16

Phytoplankton Primary Production

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Opposite page: Chlorophyll concentration in the WIO during the austral summer (Dec 2011-Mar 2012). © Nasa/Suomi NPP/Norman Kuring

INTRODUCTION

The plankton

Primary productivity may be defined as the amount of organic material produced per unit area per unit time; or simply as the product of phytoplankton biomass times phytoplankton growth rate (Cloern and others, 2014). Marine primary production plays an important role in food web dynamics, in biogeochemical cycles and in marine fisheries (Chassot and others, 2010, Passow and Carlson 2012). The term plankton, which means wandering or drifting, generally encompasses three groups: the phytoplankton, the photosynthetic (plant) component; the zooplankton, which is the animal component and the ichthyoplankton which comprise the fish larvae. However, this chapter will concentrate on the plant component, the phytoplankton. Phytoplankton is the foundation of the aquatic food web, meaning that they are the primary producers (Vargas and others, 2006). A common feature to all phytoplankton is that they contain chlorophyll-*a*; but there are other accessory pigments such as chlorophyll-*b* and chlorophyll-*c*, as well as photosynthetic carotenoids (Kirk 1994, Barlow and others, 2008). These pigments absorb solar energy and convert carbon dioxide and water into high-energy organic carbon compounds that fuels growth by synthesizing vital required components such as amino acids, lipids, protein, polysaccharides, pigments and nucleic acids. The photosynthetic process produces gross primary production; and the difference between gross primary production and respiration gives net primary production. Respiration is the release of carbon dioxide by photosynthetic organisms; leaving a net photosynthetic fixation of inorganic carbon into autotrophic biomass. Phytoplankton in the ocean contributes to roughly half of the planetary net primary production (Field and others, 1998). Through sinking of the fixed organic matter, primary production acts as a biological pump that removes carbon from the surface ocean, thereby playing a global role in climate change (ASCLME/SWIOFP 2012).

The main types of phytoplankton are cyanobacteria, diatoms, dinoflagellates, green algae and coccolithophores. In addition to phytoplankton, other primary producers contribute to ocean primary production, especially in the coastal areas. These include mangroves, seagrasses, macroalgae and salt marshes (Oliveira and others, 2005, Duarte and others, 2005). Furthermore, symbiotic algae, some epiphytes and benthic microalgae are also producers. However, phytoplankton contributes to more than 90 per cent of total marine primary production (Duarte and Cebrian 1996). In the group of cyanobacteria, some genera such as *Trichodesmium*, *Nostoc and Richelia*, are able to fix nitrogen from the atmosphere, thereby increasing sources of nutrients (Lyimo and Hamis 2008, Poulton and others, 2009). Under increased nutrient concentration, other genera from among the dinoflagellages such as *Dinophysis* can form blooms that could be harmful (harmful algal blooms – HABs or red tides) or be a nuisance to other aquatic organisms like fish and shellfish, the environment, as well as humans, and could cause serious economic losses in aquaculture, fisheries and tourism-based activities (Babin and others, 2008).

A general classification of microalgae is illustrated in Table 16.1. The table gives a total of 13 divisions/classes. Size-wise, phytoplankton can be sub-divided into three groups, namely: pico-phytoplankton (0.2 – 2.0 µm), nano-phytoplankton (2.0 – 20 µm) and micro-phytoplankton (20 – 200 µm), see Table 16.1. The primary consumers, zooplankton, also play an important role in the transfer of energy from one trophic level to another in the marine food web, thereby acting as a link between producers and higher consumers. Zooplankton is sub-divided into two groups, namely, the protozoa zooplankton with two phyla and Eumetozoan zooplankton with about 14 phyla. In zooplankton, the size ranges from 0.01 mm to several centimeters, although most of them do not exceed 5 mm (Conway and others, 2003). Herbivorous zooplankton feed on phytoplankton, and these feed carnivorous zooplankton, which in turn are eaten by other larger animals (see schematic illustration in Figure 16.1), thus playing a very important role in supporting the productivity of marine/coastal fisheries. Zooplankton is the basic food for most fish larvae and some adult fishes as well as cetaceans. As such, its distribution is considered as a proxy for ocean fertility, providing information on potential fishing zones (Reid and others, 2000).

