Western Indian Ocean JOURNAL OF Marine Science

Volume 15 | Issue 1 | Jan – Jun 2016 | ISSN: 0856-860X

Chief Editor José Paula

Western Indian Ocean JOURNAL OF Marine Science

Published biannually

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ISSN 0856-860X

Cover image: Fisherman pushes his boat along the channels around Inhaca Island, Mozambique (© José Paula)

The decline in phytoplankton biomass and prawn catches in the Rufiji-Mafia Channel, Tanzania

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Abstract

The world's oceans have seen significant declines in phytoplankton-the primary food source in the marine environment. This decline in primary producers is likely to impact the food chain and functions of most coastal and marine ecosystems. Despite being one of the most productive marine fishing grounds in the Western Indian Ocean (WIO) region, the information about phytoplankton biomass in the Rufiji-Mafia Channel is poor. This study aimed to narrow this information gap by assessing phytoplankton biomass in the Channel and its association with the decline of the prawn fishery. We combined in-situ measurement and ocean colour satellite data to determine and assess trends in phytoplankton biomass and sea surface temperature between 2002 and 2014. These trends were related to a declining prawn fishery in the Channel. While phytoplankton displayed a significant declining trend during the southwest monsoon, sea surface temperature showed an insignificant increasing trend. Phytoplankton declined at the rate of 1.2 percent per year (*tau* = 1.2, z = 3.52, p = 0.004) between 2002 and 2014. This declining trend in Chl-a matches well with the decreasing trend in the prawn fishery (*tau* = 0.57, z = 3.39, p = 0.0006) and the insignificant increasing trend in sea surface temperature (*tau* = 0.02, z = 0.43, p = 0.66). This study provides quantitative evidence of trends in chlorophyll and SST and the link with trends in the prawn fishery, which increases our understanding of the changes in marine primary productivity in the coastal waters of Tanzania.

Keywords: phytoplankton, Chl-a, sea surface temperature, Rufiji-Mafia Channel, Rufiji River, satellite data, prawn fishery, Tanzania

Introduction

Phytoplankton are mostly single celled aquatic microalgae that use Chlorophyll-*a* (Chl-a) to carry out photosynthesis (Kyewalyanga, 2005; Kyewalyanga, 2015). Phytoplankton contain Chl-a, a green and photosynthetic pigment that absorbs photons from solar radiation and converts it into energy (Kevin *et al.*, 2015; Roy, 2009), which stored as food. Phytoplankton are at the base of the food chain, composed of primary producers (Klemas, 2013). They not only form the diet of typical herbivorous zooplankton, but are also food sources of other invertebrates, fishes and large mammals, including whales (Roy, 2009). Generating roughly half the planetary primary production, marine phytoplankton affect the abundance and diversity of marine organisms, drive marine ecosystem functioning, and set the upper limits to fishery yields (Allan *et al.*, 2014; Anilkumar *et al.*, 2014; Baliarsingh *et al.*, 2013; Bouman *et al.*, 2006). Phytoplankton strongly influence climate processes and bio-geochemical cycles, particularly the carbon cycle (IPCC, 2014). The ocean absorbs about 25 percent of global carbon dioxide, which is the main source of global warming (Allan *et al*., 2014).

Phytoplankton account for about half of global, and nearly all of marine primary productivity (Barlow *et al*., 2011; Lamont *et al*., 2014); consequently, any drop in phytoplankton biomass would almost certainly have severe ecological consequences (Rykaczewski and Dunne, 2011). Recently, Boyce *et al*. (2010) reported an alarming, century-long decline in marine phytoplankton biomass of 1% per year at a global scale. A similar trend has been observed in the northern hemisphere, where phytoplankton have decreased by 1% per year between 1998 and 2012 (Kevin *et al*., 2015). This decreasing trend of phytoplankton biomass suggests major changes in ecosystem processes and biogeochemical cycling, with significant implications for ecological functioning of coastal and marine ecosystems (Bouman *et al*., 2006; Boyce *et al*., 2010; Jutla *et al*., 2011; Marinov *et al*., 2006), including fisheries.

While phytoplankton are invisible to the naked human eye (Kumar and Perumal, 2012), they can be detected from space by ocean color remote sensing – a technique used to gather information on Chl-a concentration without being in contact with the surface of the ocean (Grémillet *et al*., 2008; Kachelriess *et al*., 2014; Kratzer *et al*., 2014; Picart *et al*., 2014; Raitsos *et al*., 2013; Rykaczewski and Dunne, 2011; Sherman *et al*., 2011). Recent advances in observational satellite technology, free-floating drifters and other devices, have made large-scale monitoring of the oceans possible (Blondeau-Patissier *et al*., 2014; Chawira *et al*., 2013; Grémillet *et al*., 2008; Kachelriess *et al*., 2014; Vanhellemont and Ruddick, 2015). With the aid of remote sensing technology it is possible, for example, to determine with high accuracy the abundance of phytoplankton in surface waters using the color reflected by the Chl-a pigment (Grémillet *et al*., 2008; Sherman *et al*., 2011). The presence of Chl-a in surface water has been widely used as an indicator of primary production and ecological functioning of freshwater and marine ecosystems (Boyce *et al*., 2010).

Marine phytoplankton have recently been observed, using satellite remote sensing, to vary on a global scale. Several studies have shown an alarming productivity decrease in the Indian and Pacific Oceans (Wernand *et al*., 2013). Other studies have shown increasing trends associated with large inter-annual and decadal-scale variability (Boyce *et al*., 2010; Rykaczewski and Dunne, 2011; Thangaradjou *et al*., 2014; Wernand *et al*., 2013). Although satellite ocean color data have been available since the early 1980s, empirical estimates of long-term trends in phytoplankton abundance in the Rufiji-Mafia Channel remain limited. Assessing long-term changes in phytoplankton and the ecosystem condition in the Channel is of increasing importance because of possible links to declining marine fishery resources (Jiddawi and Ohman, 2002; Slater *et al*., 2014).

The Rufiji-Mafia Channel is one of the most important prawn fishing grounds in Tanzania. It contributes about half of the total annual prawn production (Masalu, 2003). Nutrient-rich waters and sediments flowing into the Channel from the Rufiji River contribute to its high primary production. It is the only fishing ground in the coastal waters of Tanzania where industrial and artisanal prawn fisheries are conducted (MLFD, 2012). The prawn fishery was amongst the major commercial fishing activities in Tanzania, but since 2000 this fishery has shown evidence of serious unsustainable exploitation levels. Increased fishing effort, exploitation above the maximum sustainable yield, and destruction of habitats were cited as causes for the decreasing catch rate. However, although fishing effort was reduced significantly, the yield continued to decline (MLFD, 2012). This suggested that the stocks had not only dwindled, but had shrunk, and the fishery was temporary closed in 2008 for two years to allow recovery. A prawn stock assessment survey conducted in 2011 found no sign of recovery. This finding led the government, through the Fisheries Division, to declare full closure of the prawn fishery in 2012 (MLFD, 2012).

