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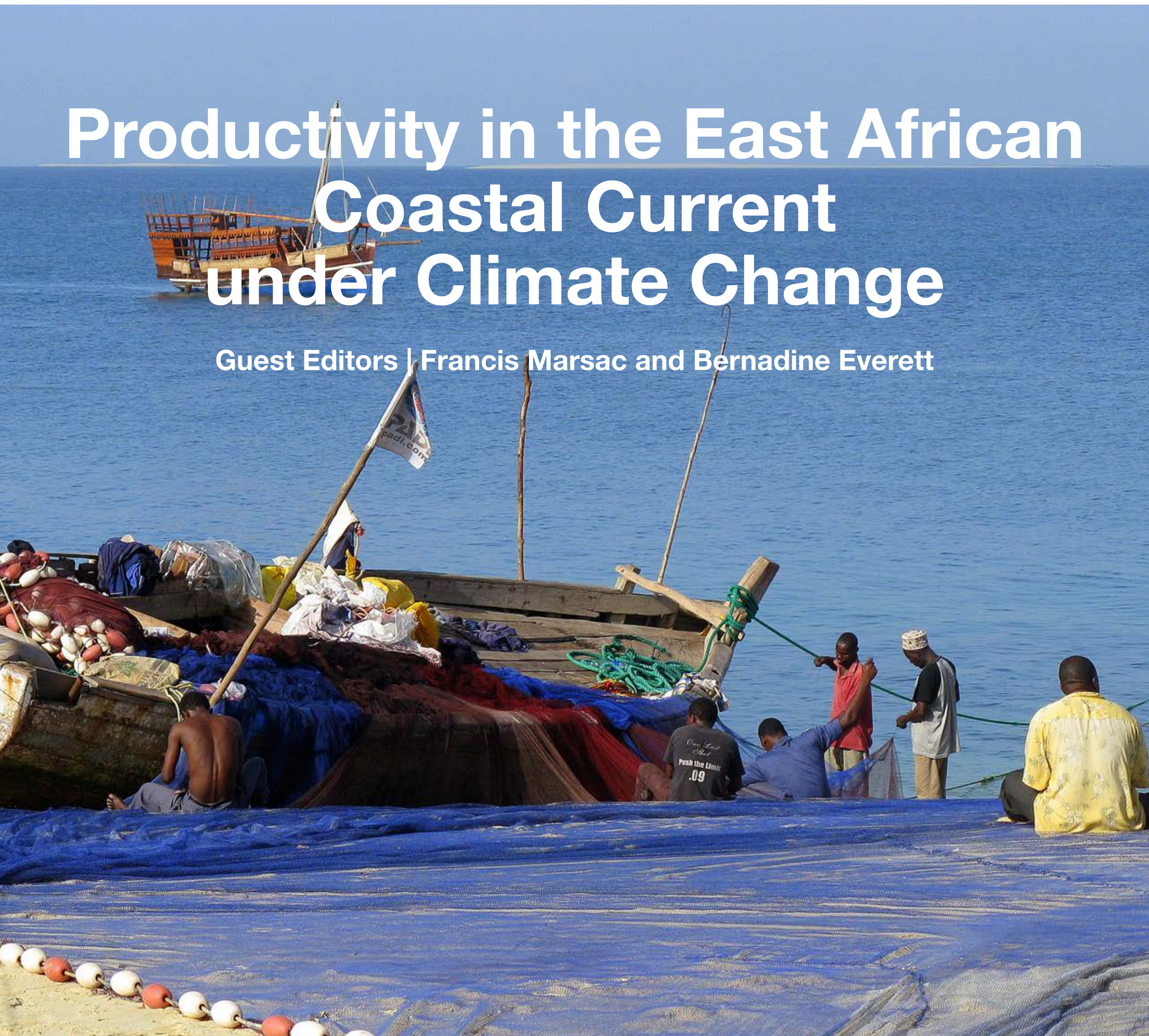
Productivity in the East African Coastal Current under Climate Change

Guest Editors | Francis Marsac and Bernadine Everett



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Employing multivariate analysis to determine the drivers of productivity on the North Kenya Bank and in Kenyan territorial waters