The Western Indian Ocean (WIO) region

The WIO region could be sub-divided into two large marine ecosystems, namely: the Somali Current Large Marine Ecosystem (SCLME) and the Agulhas Current Large Marine Ecosystem (ACLME); the region also covers areas that are outside the two LMEs (ASCLME/SWIOFP 2012). The ACLME is located in the southwestern Indian Ocean, encompassing the continental shelves and coastal waters of mainland states of Mozambique and eastern South Africa, as well as the archipelagos of the Comoros, the Seychelles, Mauritius and La Reunion-France (Heileman and others, 2008). At the northeastern end of the ACLME is Madagascar, the world's fourth largest island with extensive coastline of more than 5 000 km (McKenna and Allen 2005). The SCLME extends from the Comoro Island and the northern tip of Madagascar in the south to the Horn of Africa in the north, bordered by Somalia, Kenya and Tanzania.

In the WIO region, circulation pattern differs between the southern and the northern parts of the region. In the south, circulation is persistent throughout the year, being wind driven anti-cyclonically, whereas in the north circulation is forced by the monsoon winds that reverse seasonally (Mengesha and others, 1999, Lutjeharms 2006). According to Lutjeharms (2006), the flow during the north-east monsoon is directed southwards along the East African coast and during the southwest monsoon it is directed northwards, becoming the East African Coastal

Table 16.1. Classification of phytoplankton algal types (adopted from Jeffrey and Vesk 1997)

Algal Division/Class	Microplankton 20 – 200+ µm	Nanoplankton 2 – 20 µm	Picoplankton 0.2 – 2 µm
Bacillariophyta	+	+	+
Chlorophyta	+	+	+
Chrysophyceae	+	+	+
Cryptophyta	+	+	-
Cyanophyta	+	+	+
Dinophyta	+	-	-
Euglenophyta	-	+	-
Eustigmatophyta	+	+	-
Prasinophyta	+	+	+
Prochlorophyta	-	+	-
Prymnesiophyceae	+	-	-
Rhodophyta	-	+	-