This study, therefore, aimed at assessing the trend in phytoplankton production and changes in sea surface temperature (SST) in the Rufiji-Mafia Channel, and to relate these to the observed fluctuations in the prawn fishery in the Channel. We combined in-situ measurements and long-term time series data of moderate resolution ocean colour satellite images (Rousseaux and Gregg, 2015) in order to assess the trends in Chl-a concentration as a proxy for primary production.

Methods

Study area

The Rufiji–Mafia Channel is located between latitudes 06°50’S and 08°40’S and longitudes 39°20’E and 39°40’E (Fig. 1). The area includes the Rufiji Delta and the Mafia Channel within the bounds described above. The Channel is approximately 21 km wide at its narrowest (between the mainland and Bwejuu Island)

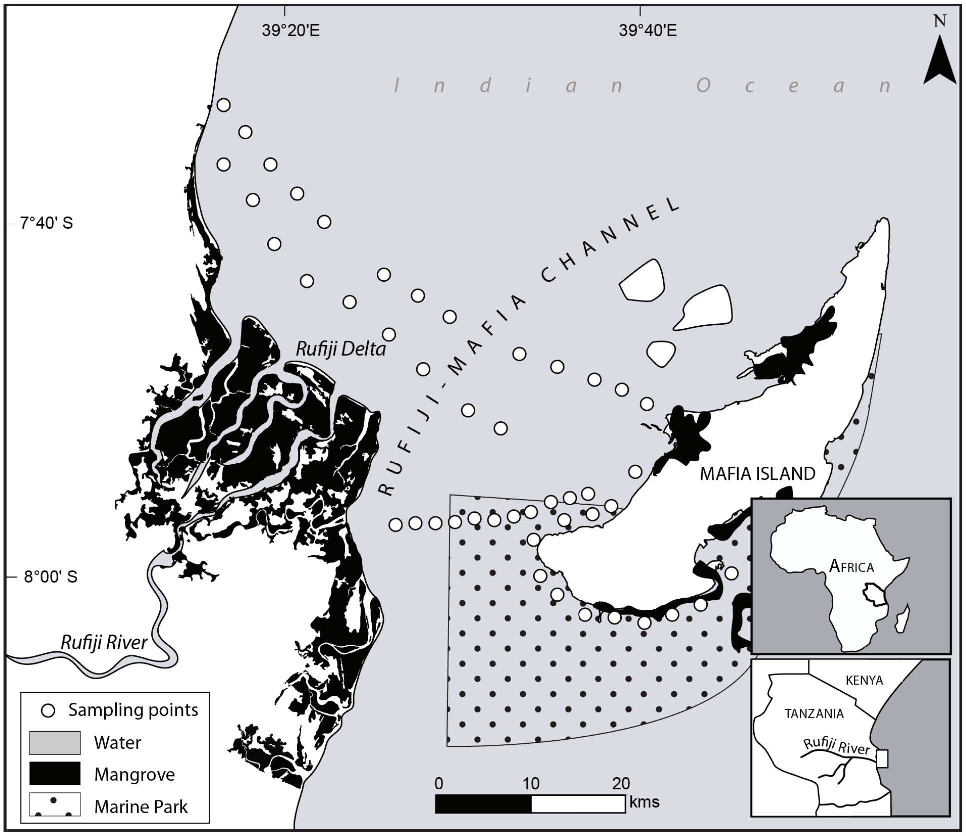

Figure 1. Map showing the location of the Rufiji-Mafia Channel, with in-situ sampling stations. The inset maps indicate the study area in Tanzania and its position in Africa.

and 70 km at its widest (just south of the mouth of the Rufiji River estuary). Much of the Channel is shallow. At the point where the Rufiji River flows into the Channel, the average depth is 6m. On average, the depth of the Channel is 22m and about 61% of the Channel area is less than 20m deep (Semba, unpublished data). Because the Channel is adjacent to a large estuary, it contains zones of fresh water, salt water and brackish water, with the freshwater zone in the vicinity of the mouth of the Rufiji River. Salinity varies from 0.5 to 10 ppt at the mouth of the Rufiji River to 18.7 to 36 ppt in the Channel.

The climate of the Channel is influenced by the seasonal reversal of monsoon winds. There are mainly two monsoon seasons, the northeast monsoon ("*Kaskazi*"), which prevails from November to March and is characterized by a mean surface temperatures of 30°C, and weaker winds and calm sea conditions. The other season is the southeast monsoon ("*Kusi*"), which runs from April to September and is marked by a mean surface temperature of 23°C, stronger winds and rough sea conditions. The area receives an annual average rainfall of 1800 mm, which is divided into two seasons - "long-" and "short" rains occurring mainly between March and May and from November to early December respectively. The Channel is strongly influenced by the Rufiji River which, apart from discharging a large quantity of fresh water (900 m^3/s), transports sediments and nutrients (Garpe and Öhman, 2003). The strongest outflows are in the northern Channels, with more saline conditions to the south. The Rufiji River flows into the Indian Ocean and influences the coastal environment within the Channel through the creation of productive brackish water in the estuary, maintenance of deltas, tidal flats and shorelines, and nourishment of mangroves and seagrass beds.

Known for both its beauty and bounty, the Rufiji-Mafia Channel forms one of the finest complexes of estuaries, mangroves, coral reefs and marine Channel ecosystem (Masalu, 2003). Mangroves and seagrass beds filter freshwater discharges from the Rufiji River that are rich in nutrients (Kimirei *et al.*, 2016) while the detritus from mangroves provide food for many commercially important species, mostly demersal fish and benthic invertebrates, thereby supporting a wide variety of sea life (Igulu *et al.*, 2014). The Channel is an extremely high primary and secondary productivity area and supports a great abundance and diversity of fish, birds, invertebrates and macro-fauna (Gaspare and Bryceson, 2013). The Channel was previously known for prawn production, which contributed about half of the total annual prawn production in Tanzania (Sobo and Mahongo, 2007)

Data Collection, Processing and Analysis

In-situ measurements and Prawn data

Biological, physical and chemical variables in the Rufiji-Mafia Channel were recorded in July 2013. July was chosen for sampling because it fell within the southeast monsoon season which has high primary productivity. A total of 48 stations in three transects were chosen for sampling (Fig. 1). The sampling stations were at an interval of 3 kilometers apart. The longitude and latitude coordinates of each sampling station were recorded using the Essential GPS App version 3.1 installed in a Samsung Galaxy Smartphone which was running on a Gingerbread Android Operating system, version 2.3.