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Abstract

A complex mix of natural processes exist in nearshore and offshore waters which influence coastal and marine ecosystem productivity. An understanding of the biogeochemical processes involved is a key element in interdisciplinary studies of primary production, oceanic flux and storage of carbon dioxide. Water circulation in the East African region is influenced by coastal currents driven by monsoon winds. There are four oceanic currents influencing Kenya's coastal waters; namely the East African Coastal Current, the Somali Current, the Southern Equatorial Current and the Equatorial Counter Current. The Kenyan fishing industry is slowly embracing offshore fishing grounds, and the North Kenya Bank is emerging as the next fishery frontier. This study aims to provide insight on the processes driving the productivity of Kenya's territorial waters. The variable Si* (the difference between available silicate [$Si(OH)_4$] and nitrate [NO_3^-]) was employed as a proxy of upwelling. It was highly positively correlated to chlorophyll-a, indicating that upwelling is a major phenomenon driving productivity in Kenyan territorial waters. Particulate Organic Carbon (POC) and Dissolved Oxygen (DO) exhibited a lesser positive correlation with chlorophyll-a, implying that remineralization also has some influence in the productivity of the area.

Keywords: Nitrate, Silicate, Productivity, Kenya, North Kenya Bank

Introduction

The marine fishery within the East African region provides a critical source of food security and livelihoods to coastal communities, as is the case in many developing countries around the world (Fondo, 2004; Munga, 2013; Kiilu *et al.,* 2019; Le Manach *et al.,* 2015; Zeller *et al.,* 2014). The western Indian Ocean region has a rich fisheries resource presumed to be dependent on wind driven upwelling systems (Kiilu *et al.,* 2019). Coastal upwelling is often associated with increased productivity of both primary producers and small pelagic fishes (McClanahan, 1988). Johnson *et al.* (1982) postulated that the deflection of the East African Coastal Current (EACC) seawards at its point of convergence with the Somali Current (SC) is mainly due to topographic forcing on the North Kenyan Bank (NKB). Similarly, Gallienne and Smythe-Wright (2005) attributed the large levels of zooplankton biomass observed in the Mascarene Basin to the east, to topographic forcing causing turbulence, as the Plateau obstructs the flow of the South Equatorial Current (SEC). A study by Jacobs *et al.* (2020) further demonstrated that some degree of wind-driven coastal upwelling occurs along the wider Kenyan coastline every year during the months of the North East Monsoon (NEM).

Studies have associated abiotic and biotic factors with the productivity of a system. It has been reported that for about 90 % of the ocean surface, primary production at the euphotic layer is almost certainly limited

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by the supply of nutrients, especially nitrate (N) and (P) (Nifong and Silliman, 2017). Globally, nitrogen and phosphorus are the two elements that potentially limit the biologically mediated assimilation of carbon in the oceans by photoautotrophs. Consequently, a major part of primary production is considered to be supported by upwelling of deep waters rich in N and P (Broecker and Peng, 1972).

Studies conducted in Kenyan coastal waters by Jacobs *et al.* (2020) employing the NEMO (Nucleus for European Modelling of the Ocean) model with a biogeochemistry component represented by an embedded MEDUSA-2 model, postulated a water column-integrated primary production, with a maximum productivity rate of up to 1.5 g C/m^{-2}/day over the NKB, which was aligned with a high nutrient availability associated with upwelling. The SC and the EACC converge during the NEM, and flow away from the coast to form the SECC. This induces the upwelling of cold, nutrient-rich waters, which are brought up from the deep waters to the surface, resulting in the NKB being a highly productive area (Jacobs *et al.,* 2020). Enhanced upwelling events, associated with cool temperatures, result in elevated productivity.

In addition to nutrient availability, ocean productivity is to a large extent limited by physicochemical parameters; mainly temperature, salinity, and light (Lathuiliere *et al.,* 2011, Broecker and Peng, 1972). However, light penetration is not a limiting factor in the photic zone within the tropical region where consumption of nitrate by phytoplankton renders the sunlit ocean devoid of nitrate. Nitrate, however, increases rapidly with depth in the underlying region, where it is resupplied through the remineralization of organic matter (Broecker and Peng, 1972). Biogeochemical processes such as the production and decomposition of biogenic organic matter and the sinking of particulate matter determine the distribution of nutrients in the ocean (Hirose and Kamiya, 2003). The vertical supply of nitrate to the surface ocean depends not only on the vertical transport induced by dynamical processes like turbulent entrainment, Ekman pumping, and frontal and eddy-induced upwelling, but also on the vertical gradient of nitrate (Mahadevan, 2014; Omand and Mahadevan, 2015). Further, it depends on the depth from which nitrate needs to be drawn (Omand and Mahadevan, 2015).

The study area is relatively shallow (200-1500 m) and can be construed to experience faster nutrient replenishment due to the shorter migration distances from the sediment source. The area is however assumed to hold low nutrients due mainly to the high productivity associated with optimal physical parameters leading to high nutrient depletion, complicating the use of nutrients as a productivity proxy.