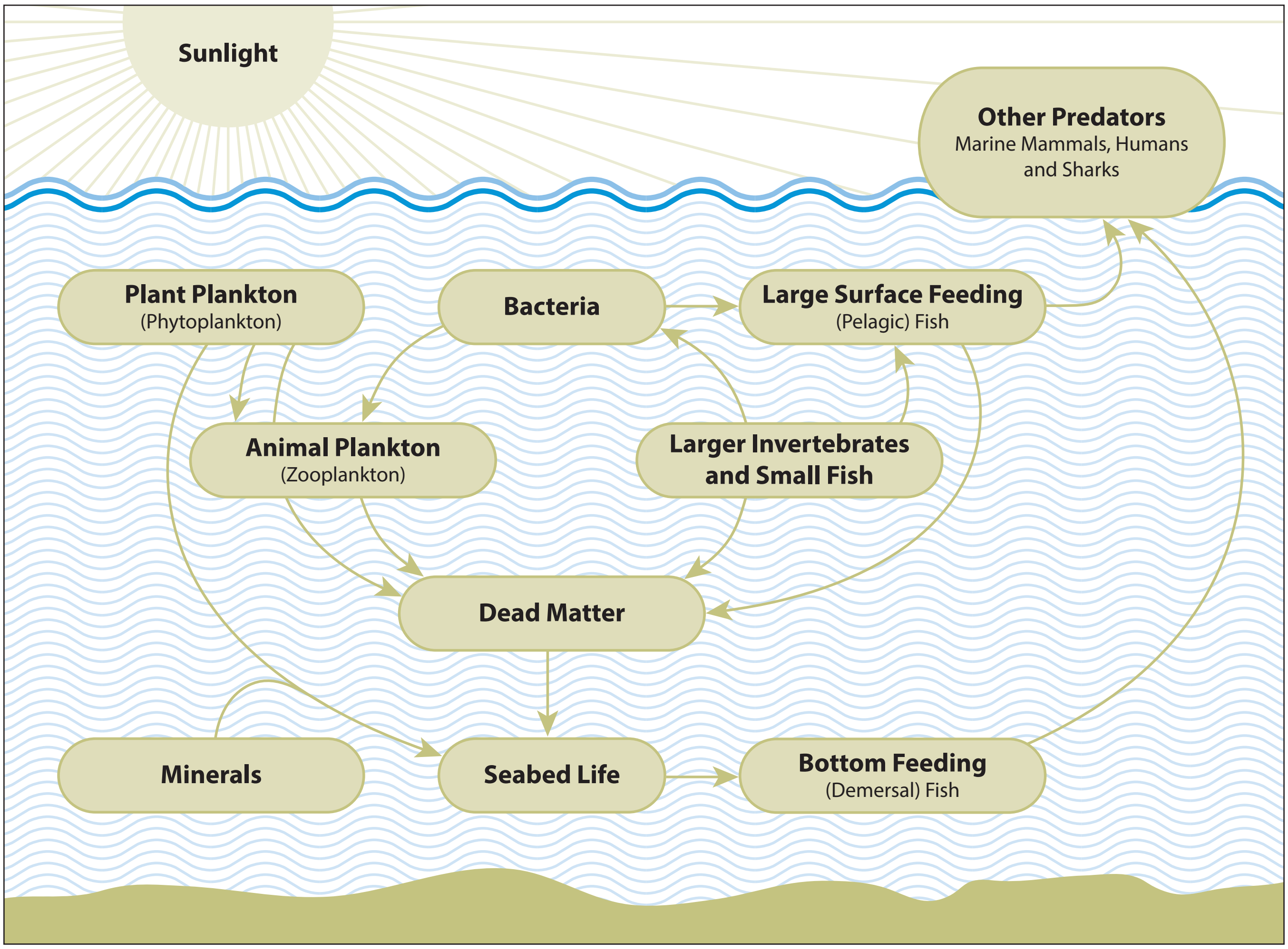


Figure 16.1. Simplified illustration of the marine food chain. In the real sense, the marine food web is very complex with interactions between organisms in the ecosystem, composed of detritus, numerous organisms such as bacteria, phytoplankton, zooplankton, fish, birds, marine mammals and humans. (Source: adapted from http://www.goldridge08.com).

Current. This current originates from the bifurcation of the East Madagascar Current, at the African coast around 10^{0}S.

Both LMEs are moderately productive with an average production ranging between 150 and 300 g C m^{-2} a^{-1} (Heileman and Scott 2008, Heileman and others, 2008). For the ACLME, primary production is largely driven by the Mozambique Channel eddies and localized eddies or topography-driven upwelling (Quartly and others, 2005, Kyewalyanga and others, 2007, Barlow and others, 2013). Relative to other parts of the Indian Ocean and the Atlantic Ocean that borders western Africa that seem to be more productive (Figure 16.2), productivity in the WIO region is between low and moderate levels, although there are some highly productive areas, especially along the coasts. In summary, the WIO waters are characterized by warm temperatures and low nutrients, low biomass and relatively low-moderate primary production (Karl and others, 1999). The phytoplankton communities are usually dominated by pico-phytoplankton and nano-phytoplankton (Barlow and others, 1999, Barlow and others, 2007, Goericke and others, 2000, Sá and others, 2013).

Factors affecting productivity and the distribution of primary producers

Primary production, phytoplankton distribution and abundance are influenced by several factors, thus they vary both seasonally and spatially. Primarily, phytoplankton depends on carbon dioxide, sunlight and nutrients for growth, but some other factors such as water depth, water temperature, wind and grazers also play a significant role. The South and Western Indian Ocean are probably the least studied areas. Research has so far focused on the Arabian Sea (northwestern Indian Ocean) while extensive regions of oceanic waters remain unknown. Therefore, in the WIO region, information on primary production and phytoplankton