Water samples for Chl-a analysis were collected and filtered through 0.45µm pore size membrane filters. Five litres (5L) of water were filtered per sample. Filters were then folded in aluminum foil, stored frozen in Ziploc bags and transported to Unguja Island for laboratory analysis at the Institute of Marine Sciences. Chl-a was extracted by adding 10ml of 90% (v/v) acetone to vials containing the filter papers. These tubes were then covered with aluminum foil and refrigerated for 24 hours. After that, the test tubes were centrifuged for 10 minutes at a speed of 3000 revolution per minute (rpm), and then stored in cuvettes. A fluorometer was used to determine the fluorescence value of Chl-a in the cuvettes. The fluorometer reading before addition of acid in the sample was recorded, to obtain corrected Chl-a, after which 2 drops of 10% hydrochloric acid was added to the cuvettes, and a new fluorometer reading recorded. The concentration of Chl-a in the sample was then calculated according to Lorenzen (1966). Ammonia was analyzed according to standard procedures and methods detailed in APHA (1998). The clarity (transparency) of water was measured at the sampling sites using a 20 cm black and white Secchi disc. The prawn catch data used in this study were obtained from the Tanzania Fisheries Research Institute (TAFIRI) in Dar es Salaam. The archive contains raw catch data for the commercial prawn fishery for three fishing zones - Bagamoyo, the Rufiji-Mafia Channel, and Kilwa. Since the Rufiji-Mafia Channel is the largest prawn fishing zone; and that no commercial prawn catch data are available in the Channel before 1991, we used all available data for the period 1991 - 2006. The monthly catch data during the prawn fishing season for each year was computed to obtain an annual mean average.

Satellite Data

The strong thermal gradients and primary production associated with the monsoon seasons in the WIO make it particularly amenable to monitoring via satellite remote sensing observations, such as those derived from radiometry and microwave. Sea surface temperate (SST) and Chl-a (Chl-a) data from Moderate Resolution Imaging Spectroradiometer (MODIS) were used to assess trends in warming and primary productivity in the Rufiji-Mafia Channel. MODIS was launched by the National Aeronautics and Space Administration (NASA) in 2002 on board the Aqua satellite platform to study global dynamics including the oceans (David, 2002). MODIS captures data in 36 spectral bands ranging in wavelength from 0.4 um to 14.4 um and at varying spatial resolutions. The MODIS instrument images the entire Earth every 1 to 2 days. Level 3 standard mapped gridded MODIS SST and Chl-a data were obtained from the (SeaWIFS data center that archives and distributes satellite data (http://modis.gsfc.nasa.gov). The monthly gridded data with horizontal resolution of 4 kilometer at the Equator were downloaded in Hierarchical Data Format (HDF). For the purpose of this study only SST and Chl-a gridded MODIS data for Tanzanian coastal waters, where the Rufiji-Mafia Channel is found, were considered, for the period 2000-2014.

Data Processing

Because of the inability of some GIS software to directly read the general purpose Hierarchical Data Format (HDF), the downloaded data were first processed to tab-delimited text data format and remapped using HDFView software that is freely available at the National Center for Supercomputing Applications website (http://hdf.ncsa.uiuc.edu//index.html). The raw data were then converted to spectral reflectance, which is used as a proxy for Chl-a concentration. The conversion process explained above was carried out using the metadata information (spatial resolution; number of rows and columns; no data value; southwest point for longitude and latitude) embedded in the MODIS data.

The physical, chemical, and biological variables, and position information (latitude and longitude) at each sampling station were collected. The satellite chlorophyll concentration at each sampling station was calculated from successive positions for the individual station. Prior to overlay of the gridded Chl-a satellite data on the sampling stations shapefile, the two datasets were transformed and projected to the same geographical coordinate system. The longitude and latitude of each sampling station were first converted into the GIS environment and presented as a point shapefile. The two datasets (gridded satellite of Chl-a and point shapefile) were the transformed into the World Geodetic System of 1984 (GCS WGS 84) and projected to the Universal Transverse Mercator (UTM). To obtain the satellite derived Chl-a value at the sampling locations, a point shapefile of the sampling stations was overlaid on gridded satellite data. Chl-a values from satellite data at each sampled locations were then extracted using the 'extract tool' of ArcGIS's Spatial Analyst Extension Version 10.2 (www.esri.com).

Depth classes and distance of sampling station from the coastline

The water depth at every sampling station in the Channel was recorded using an echo sounder. The recorded depths were then grouped into depth classes which were used to create an ordinal variable of four depth classes; that is 0 – 9.9, 10 - 19.9, 20 - 29.9, and deeper than 30 meters. The relative distances of all in-situ sampling stations from the coastline in the Rufiji-Mafia Channel were computed using a linear referencing method in ArcGIS 10.2 (www.esri.com). The method has an advantage of storing nearest distances of each station using a relative position. The coastline of Channel was used as reference points. Three steps were involved to determine the distances of the sampling stations from the coastline. First, a vector shapefile representing the coastline of the Rufiji-Mafia Channel and its geographical positions was created by tracing the high resolution imagery acquired in 2012. The images were obtained from the National Bureau of Statistics of Tanzania (www.nbs.go.tz). Second, a coastline shapefile was converted to route, which stores both geographical locations and distance from a specified reference location. The distances of each surveyed station from the coastline were exported into a tabular form in ArcGIS. The linear distances of each sampling station to the relative position on the coastline were then estimated using linear referencing tools in ArcGIS. The calculated distances were ordered into classes at intervals of 5 kilometers to obtain three distance classes in kilometers (below 5, 5.1 – 10; above 10).

Statistical Analysis and Trend Estimations

The Chl-a data from both in-situ and satellite measurements, and sea surface temperature (SST) data from satellite data, were checked for errors and cleaned before they were analyzed. Any inaccurate in-situ measurements or those that were mismatched with satellite observations were removed from the analysis. A non-parametric Spearman rank correlation was used to estimate the strength of the association (correlation coefficient) between in-situ and satellite Chl-a data. A Spearman rank correlation was also used to assess the association between the above parameters and catch rate over time. The annual satellite-derived sea surface temperature and Chl-a data did not conform to the assumptions of normal distribution and homoscedasticity (Steven, 2013), and therefore a non-parametric Mann-Kendall trend analysis test was used to assess the trends in Chl-a, sea surface temperature, and the prawn fishery. The Mann-Kendall test was used because it can detect trends even in noisy observations; and has the ability to detect both intra (seasonal) and inter-annual trends in data described with non-normality and heteroscedasticity.