This study therefore seeks to employ a multivariate model to investigate the parameters that drive productivity within the study area by relating the concentration of chlorophyll-a with parameters presumed to enhance its production. Variation in primary productivity, measured typically as the concentration of *chlorophyll-a* in water, is a primary determinant of all biological productivity up the food web and trophic pyramid (Jacobs *et al.,* 2020; Weeks and Shillington, 1996; Lutjeharms, 1985).

Materials and methods

Study Area

The study site spans across the entire coastline encompassing the territorial waters of Kenya (Fig. 1). This region was presumed to experience high productivity due to wind driven upwelling systems. The territorial waters extend from a latitude of about 4.5 degrees South (towards the Tanzania boarder) to about 1.5 degrees South (towards the Somali boarder).

These areas experience the influence of the north flowing EACC (Fig. 2). The velocity of the EACC varies between 0.5 to 2 m/s, flowing more rapidly during the South East Monsoon (SEM) season and slower during the NEM season (Schott and McCreary, 2001; Swallow *et al.,* 1983; Swallow *et al.,* 1991).

During the NEM, the SC reverses and flows southward at speeds of 0.5–1 ms^{-1} (Leetmaa *et al*., 1982; Molinari *et al*., 1990). It then meets the northward flowing EACC to form a confluence zone at 2–4°S, before the flow veers offshore as the eastward flowing SECC (Shenoi *et al*., 1999; Schott and McCreary, 2001; Schott *et al*., 2009). This offshore flow leads to divergence at the coast. To ensure continuity of mass, the flow results in the upwelling of cold, nutrient-rich deeper waters (Kabanova, 1968; Liao *et al*., 2017).

Methodology

Water samples were collected within the territorial waters of Kenya in the month of January, 2017 at the stations indicated in Fig. 1. The samples were collected from the RV Mtafiti with Niskin bottles at depth intervals of 20m to a maximum depth of

300 m. Physicochemical parameters were measured using a Sea-Bird CTD (SBE 19 plus V2 SeaCAT CTD) equipped with a SBE 63 Optical dissolved oxygen Sensor, and a SBE 27 pH/O.R.P pH meter. Temperature was measured in ITS-90 degrees Celsius (°C), while the measure of conductivity, temperature, and pressure provided for the calculation of the amount of dissolved salts in the water – the salinity. Quality control on dissolved oxygen (DO) measurements was carried out using a representative sample for DO and the Winkler method (Parsons *et al*., 1984).

Nutrient samples were collected in 100 ml polyethylene bottles pre-rinsed in 10 % HCl, after which the samples were stored in a freezer awaiting analysis in the laboratory. Particulate organic carbon samples were obtained by filtering a 3 l water sample through glass fiber (GF/F) filters pre-combusted in a muffle furnace for 4 hours at 500 °C, and the filtrate stored at -20 °C to await analysis. Three litre samples for chlorophyll-a analysis were collected in pre-rinsed plastic bottles and filtered under vacuum onto 25mmWhatman GF/F (glass fibre filter) paper (Parsons *et al.,* 1984). The filtrate on the filter papers were enclosed in aluminium foil pouches and frozen to await analysis in the laboratory. Chlorophyll-a was measured on a spectrophotometer (Thermo Fisher Scientific Model Genesys 10S; USA make) after extraction in 90 % acetone. Nutrient samples were analysed in the laboratory using a four-channel auto-analyzer (Seal QUAATRO Auto Analyzer), while Particulate Organic Carbon (POC) samples were analyzed through the dichromate