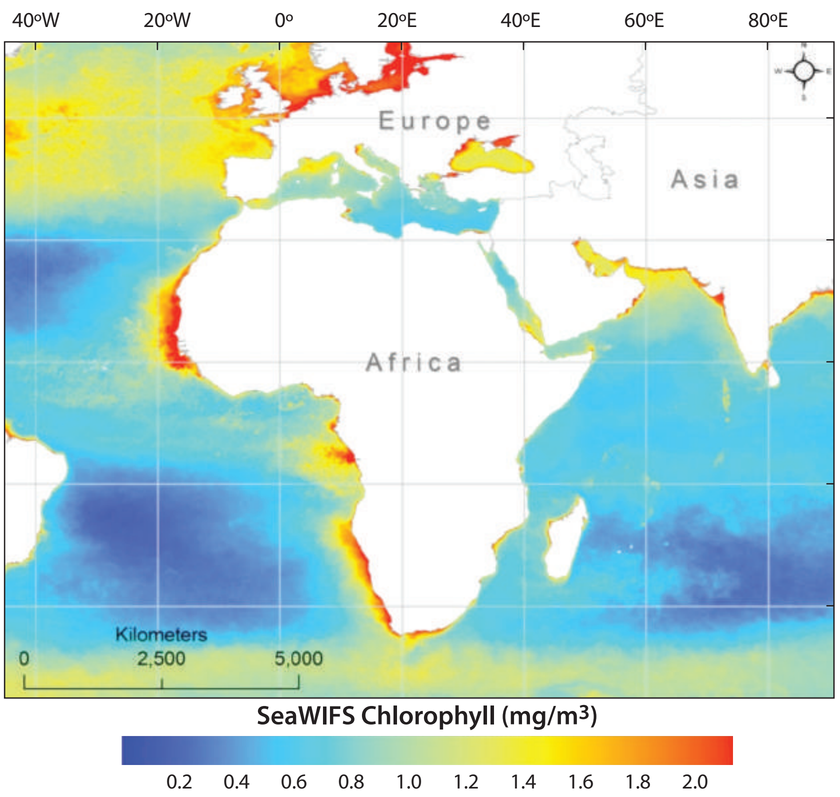


Figure 16.2. Calculated annual average (year 2009) of chlorophyll-*a* concentration (mg m^{-3}) extracted from satellite data (SeaWIFS) for the Indian Ocean and the Eastern Atlantic Ocean. It clearly shows how oligotrophic the waters of the Western Indian Ocean are in comparison to other adjacent waters that border the African continent (Arabia Sea, Mediterranean Sea and the Atlantic Ocean). Data downloaded from NASA (National Aeronautics and Space Administration) – GIOVANNI Ocean Colour Radiometry online visualization and analysis – Global monthly products (http://www.gdata.sci.gsfc.nasa.gov/).

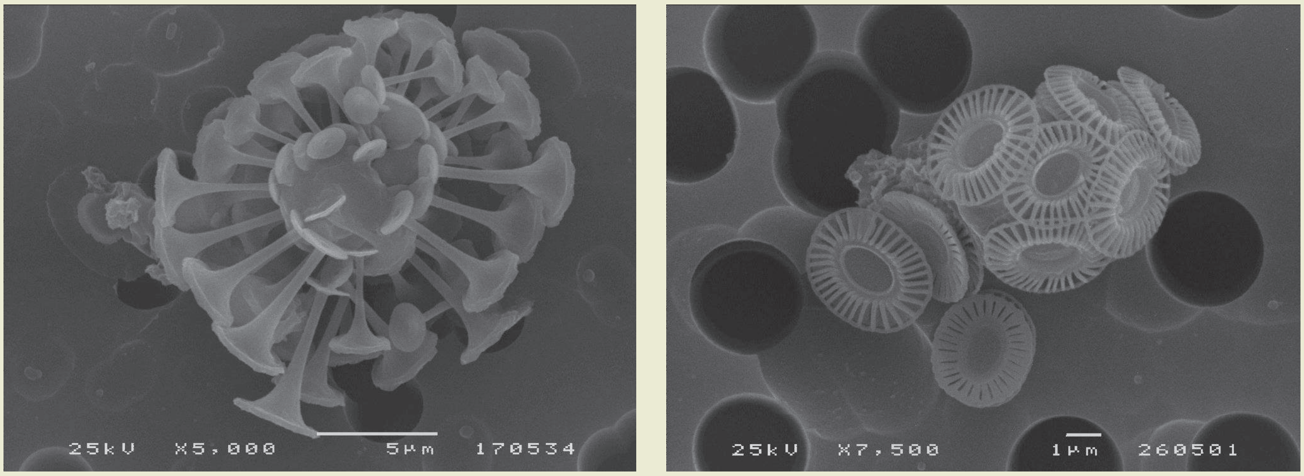
communities' distribution and abundance is sparse and less homogeneous (Sá and others, 2013). Comparing the two LMEs for primary production studies, the waters of the Somali Current LME are less studied relative to the ACLME (in the South Western Indian Ocean region), which has received much more attention (Meyer and others, 2002, Barlow and others, 2008, Barlow and others, 2010, Barlow and others, 2011, Barlow and others, 2013, Barlow and others, 2014, Kyewalyanga and others, 2007, Sá and others, 2013, Lamont and others, 2010, Lamont and Barlow 2014). The following two paragraphs looks at the drivers of primary production and the rates in the region.