The WIO region has two contrasting seasons that obscure linear trends over longer-time scales. To assess the trends therefore, the monsoon seasons were treated and analyzed separately. First, the satellite derived SST and Chl-a data were broken down into the southeast (June to September) and northeast (November to April) monsoon seasons. Then, the Mann-Kendall test was used to assess the direction of the trends (decreasing or increasing) at a 95% confidence level (Steven, 2013). The inter-annual mean differences in Chl-a, and SST were analyzed with a non-parametric Kruskal-Wallis test - a nonparametric equivalent of the One-Way ANOVA, because the data were non-normal. The difference in mean Chl-a concentration among depth and distance groups was tested using a Tukey HSD test. Statistical analyses were performed in R (version 3.1.2), python (version 2.7), and Matlab (version 8.5). Some of the statistical packages used include EnvStats in R environment; Numpy, scipy and pandas python packages; and the Statistics and Machine Learning toolbox in MATLAB.

Results

Influence of depth and distance on in-situ measured chemical and physical variables

The results of the in-situ measurements for the different parameters and depth levels are presented in Table 1. Most of the sampling stations (75%) were located within shallow waters (i.e. less than 10 meters

Table 1. Descriptive statistics showing the mean ±SD of Chl-a, dissolved oxygen, temperature, ammonia, and water transparency at different depths in the coastal water column of the Rufiji-Mafia Channel for July 2013. Different superscript letters indicate significant differences.

Depth (m)	N	Chl-a (mg/L)	DO (mg/L)	Temperature (°C)	Ammonia (µg/L)	Transparency (m)
0 – 10	6	0.28 ± 0.22^{a}	6.00±0.76	29.34±0.77	0.77±0.41	2.48±2.26
10 – 20	36	0.10 ± 0.01^{b}	6.71±0.52	28.65±0.51	1.14±0.58	10.38±0.75
20 – 30	4	0.26 ± 0.27^{ab}	6.30±0.43	29.03±1.19	1.48±0.17	12.33±4.93
> 30	2	0.15 ± 0.03^{ab}	7.07±0.01	26.83±0.14	0.77±0.07	19.45±1.34

Table 2. Descriptive statistics showing mean ±SD of Chl-a, dissolved oxygen, water temperature, ammonia and water transparency at different distances from the coastline in the Rufiji-Mafia Channel for July 2013. Different superscript letters indicate significant differences.

Distance (km)	Count (N)	Chl (mg/l)	DO (mg/l)	SST (°C)	Ammonia (µg/L)	Transparency (m)
Below 5	5	0.65 ± 0.24^{a}	5.68±0.11	30.02±0.18	0.54±0.04	0.43±0.76
5.1-10	9	0.37 ± 0.20^{b}	6.05±0.18	29.59±0.75	0.55±0.28	3.05±3.12
Above 10	10	0.18 ± 0.12^{b}	6.47±0.40	28.73±0.61	1.12±0.51	6.46±9.66

deep). While water transparency increased with depth in the Channel, Chl-a, dissolved oxygen, temperature and ammonia did not follow any visible trend (Table 1). Chl-a concentration (mean ± SD) varied from 0.28 ±0.22 mg/L in the shallow coastal waters (≤10 m) to 0.10 ±0.01 mg/L in water depths between 10.01 to 20.0 meters. There were significant differences in Chl-a concentrations between depth groups ($X^2_{(3,43)} = 14.68$, $p = 0.002$). However, the differences were only found between the shallower (≤ 10m) and the 10-19.9m depth groups (Tukey HSD test, $p < 0.001$). Dissolved oxygen ranged from 6.00 ±0.76 in shallow waters to 7.07 ±0.01 in water with depths ≥30 meters. While the shallow coastal waters had the highest surface temperature of 29.34 ± 0.77°C, stations in waters with depths above 30 meters had the lowest mean temperature of 26.83 ± 0.14°C. In contrast to temperature, high concentrations of ammonia were found in waters with depth ranging between 20 and 30 meters, and stations in shallow waters of less than 10 meters deep had the lowest concentrations (Table 1).

Table 2 shows mean (±SD) data of Chl-a concentration, dissolved oxygen, water temperature, ammonia, and water clarity at different distances from the coastline. Dissolved oxygen (DO), transparency and ammonia increased with distance from the coastline, while temperature and Chl-a decreased with distance from the coastline. The concentration of ammonia varied between 0.54 µg/L within 5 km from the coastline and 1.12 µg/L for coastal water at distance above 10 km from the coastline. The clarity of the water ranged from 43 cm in water within 5km from the shore to about 6.46 meters for water more than 10 km from the coastline, indicating that water close to shore is turbid, and gradually clears further from the shore. Contrary to DO, ammonia and transparency, sea surface temperature and Chl-a showed high values in waters close to the coastline that decreased with increasing distance from the coastline (Table 2). Chl-a concentrations were significantly different among distance groups ($X^2_{(22)} = 10.97$, $p = 0.004$) where coastal waters located within 5 km from the coastline had significantly higher Chl-a concentration than those above 10km (Tukey HSD test, $p = 0.0035$).

In-situ and satellite derived Chl-a distribution

Chl-a concentration in the Rufiji-Mafia Channel was found to vary non-linearly and significantly with depth ($R^2 = 0.74$, $p < 0.014$; Fig. 2a) and distance from the Rufiji Delta ($R^2 = 0.42$, $p < 0.05$; Fig. 2b). Higher Chl-a values (>0.5mg/L) were found within the top 5 m (Fig. 2a) and within 8km from the coastline (Fig. 2b). Satellite data also indicated that nearshore waters had higher Chl-a concentrations than those further from the coastline (Fig. 3). The areas around the Rufiji Delta (western side of the Channel) had higher Chl-a values than around Mafia Island (eastern side) where pockets of high Chl-a were observed (Fig. 3). Although the in-situ Chl-a values were about