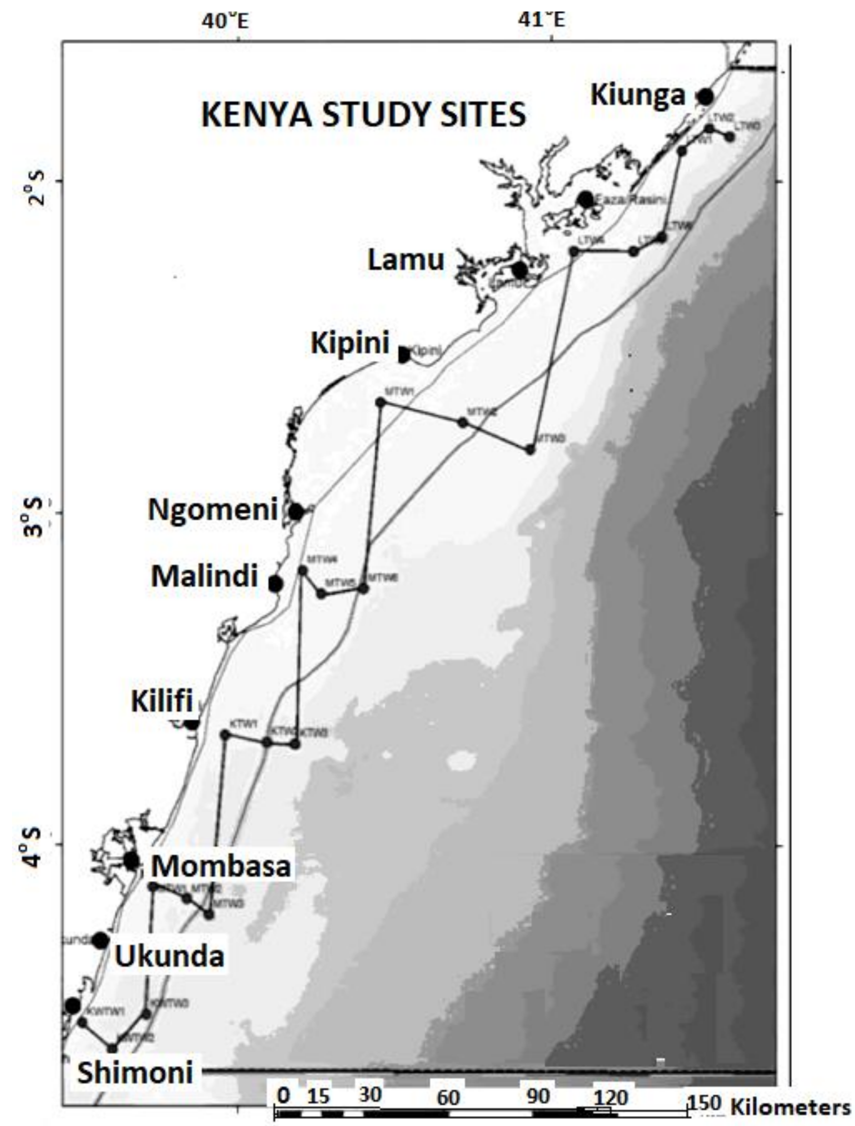

Figure 1. Map showing the sampling sites within Kenyan territorial waters.