Some of the main drivers of productivity include monsoon seasons (Kromkamp and others, 1997, McClanahan 1998), circulation, upwelling and eddies (Meyer and others, 2002, Quartly and Srokosz 2004), nutrients (Kyewalyanga and others, 2007, Leal and others, 2009, Tew-Kai and Marsac 2009, Koné and others, 2009, Sá and others, 2013, Sadally and others, 2004), irradiance and temperature (Bowman and others, 2003, Lamont and Barlow 2015), bottom topography that might cause upwelling (Galliene and Smythe-Wright 2005), growth rates (Cloern and others, 2014), grazing (Calbet 2008, Loebl and Van Beusekom 2008, Ward and others, 2012, Lee and others, 2012) and water column stability (Barlow and others, 2007). The levels of ultra-violet radiation (UVR) can also affect primary production. The enhanced level of radiation, ultra-violet B (UV-B; 280-315 nm) is more harmful than the normal level known as ultra-violet A (UV-A; 315-400 nm). UVR causes harm by inhibiting photosynthesis, photo-protection and affects the DNA molecule (Smith and others, 1992, Helbling and others, 2005). In temperate regions with strong seasonality and close proximity to the ozone "hole", Helbling and others (2005) found that strong levels of UVR result in phytoplankton being dominated by small sized cells (pre- and post-bloom conditions), whereas during the winter bloom with less UVR, micro-phytoplankton dominate.

Rates of primary production in the region vary significantly both in space and time. For values measured *in-situ*, primary production has been shown to range from less than 0.1 g C m^{-2} d^{-1} (Steeman-Nielsen and Jensen 1957, Mitchell-Innes 1967) to more than 3.0 g C m^{-2} d^{-1} especially in coastal embayments and along productive continental shelves such as the Natal and Delagoa Bights (Ryther and others, 1996, Barlow and others, 2010, Barlow and others, 2011). However, these are the extreme cases. Most of the values determined in the WIO region fall in the range between 0.5 and 2.0 g C m^{-2} d^{-1}. For example, in Tanzanian waters, Ryther and others (1966) found rates ranging from about 0.3 to 1.00 g C m^{-2} d^{-1} while Barlow and others (2011) observed rates in primary production ranging from 0.79–1.89 g C m^{-2} d^{-1} in Pemba and Zanzibar Channels. In the Delagoa Bight, primary production rates have been shown to range from 0.6 to 0.85 g C m^{-2} d^{-1} (Mitchell-Innes 1967, Kyewalyanga and others, 2007). In the Natal Bight however, maximum values are > 2.0 g C m^{-2} d^{-1} (Burchall 1968a, Burchall 1968b, Barlow and others, 2010). In the northern part of the WIO region, the Arabia Sea, a comprehensive study during the Joint Global Ocean Flux Studies (JGOFS) was conducted between 1994 and 1996. The various data collected, both *in-situ* and remotely-sensed have revolutionised the understanding of the Arabian Sea and uncovered new findings on the effects of the monsoons and on

BOX 16.1

INFLUENCE OF PRODUCTIVITY DRIVERS ON THE VARIATION OF PHYTOPLANKTON ASSEMBLAGES ALONG THE MOZAMBIQUE COAST



The species *Discosphaera tubifera* (left) and *Emiliana huxleyi* (right). © Carolina Sá.

Drivers of phytoplankton distribution, abundance and productivity could vary significantly, even within the coastal waters of a given country. A good example is Mozambique, which has a long coastline, about 2 500 km in length, influenced by different water masses and other factors such as tides, river flow and upwelling due to eddies. These influence nutrient concentrations as well as exposure of phytoplankton to varying degrees of photosynthetically available irradiance (PAR), temperature and salinity, thereby having a direct impact on phytoplankton abundance, distribution and community composition. A recent study carried out along the entire coast of Mozambique assessed pigment and microscopic analysis of phytoplankton (Sá and others, 2013). At each station, sampling took place in surface waters as well as at the sub-surface chlorophyll maximum (SSM). A north-south gradient in temperature and salinity was observed in which the northern coast had higher surface temperature but relatively low salinity, while the southern coast had the reverse conditions (Sá and others, 2013). There were notable patterns of phytoplankton distribution and community composition that changed between regions; such that the Delagoa Bight, Angoche and the Sofala Bank in the southern part of the coast were found to be the most productive regions. Micro-phytoplankon were associated with the cooler water masses off the southern coast, whereas pico-phytoplankton were found to be associated with the warmer water masses off the northern coast. In the water column, the relatively large phytoplankton (micro), contributed significant biomass both at the surface and at the SSM; the smallest proportion (pico-phytoplankton) contributed mostly at the surface while the medium-sized ones (nano-phytoplankton) were more abundant at the SSM. On composition, nano-sized phytoplankton were dominated by *Discosphaera tubifera* and *Emiliania huxleyi*, while the most abundant micro-phytoplankton were mostly diatoms of the species: *Cylindrotheca closterium, Hemiaulus haukii, Proboscia alata, Pseudo-nitzschia* spp. and *Chaetoceros* spp.