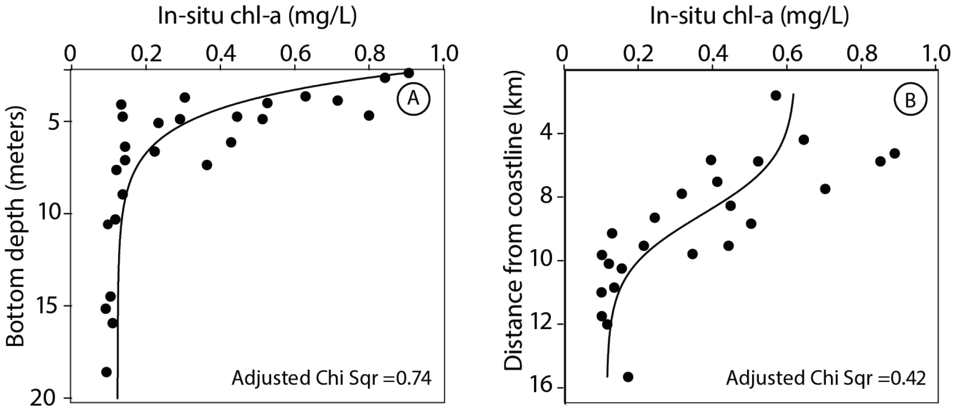

Figure 2. Non-linear plots of in-situ Chl-a data measured in the Rufiji-Mafia Channel plotted as a function of (a) depth and (b) distance from the coastline of the Rufiji River.

9 fold lower than those derived from the satellite data (Table 3), there is reasonably good agreement in large scale patterns of Chl-a concentration of the two datasets. There was a significant correlation between the in-situ and satellite Chl-a concentrations ($R^2 = 0.81$, $p < 0.05$; Fig. 4). The Spearman rank correlation model therefore explained about 81% of the differences in chlorophyll values, which indicates that the in-situ and satellite chlorophyll concentrations were remarkably similar.

Trends in Chl-a, SST and prawn catches in the Rufiji-Mafia Channel

The concentration of chlorophyll from the MODIS satellite data indicated negative trends over time in the Rufiji-Mafia Channel (Table 4, Fig. 5). This decline in Chl-a was observed both in monthly and inter-annual values. The Mann-Kendall test shows a significant annual decreasing trend of Chl-a concentration ($z = 3.52$, $p < 0.05$) and an insignificant decreasing trend at a seasonal scale ($z < 1.98$, $p = 0.30$). Chl-a

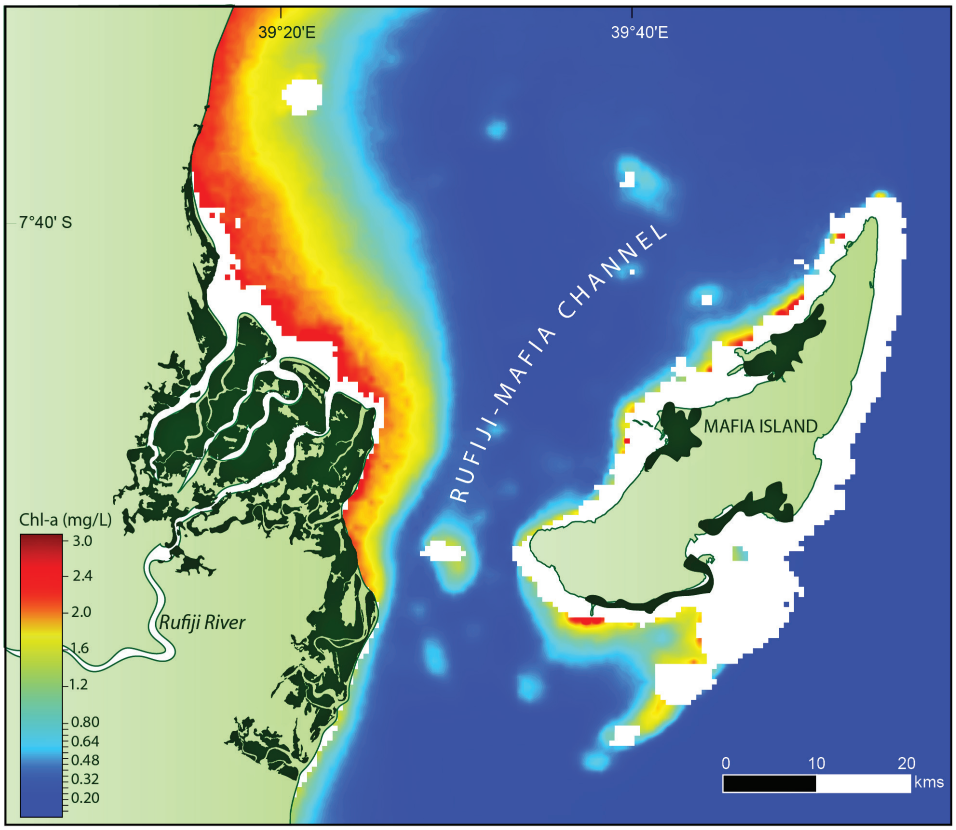

Figure 3. The spatial distribution of satellite derived mean concentration of Chl-a in the Rufiji-Mafia Channel.

Table 3. Summary statistics of minimum, maximum, mean and standard deviation (SD) of in-situ and satellite Chl-a concentration for July 2013.

		Chl-a concentrations (mg/L)		
Source	**n**	**Minimum**	**Maximum**	**Mean ±SD**
In-situ	38	0.09	0.91	0.27 ±0.23
Satellite	38	0.37	4.34	2.40±1.27

concentration showed an annual decreasing rate of 12% from a peak value (0.88mg/l) in 2003 to 0.62 mg/l in 2014 (Fig. 5). On the contrary, SST shows increasing seasonal and annual trends although the trends are insignificant (z ≥0.13, $p \geq 0.43$; Table 4).

The Chl-a concentration across the Channel exhibited both annual and seasonal variability between 2002 and 2014 (Fig. 5). The annual concentration of Chl-a fell from an average of 0.75 mg/l in 2002 to the average of 0.60 mg/l in 2014. The strongest decline in Chl-a concentration occurred between 2003 and 2006. During the same period the concentration of Chl-a also slowed down in the Southeast and Northeast monsoon seasons (Fig. 5a). Both seasons experienced the same pattern of decline between 2002 and 2012. The decline in Chl-a during the southeast season is particularly important as this is the season of high primary production. In 2013, the mean Chl-a concentration increased from 0.61 mg/l to 0.71 mg/l and then fell to 0.65 mg/l in 2014 (Fig. 5a). But the decline of Chl-a concentration during the Northeast monsoon was gradual and reached the lowest average of 0.48 mg/l in 2014. The Hovmoller plot of Chl-a concentration from MODIS satellite is shown in Fig. 5b and represents the period from January 2002 to December 2014. In general, the pattern displayed in the Hovmoller plot suggests the presence high Chl-a concentration during the southeast monsoon season (April and August; Fig. 5b). In contrast, the northeast monsoon season shows the propagation of low Chl-a concentration. A closer look suggests that the onset of the high productivity season in the Channel was shifting during the study period.