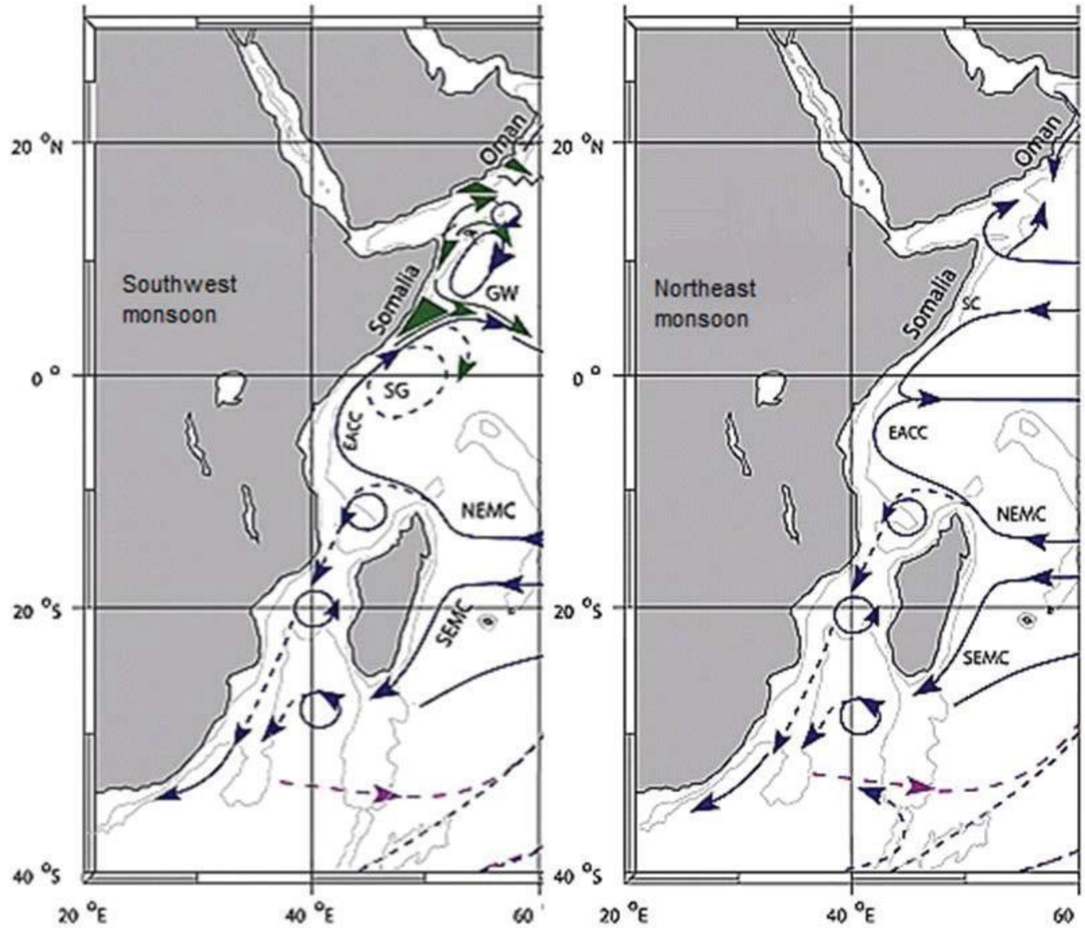

Figure 2. Schematic representation of identified current branches during the southwest and northeast monsoons in the western Indian Ocean region. Current branches shown include the South Equatorial Current (SEC), South Equatorial Counter Current (SECC), Northeast and Southeast Madagascar Current (NEMC and SEMC), East African Coastal Current (EACC), Somali Current (SC), Southern Gyre (SG) and Great Whirl (GW), Southwest and Northeast Monsoon Currents (SEMC and NEMC) (Adapted from Schott *et al*., 2009)

redox colorimetric method. The dichromate redox colorimetric method utilizes the formation of the green Cr III species resulting from the reduction of the orange dichromate (Cr VI) species. The amount of dichromate consumed is determined against a set of standards and measured on a spectrophotometer in the visual range.

Statistical analysis

The data was analysed statistically using Statistica 8.0 software. Variables with values above 10 were log transformed to normalize the data. Principle component analysis was the multivariate method of choice. In principle component analysis (PCA), straight lines are sought that best fit the clouds of points in the vector spaces (of variables and cases), according to the least squares criterion. This in turn yields the principal components (factors) that result into the maximum sums of squares for the orthogonal projections. Consequently, a lower dimensional vector subspace is recovered, that represents the original vector space (Miranda *et al.,* 2008). Factor coordinates of the variables also referred to as 'factor loadings' are the correlations between the variable and the factor axes. Mathematically speaking, a principal component is a linear combination of the variables that are most correlated with that component. The first factor holds a higher correlation between the variables than the second factor does. This is to be expected because these factors are extracted successively and will account for less and less variance overall (Miranda *et al.*, 2008).

Mean subtraction ("mean centering") is necessary for performing PCA to ensure that the first principal component describes the direction of maximum variance. If mean subtraction is not performed, the first principal component will instead correspond to the mean of the data. A mean of zero is needed for finding a basis that minimizes the mean square error of the approximation of the data (Miranda *et al.*, 2008) Assuming zero empirical mean (the empirical mean of the distribution has been subtracted from the data set), the principal component w_1 of a data set x can be defined as:

$$\mathbf{w}_1 = \underset{\|\mathbf{w}\|=1}{\arg\max} \operatorname{Var}\{\mathbf{w}^T\mathbf{x}\} = \underset{\|\mathbf{w}\|=1}{\arg\max} E\left\{\left(\mathbf{w}^T\mathbf{x}\right)^2\right\}$$

Results and discussions

Multivariate analysis was employed to identify the oceanographic parameters influencing the productivity in the study area as well as to capture the influencing biogeochemical processes. The data was analysed by PCA using Statistica 8.0 software and is presented as a projection of variables on factor-planes, as factor coordinates of variables, and as 3D surface plots (Fig. 3 to 6; Table 1). PCA allows summarising and visualisation of the information in a space containing observations described by multiple inter-correlated quantitative variables. Thus, PCA extracts the important information from a multivariate data table and generates a set of fewer new variables called 'principal components/factor axis'. The information in a given data set corresponds to the 'total variation' it contains. The goal of PCA is to identify directions (or principal components) along which the variation in the data is maximal. In the PCA model a zero loading means that the variable does not contribute to the component shown. The uniqueness of a variable is described by values near 1.0, indicating variables that are tending to measure unique properties in the data set.

