea cucullata* (born, 1778) (Ostreidae) in a mangrove creek (Gazi, Kenya). Hydrobiologia 247, 109–117.

Wakelin, S.L., Artioli, Y., Butenschön, M., Allen, J.I., Holt, J.T., 2015. Modelling the combined impacts of climate change and direct anthropogenic drivers on the ecosystem of the northwest European continental shelf. J. Mar. Syst. 152, 51–63.

Walczowski, W., Piechura, J., 2011. Influence of the West Spitsbergen current on the local climate. Int. J. Climatol. 31, 1088–1093. http://dx.doi.org/10.1002/joc.2338.

Wang, X.M., Tang, J.W., Ding, J., Ma, C.F., Li, T.J., Wang, X.Y., Bi, D.Y., 2005. The retrieval algorithms of diffuse attenuation and transparency for the case-II waters of the Huanghai Sea and the East China Sea. Acta Oceanol. Sin. 27 (5), 38–45.

Wilkinson, C., Lindén, O., Cesar, H., Hodgson, G., Rubens, J., Strong, A.E., 1999. Ecological and socioeconomic impacts of 1998 coral mortality in the Indian Ocean: an ENSO impact and a warning of future change? Ambio 28, 188–196.

Winterfeldt, J., Geyer, B., Ralf, W.R., 2011. Using QuikSCAT in the added value assessment of dynamically downscaled wind speed. Int. J. Climatol. 31, 1028–1039. http://dx.doi.org/10.1002/joc.2105.

Wolter, K., Timlin, S., 2011. El Niño/Southern Oscillation behaviour since 1871 as diagnosed in an extended multivariate ENSO index (MEI.ext). Int. J. Climatol. 31, 1074–1087. http://dx.doi.org/10.1002/joc.2336.

Yamaguchi, S., Kawamura, H., 2005. Influence of orographically steered winds on Mutsu Bay surface currents. J. Geo. Res.: Oceans 110, C9. http://dx.doi.org/10.1029/2004JC002462.

Zhang, R., Sumi, A., Kimoto, M., 1996. Impact of El Niño on the East Asian monsoon: a diagnostic study of the '86/87 and '91/92 events. J. Meteorol. Soc. Jpn. 74, 49–62.