Sea surface temperatures (SST) were slightly higher during the northeast monsoon season (Fig. 6a) compared to the southeast monsoon season (Fig. 6b). The northeast monsoon exhibited a decreasing trend in SST between 2002 and 2008, which was followed by a rapid increase in 2009/2010, and then a decrease gradually from 2011 to 2014. In contrast, the southeast monsoon season experienced a gradual increase in SST from 2002 to 2010, then a decrease between 2011 and 2013, followed by a slight increase in 2014 (Fig. 6b). The strength and position of the cold and warm months from 2002 to 2014 are shown in Fig. 7c. The inter-annual variability in temperature during the study period was insignificant, but SST in cold water months (June-September) were getting warmer over time (Figure 6c). This is consistent with increasing trend in SST during the southeast monsoon season (Fig. 6b).

Similar to Chl-a concentration, the prawn catch rates in the Rufiji-Mafia Channel showed an annual decreasing trend. The catch rates of the prawn fishery showed a monotonic decreasing trend, where catch rates declined from a peak (62 kg/hour) in 1991 to below 23kg/hour in 2006 (Fig. 7). The catches declined by more than 50% during the study period (Mann-Kendall test, *tau* = -57, p <0.05), suggesting a significant decreasing trend in the annual prawn catch rates. Applying a non-parametric Spearman linear fit to the annual prawn catch rates over the study period yields a strong negative association (Fig. 7), suggesting a significant catch decline of about 81% since 1991 (rho = 0.81, p < 0.001). This indicates that the oceanographic processes driving the Chl-a trends may also be affecting prawn production.

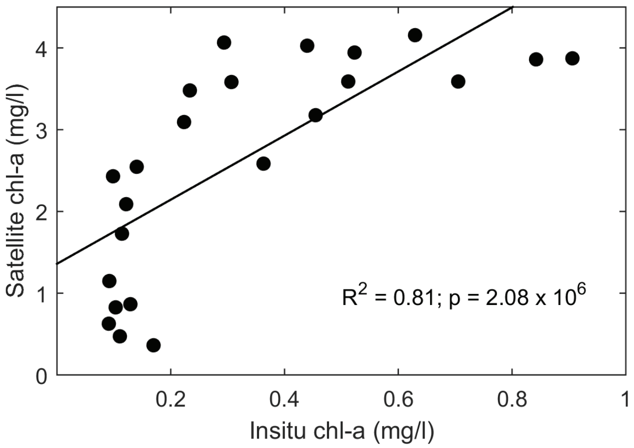

Figure 4. The association between in-situ and satellite Chl-a concentration in the Rufiji-Mafia Channel during the southeast monsoon season. The association used satellite Chl-a acquired on July, 2013, a time during which in-situ measurements were conducted.

Table 4. Mann-Kendall (*tau*) test results showing monthly and annual trends in Chl-a concentration and sea surface temperatures in the Rufiji-Mafia Channel.

		Monthly Trend			Annual Trend		
Variable	**n**	***tau***	***Z***	***p***	***tau***	***Z***	***p***
SST	156	0.09	0.13	0.5	0.02	0.43	0.66
Chl-a	156	-0.27	3.84e-6	0.302	-1.19	-3.52	<0.05

Z= Mann-Kendall Trend Statistic

Discussion

In this study we assessed, for the first time, spatial and temporal patterns in phytoplankton biomass (measured as Chl-a concentration) in relation to selected environmental variables and distance from the shoreline in the Rufiji-Mafia Channel in Tanzania. We also attempted to find seasonal and annual trends in primary production and sea surface temperature in the Channel in order to unveil the underlying processes causing the dwindling prawn harvests in the Channel. By combining ocean colour satellite data with in-situ measured Chl-a concentration, we showed a trend of decreasing phytoplankton biomass. Both the northeast and the southeast monsoon seasons showed a decreasing trend in Chl-a concentration. However, it is the southeast monsoon season, which is the high productive season, that showed a significant decline in phytoplankton biomass. The phytoplankton biomass in the Rufiji-Mafia Channel has declined at a rate of 12% between 2002 and 2014. This declining trend is in agreement with recent findings on the large-scale declines in phytoplankton biomass in the WIO region (Kyewalyanga, 2015; Roxy *et al.*, 2016), the Indo-Pacific region (Mélin, 2016; Wernand *et al.*, 2013), and the Northern hemisphere (Boyce *et al.*, 2010; Boyce *et al.*, 2012; Boyce *et al.*, 2014), but it is noted that Rykaczewski and Dunne (2011) and Wernand *et al.* (2013) have different views on declining chlorophyll in the Northern hemisphere. Moreover, a recent study led by NASA found that the population of phytoplankton

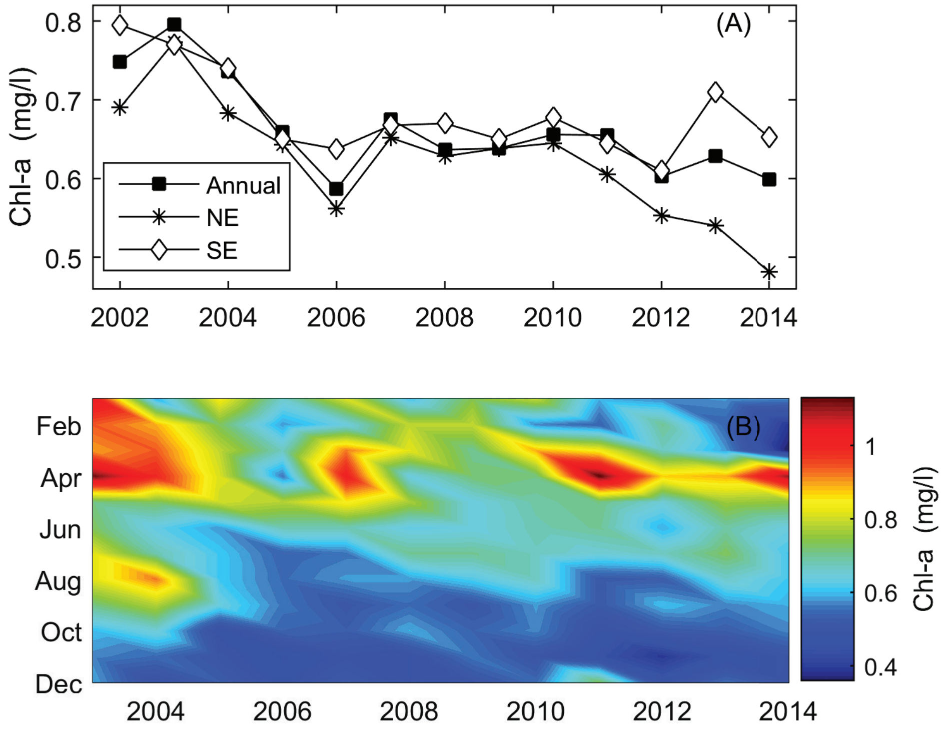

Figure 5. Evolution in satellite derived Chl-a concentrations between 2002 and 2014 for the Rufiji-Mafia Channel derived from MODIS Aqua satellite showing (A) annual variability, inter-annual trend during the Northeast monsoon season (October – April), inter-annual trend in the Southeast monsoon season (May – September) and (B) Hovmoller diagramme, which represents inter-annual and monthly change in Chl-a concentration.