Figure 3 presents a projection of variables on the 1x2 factor-plane; the variables on the factor coordinates are in reference to their relation to the grouping variable chlorophyll-a. Employing chlorophyll-a as a grouping variable enables the PCA to relate all the variables relative to chlorophyll-a. Factor axis 1 describes 27 % of the interaction of chlorophyll-a with the measured variables.

Biogeochemical processes provide key information in a study area and can be applied to understand the processes influencing productivity of a system. The ocean is expansive and the use of models and proxies helps researchers to better understand the functioning of a system. Signatures that indicate deep water influx/upwelling are important in understanding productivity drivers. The current study employed Si* (the difference between available silicate [Si(OH)4] and nitrate [NO_3^-] to study upwelling. Sarmiento *et al.* (2004) used Si* as a tracer of the return path of deep waters upwelled into the thermoclines of ocean systems. The rational is that when

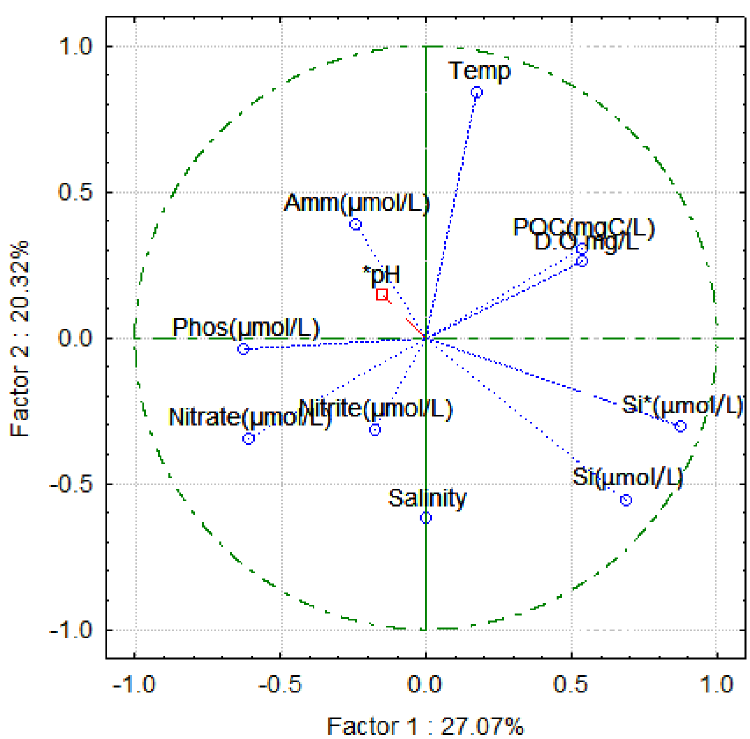

Figure 3. PCA analysis showing projection of variables on the factor-plane (1x2) with chlorophyll-a being the grouping variable.

Table. 1 Factor axis 1x2 of variables with chlorophyll-a as the grouping variable

Variable	Factor 1	Factor 2
Salinity	-0.004425	-0.619442
Temp	0.172199	0.842886
Nitrate(µmol/)	-0.613951	-0.345378
Nitrite(µmol/)	-0.179145	-0.314980
Amm(µmol/)	-0.244941	0.392273
Phos(µmol//L)	-0.626469	-0.037617
Si(µmol/L)	0.687051	-0.554896
Si*(µmol/L)	0.875168	-0.305875
POC(mgC/L)	0.532628	0.307775
DO mg/l	0.542712	0.260109

sufficient light and nutrients (including iron) are available, diatoms accumulate biomass with silicate and nitrate at a molar ratio of 1:1. In the deep near bottom layers of the ocean the dissolved Si concentration tends to increase more relative to that of nitrate, this being associated with the continued dissolution of skeletal opal, under high pressures (Kumar, 2006). Similarliy, Da' vila *et. al.* (2002) reported the influx of continental waters rich in dissolved silicate (DSi) and inherently poor in inorganic nitrogen (Perakis and Hedin, 2002; Huygens *et al*., 2008; Vargas *et al*., 2010). Whereas, Grasse *et al*. (2016) observed that waters on the shelf showed high Si $(OH)_4$ concentrations as a consequence of intense Si remineralization in the deep waters.

A cruise conducted by RV. Mtafiti within Kenyan waters observed dominant phytoplankton species to consist of diatoms *Chaetoceros* sp and *Rhizosolenia* sp (KMFRI, 2018). These ultimately add to the biotic particle flux to the bottom waters, while the Si pool is further enhanced by an annual terrigenous riverline sediment influx of around 7 million tonnes (Kitheka *et al.,* 2005).