phytoplankton and their productivity (Watts and Sathyendranath 2002). The entire dataset on carbon assimilation showed that rates of primary production ranged from 0.12 to 3.0 g C m^{-2} d^{-1} (Owens and others, 1993, Madhupratap and others, 1996, Marra and others, 1998, Savidge and Gillpin 1999, Barber and others, 2001).

Irradiance and temperature

Irradiance is a major driving force for photosynthesis; it warms the surface waters of the oceans, thereby regulating the water temperature. Both temperature and irradiance vary with the seasons of the year. Temperature is an important environmental parameter that influences biological processes in the ocean, and various studies have demonstrated that phytoplankton community structure varies in a regular, predictable pattern with temperature, especially in temperate regions (Boumann and others, 2005, Platt and others, 2005). To be able to utilize irradiance efficiently, phytoplankton has evolved taxon specific suites of pigments in their pigment–protein complexes for light absorption in the visible spectral range of 400-700 nm (Porra and others, 1997). Phytoplankton cells quickly adapt to changes in light quantity and quality and have developed different suites of pigments to deal with varying light regimes in different ecosystems (Falkowski and La Roche 1991, Kirk 1994, Barlow and others, 2007).

For example, they can do this by regulating the proportion of their photosynthetic or photo-protective carotenoids to total carotenoids or by a shift in phytoplankton communities (Barlow and others, 2002, Barlow and others, 2011, Barlow and others, 2013, Barlow and others, 2014). In the tropical Zanzibar waters, Barlow and others (2011) showed that phytoplankton do maximize their photosynthesis in the upper waters with high irradiance and low nutrients. However, in deeper waters where irradiance is low, phytoplankton tend to adapt to this condition by increasing their quantum yield of photochemistry. This is done by increasing their accessory pigments such as chlorophyll-*b*, chlorophyll-*c* and photosynthetic carotenoids (Barlow and others, 2011). Along the Mozambique coast, Sá and others (2013) found that different size classes of phytoplankton dominated different water masses (see Box 16.1). The warmer (nutrient poor) northern water masses were dominated by the small pico-phytoplankton while the southern water masses, cooler and rich in nutrients were dominated by micro-phytoplankton, especially diatoms.

Nutrients

Nutrient availability (especially nitrogen and phosphorus) is one of the primary factors that control the distribution of phytoplankton communities in the WIO region, while silicate was shown not to be limiting for this region (Barlow and others, 2007, Kyewalyanga and others, 2007, Leal and others, 2009, Sá and others, 2013). Nutrients distribution vary both horizontally and vertically in the water column. Most nutrient profiles show low values in surface (euphotic) layer, and the concentration increases with depth. This is because the presence of enough irradiance in the surface waters stimulates productivity, which consumes the nutrients. A general assessment of nutrient distribution in some of the areas of the WIO region, based on recent studies also revealed significant spatial variations. Along the Mozambique coast, Sá and others (2013) observed that nitrogen-nutrients concentration was below detection limit; while silicate ranged from between 6 and 10 µmol l^{-1} and in some areas was as high as 17 µmol l^{-1}. In the Delagoa Bight region (southern coast of Mozambique) from onshore to offshore, vertical profiles of nitrate presented values that ranged from below detection limit to 0.95 µmol l^{-1}; those of phosphate concentrations had values that ranged from 0.1 to 1.05 µmol l^{-1}; while for silicate concentrations values ranged from 0.1 to 4.4 µmol l^{-1}. With such nutrient concentrations, primary production values of the water column for the entire sampling area were found to range from low to medium values, namely 0.22 – 0.85 g C m^{-2} d^{-1} (Kyewalyanga and others, 2007).