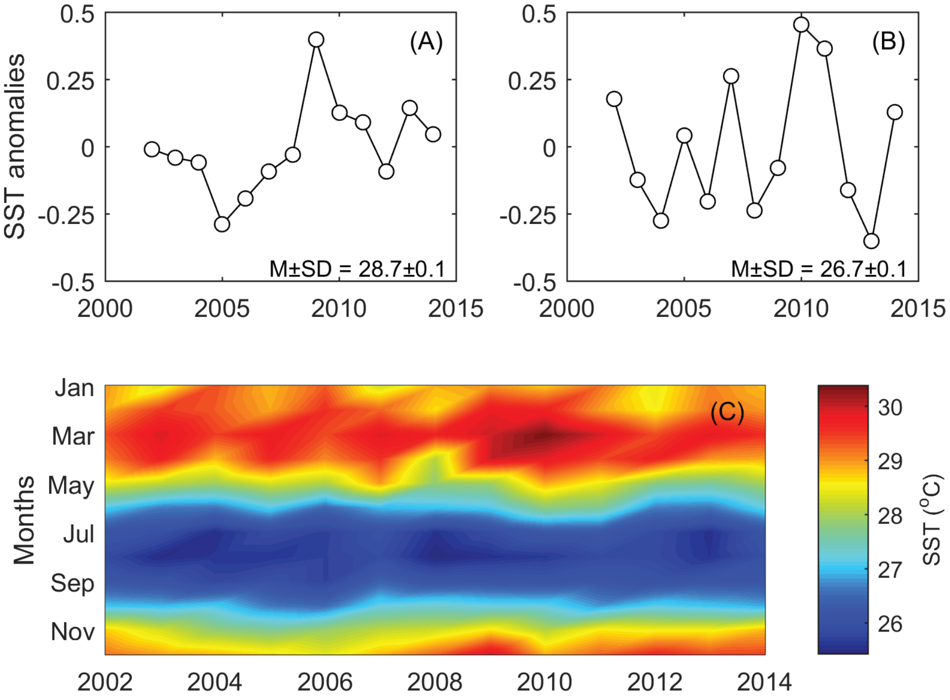

Figure 6. Climatological sea surface temperature (SST) between 2002 and 2014 derived from MODIS Aqua satellite showing (A) inter-annual SST anomaly during the northeast monsoon season (October–April), (B) inter-annual anomaly in southwest monsoon season (May – September) and (C) Hovmoller diagramme combining inter-annual and monthly sea surface temperature in the Rufiji-Mafia Channel.

have decreased in recent years (Kevin *et al.*, 2015), further supporting our findings. The decline in chlorophyll is not a worldwide phenomenon however, since some oceans have registered increasing trends (e.g. Atlantic, Mediterranean and the China Sea; Wernand *et al.*, 2013).

Phytoplankton production is influenced by several factors among which nutrient availablity, circulation, irradiance, water column stability and temperature are key (Barlow *et al.*, 2007). The Rufiji-Mafia Channel receives about 35,000 mm^3/yr and about 17 million tons/yr of water and sediment respectively, from the Rufiji River (Temple *et al.*, 1972; UNEP and WIOMSA, 2009). With agricultural intensification, which uses large quantities of chemical fertilizers, the Rufiji River is influencing the nutrients balance of the Channel. The nutrients that enter the ocean are often trapped in the nearshore zones, thereby enhancing productivity of the mangroves and the nearshore waters (Francis, 1992). Nonetheless, our data indicate that relatively higher ammonia concentrations were present in deep offshore waters as compared to inshore areas. This can be explained by higher nutrient turnover and uptake by phytoplankton, or remineralization, in inshore waters than is the case for offshore waters which are more likely to be stratified and less mixed. The present study found that nearshore areas and shallow waters had relatively higher Chl-a concentrations than distant and relatively deep offshore waters, which are less influenced by the discharge of nutrients-rich water from the Rufiji River.

While the nutrient input favours phytoplankton growth, the declining phytoplankton biomass does not agree follow this logic. Therefore, a different driver of phytoplankton production must be playing an accessory role to cause the observed decline. Local climate can induce variations around these long-term trends, and coastal processes such as land runoff from the Rufiji River may modify Chl-a trends in nearshore waters of the Channel. Multiple lines of evidence suggest that the linear drop in phytoplankton biomass during the study period is generally related to climatic and oceanographic variability, particularly to increasing SST over the past century.

This study also reports an increasing annual trend in SST data within the study area. The annual mean SST has increased from 27.17 °C in 2002 to 28.66 °C in 2014, indicating a 1.49 °C increase in temperature for that period. The cause-and-effect of high temperatures in oceans may not be simple or straight forward. However, high temperatures can affect the physiological function and behavior of phytoplankton. High irradiance for example can cause photo-inhibition where phytoplankton primary production is affected, resulting is low Chl-a concentrations (Kyewalyanga, 2015; Roxy *et al.*, 2016).

Phytoplankton have evolved taxon-specific pigments that can readily change in different light environment (Barlow *et al.*, 2007). For example, phytoplankton have photoprotective carotenoids that are prominent in surface, high temperature, and low-chlorophyll waters (Barlow *et al.*, 2007; Vidussi *et al.*, 2001). Also, high temperatures can increase water column stability, thereby locking nutrient supply and regeneration into the photic zone where primary production takes place. The negative effects of SST on the Chl-a trend is particularly pronounced in tropical and subtropical oceans, where increasing stratification of the water column limits nutrient supply into the productive layer (Barlow *et al.*, 2007). Phytoplankton production is the base of all marine biological resources and an important source of energy and carbon flows in oceans (Hu *et al.*, 2014). However, with the current projections of climate change (IPCC 2014) and the trend in global warming (IPCC 2014), much more reduction in phytoplankton production can be expected (Roxy *et al.*, 2016), which will have unprecedented consequences on the productivity of the world's major ecosystems and fisheries.