The current study found the signature to be highly positively correlated to chlorophyll-a, the grouping variable along factor 1, employing the variable Si* as a proxy of upwelling (Fig. 3; Table 1). This indicates that upwelling is an important phenomenon driving productivity in the study area.

Seim and Gregg (1997) reported that topographic constrictions influence the basin circulation affecting the transport of dissolved nutrients between the basins separated by the topographic feature. The steep topographic elevation within Kenyan territorial waters as well as at the NKB could be influencing upward water movement/upwelling. Further, Jacobs *et al.* (2020), employing satellite imagery, documented high chlorophyll concentrations of up to 1 mg m^{-3} over the NKB, associated with colder waters (25.8 °C), in comparison to the background values of ~0.5 mg m^{-3} at ~26.5 °C in the surrounding waters. This is a clear cold productive signal, indicative of upwelling of cool, deep waters.

Further to the high Si* correlation, two other variables (POC and DO) were also significantly positively correlated to chlorophyll-a on the factor axis 2 (Fig. 3; Table 1), implying that POC remineralization also has some influence in the region's productivity. A novel study by Cavan *et al*. (2017) conducted the first ever observations of respiration rates (k) on slow-sinking particles, with k previously having only been measured on large, fast-sinking particles. Their study determined novel estimates of slow sinking POC turnover which were significantly higher (t ¼ 5.56) than the fast sinking particle turnover. They observed at least an order of magnitude difference in the rate at which the two fractions are turned over by microbes with 99 % of the carbon in the slow-sinking particles (POC) potentially being completely remineralized in less than a day. A similar level of degradation for fast-sinking particles took 36 days. The association of higher chlorophyll-a to high POC and DO concentrations can therefore be attributed to elevated microbial activity on POC boosted by high DO. The remineralized POC essentially releases nutrients to the ecosystem thus enhancing chlorophyll-a production.

The nitrate levels in the study area were negatively correlated in both factor axes, implying an inverse correlation to the productivity proxy chlorophyll-a. This may be due to the fact that the photic zone within the tropical region is not limited by light penetration and as such the nutrient consumption by phytoplankton is high, resulting in the water registering low nutrient levels (Omand and Mahadevan, 2015). Therefore, whereas the ocean productivity might be high, the nutrient content of the waters is low. It is also interesting to note that nitrate was highly negatively correlated (-0.6; see Table. 1) on factor axis 1 while corresponding to a high positive Si*correlation (0.87; see Table 1). The high Si* correlation to chlorophyll-a is indicative of high productivity. Si* is also associated with upwelling which is characterized by cool nutrient rich waters. Nutrients are essential for the occurrence of high productivity. The results of this study suggests high nutrient consumption as previously hypothesised, with low nutrient levels recorded in water samples, and an inverse correlation of nitrate to chlorophyll-a.

Figure 4 corroborates that chlorophyll-a was found to be directly proportional to Si* in this study. This is shown by the chlorophyll-a peak corresponding to the highest Si* values. Of interest is the high nitrate levels associated with high Si* levels. Upwelling is associated with the upward flow of cool nutrient rich waters, and since Si* is a proxy for upwelling, the above relationship might be indicative of nitrate also being associated with upwelled waters.

Figure 5 suggests that chlorophyll-a increases with decreasing phosphate levels, which is not the case, but could be a sign that high productivity puts a demand on phosphate, making it a limiting factor. A major part of primary production is considered to be supported by upwelling of deep waters rich in N and P. It is suggested that a limiting factor controlling primary production in the subtropical and tropical oceans is inorganic N and P (Falkowski, 1997; Capone *et al.*, 1997). The information in Table 1 further alludes to this in factor axis 1 where Si* was highly correlated to chlorophyll-a, while phosphate and nitrate were negatively correlated by similar values (-0.6). Since Si* is associated with upwelling and upwelling is associated with high productivity, the inverse relation of P and N, to chlorophyll-a could be due to their consumption by phytoplankton leading to depletion (Omand and Mahadevan, 2015).

High DO levels corresponded to high chlorophyll-a as observed in Fig. 6. According to Hirose and Kamiya

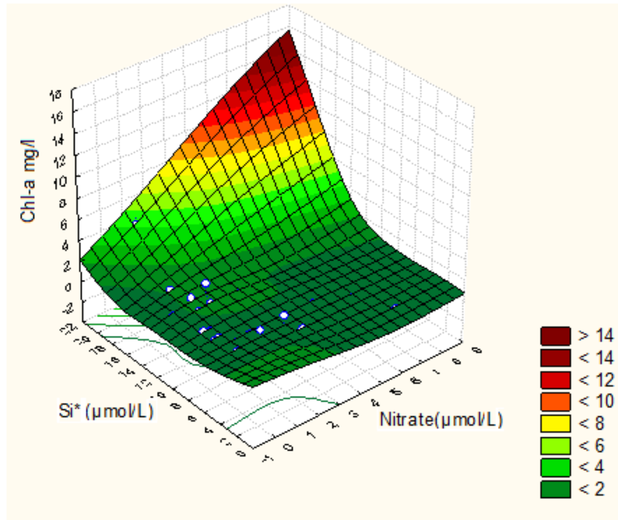

Figure 4. 3D surface plot of nitrate concentration (mmol/L) vs Si* concentration (mmol/L) vs chl-a concentration (mg/L): Z axis.

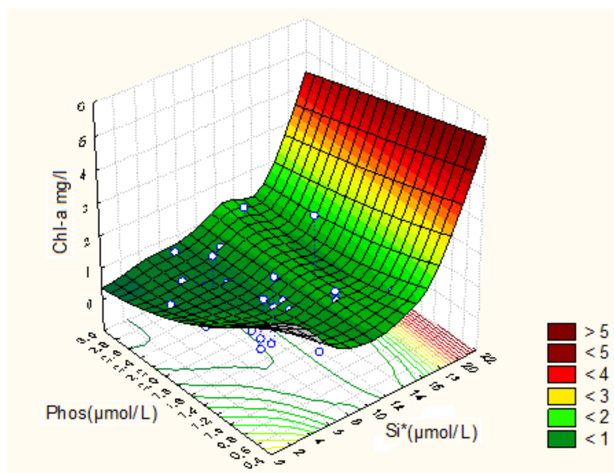

Figure. 5. 3D surface plot of Si* (mmol/L) vs Phos (mmol/L) vs Chl-a mg/L: Z axis.

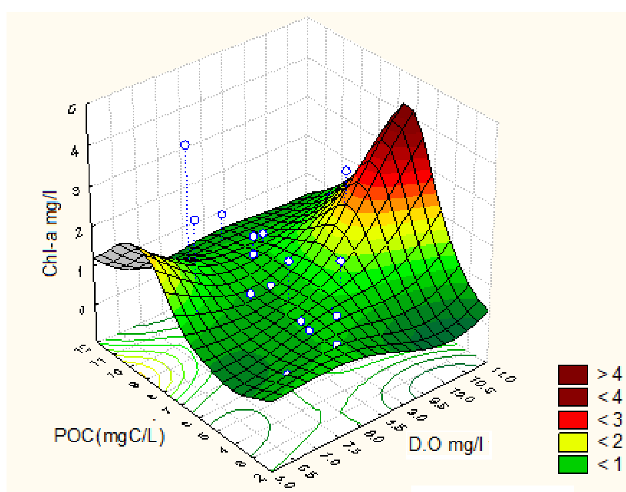

Figure 6. 3D surface plot of DO (mg/L) vs POC (mg C/L) vs Chl-a mg/L: Z axis.

(2003) abiotic and biotic factors have been known to influence productivity in about 90 % of the ocean surface. Further, as reported by Cavan *et al.* (2017) POC remineralization has been associated with microbial respiration, a process that in turn releases essential nutrients to the surrounding environment. Figure 6 illustrates chlorophyll-a as being boosted by high DO and POC levels, possibly due to the associated nutrient remineralization enhancing productivity. Azam *et al.* (1983) observed that higher temperatures with elevated microbial activity result in more efficient remineralization and leads to a lower export of POC to the abyss. Thus, lower latitude regions with low nutrient concentrations will contain a relatively active microbial loop that ensures remineralization and recycling before being exported from the euphotic zone (Azam *et al.*1983). This might explain the somewhat high direct relationship of temperature to chlorophyll-a (0.84); a further pointer to POC remineralization as observed by Azam *et al.* (1983).

This study aimed to obtain an understanding of the prevailing processes that might be driving the productivity of Kenyan territorial waters. Having employed PCA as a tool to associate the various oceanographic parameters and being cognizant of the underlining biogeochemical processes, it was possible to identify some of the abiotic and biotic factors as contributors to productivity. The analysis confirmed the fact that upwelling is a major contributor to the productivity of the study area. It was also evident that the system regenerates itself from the remineralization of POC which is further boosted by the high temperatures in the region.

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