Tanzania's prawn fishery industry was the most important of the marine fisheries in terms of income and export value (de la Torre-Castro *et al.*, 2014; Jiddawi and Ohman, 2002). It also provided employment and income to fishers and business people, therefore making an important contribution to the gross domestic product (de la Torre-Castro *et al.*, 2014; Eriksson *et al.*, 2015; Frocklin *et al.*, 2013). The Rufiji-Mafia Channel was a rich prawn fishing ground which used to contribute over 80% of the prawn catches in Tanzania (Erftemeijer and Hamerlynck, 2005; Jiddawi and Ohman, 2002). High catches were primarily a result of high primary productivity in the Channel that receives terrestial nutrients inputs from the Rufiji River (Jury *et al.*, 2010). Mangroves and nearshore shallow habitats are known to be important nursery grounds for fish and prawns (Kimirei *et al.*, 2011; Kimirei *et al.*, 2016). The decrease of phytoplankton productivity in these habitats would indeed have great consequence on both recruitment and reproduction of prawn populations. In 2008, the Tanzania Fisheries Research Institute reported a serious decline in prawn stocks and by-catches (MLFD, 2012). The decline in catches of prawn was linked to high levels of resource exploitation, leading to the closure of the prawn fishery for two years, to allow for the overexploited stocks to recover (MLFD, 2012).

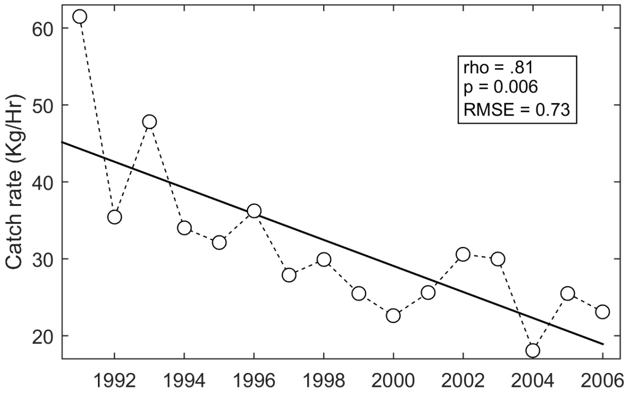

Figure 7. Annual mean catch rates of the prawn fishery in coastal waters of Tanzania between 1991 and 2006 showing a decreasing trend in catches and a negative relationship of catches over time.

Despite two years of closing the commercial prawn fishery from 2008 onwards, a stock assessment carried out in 2011 found no signs of recovery; to the contrary the situation has even worsened. Hence the then Ministry of Livestock and Fisheries Development decided on a total closure of all trawl fisheries in 2012. As reduction of the fishing pressure during two years of the closure did not yield the expected results, therefore other factors may be contributing to the reduced catch rates of prawns in the Channel. The decline in phytoplankton biomass, the food base for marine ecosystem, is probably another factor among many that could explain failure in prawn stock recovery. This illustrates that, although the importance of reducing fishing pressure is surely an important measure, it is also important to understand all potential causative factors, among which a decline in Chl-a (a proxy of primary productivity) could be important.

Although our study focused mainly on primary production, there are other factors such as fishing effort, especially by artisanal fishers who fish in non-trawlable areas close to shore, river runoff and discharges, changes in surface water circulation, and larval and post larval recruitment that play important roles in affecting prawn abundance. We acknowledge that these factors were not considered in this study, which would have painted a much clearer picture of the situation. Nonetheless, the results of this study clearly show that the decline in phytoplankton biomass and prawn catches are directly related. We are confident that the results can inform policy for the management of the prawn fishery in Tanzania.

Ocean colour remote sensing has been shown to be an important tool for monitoring and managing coastal and marine resource at reasonable spatial and temporal scales, particularly in data poor coastal areas like the Rufiji-Mafia Channel. This is because satellites have the ability to observe large areas at relatively short time intervals which makes it easy to analyze the spatial patterns and relations, rather than using localized in-situ measurement alone. This allows better and meaningful understanding of phytoplankton dynamics rather than relying on the conventional techniques alone. Unfortunately, the chlorophyll concentration discerned by satellites is only a gross indicator of a multitude of phytoplankton species which have a fairly diverse response to the environment (Roxy *et al.*, 2016). Because the Rufiji River discharges nutrient-rich water into the Channel, there is a need to calibrate satellite observations with in-situ measurement because satellites tend to overestimate chlorophyll biomass, especially in coastal waters (Reinart *et al.*, 2011).

The same tendency was also observed in our in-situ and satellite derived Chl-a concentration. When compared, the mean concentration of Chl-a derived from satellite was significantly higher than in-situ measurements. However, it is important to note that the discrepancy in the in-situ Chl-a readings and satellite estimates could be due to unavoidable errors caused by suspended solids (mainly sediments) and regional climatological bias (Mélin, 2016). Nevertheless, satellite data and in-situ observation used in this study provide for the first time evidence of a potential link between the declining trends in primary production in the Rufiji-Mafia Channel and the dwindling commercial prawn fishery catches.

The advances in ocean colour sensor technology and derived data in recent years, especially for coastal remote sensing has helped to understand the functioning of coastal ecosystems. The MODIS sensors provide valuable spatial and temporal information about the Rufiji-Mafia Channel, which is not easily recorded with the field observations. Throughout the Channel, MODIS satellite data showed that the mean chlorophyll concentration is generally high in the delta and near the shore. These data allow for the exploration of coastal and marine areas to identify particular environmental problems in ways that are not possible by means of in-situ measurement. Overall, a comparison of in-situ and satellite observations of Chl-a suggests that MODIS data is able to simulate the spatial and seasonal dynamics of primary productivity of the Rufiji-Mafia Channel with satisfactory accuracy, although some discrepancies were identified. Therefore, by combining satellite data and in-situ measurements in models, we can further improve our understanding of the Rufiji-Mafia Channel in a holistic manner, which can be used for spatial planning and devising best management options for coastal ecosystems within and even outside the Channel.

Acknowledgements

This study was funded by a grant from the Interfaculty Council for Development Cooperation (IRO) of the KU Leuven. The authors also wish to thank WIO-RISE for financial support for the in-situ data collection and laboratory analysis. Specifically we thank the Institute of Marine Sciences (IMS), Zanzibar for the technical assistance and research equipment; the Mafia Island Marine Park Administration for permission to use their research boat and collect data inside the Marine Park. We are also grateful to Mr. Mwadini of IMS for laboratory analysis of water samples.

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