In Mauritius' surface waters around Flic-en-Flac and Belle Mare, nutrient concentrations were relatively low and ranged as follows: highest values of nitrate ranged from 0.1 to 25 µmol l^{-1}; phosphate ranged from about 0.1 to 6 µmol l^{-1}; while silicate ranged from 0.1 to 23 µmol l^{-1} (Sadally and others, 2014). In the vicinity of Unguja and Pemba Islands, along the Tanzanian coast, Barlow and others (2011) determined nutrient concentrations at selected depths, between 2 and 125 m, and found nitrate concentration to be less than 0.25 µmol l^{-1} in the upper mixed layer, while in deeper waters concentration of nitrate reached as high as 8.5 µmol/l. A study across the tropical Indian Ocean (Barlow and others, 2007) revealed that nitrite+nitrate and phosphates in surface waters were very low. The concentration for nitrate+nitrite was less than 0.1 µmol l^{-1} and ranged from 0.06 to 0.14 µmol l^{-1} for phosphate. Although silicate levels were relatively higher that those of other nutrients, the observed levels (of up to 2.0 µmol l^{-1}) remain in the low range.

A recent regional-wide assessment of nutrient concentrations was conducted during a project designed to address land-based activities in the Western Indian Ocean (WIO-LaB). All WIO countries, with exception of Reunion and Somalia, participated in the sampling that was conducted from 2006-2008 at selected control and potential hotspots - test sites (UNEP/Nairobi Convention Secretariat, CSIR and WIOMSA, 2009). At the test stations, ammonium levels ranged from 0.001 – 13.44 µmol l^{-1}, nitrate-nitrogen from 0.002 – 31.38 µmol l^{-1}; nitrite-nitrogen from 0.002 – 0.43 µmol l^{-1}; and phosphate-phosphorus from 0.0002 – 0.65 µmol l^{-1}. All the highest values were observed off Madagascar, with exception of the highest phosphate concentration, which was recorded off Mauritius (UNEP/Nairobi Convention Secretariat, CSIR and WIOMSA, 2009). Since these values were taken from known hotspots, it is possible that the site off Madagascar (Nosy-By) is more polluted relative to other hotspots in the rest of the WIO countries. This area is characterised by bays where major land-based activities are situated, such that it receives discharges from the port, industries, petroleum product depot and domestic wastewaters. Fish mortality has also been occurring in the area. In the open ocean waters of the WIO region, nutrients seem to be relatively low and primary production is between low to medium. However, fish catch seems to be relatively high. Notwithstanding artisanal fisheries, it has been shown that the WIO region generates more than 4 million tonnes of fish per year, which contributes about 4 per cent of the global industrialised fish catch (SWIOPF 2012).

Ocean currents and circulation

Ocean currents are important features that strongly influence the availability of nutrients and the distribution of phytoplankton. Lutjeharms (2006) provided description of the oceanography and hydrography of the coastal oceans off southeastern Africa and their influence on biological productivity and biota. The dominant large-scale oceanographic feature of the LME is the Agulhas Current, a swift warm western boundary current that forms part of the anticyclonic gyre of the south Indian Ocean. This LME is influenced by mixed climate conditions, with the upper layers being composed of both tropical and subtropical surface waters (Beckley 1998). Large parts of the system are characterized by high levels of mesoscale variability, particularly in the Mozambique Channel and south of Madagascar. Eddy formation was also observed in the southwest side of the Mascarene Plateau, being caused by a current moving in clockwise direction with high velocities (Badal and others, 2009). In Mozambican waters, Sá and others (2013) found that micro-phytoplankton (diatoms) dominated both the surface and the sub-surface chlorophyll maxima, being associated with cooler southern water masses whereas the pico-phytoplankton was associated with the warmer northern water masses.

In the mesoscale eddies of the Mozambique Channel, Barlow and others (2014) found that in surface waters, prokaryotes were of primary importance, followed by small flagellates, while flagellates dominated the deep chlorophyll maximum layer. Diatoms were found to dominate shelf and frontal stations. To get the best from such environments, diatom-dominated communities and prokaryotes-dominated communities regulated their chlorophyll-specific absorption, proportion of photosynthetic pigments, proportion of total chlorophyll-*a* to total pigments and the proportion of photo-protective pigments in an inverse direction. For example, diatom-dominated communities showed low chlorophyll-specific absorption, high total chlorophyll-*a* proportion and high proportions of photosynthetic carotenoids and chlorophyll-*c*. The flagellates were somewhere in the middle (Barlow and others, 2014).

Upwelling and freshwater input

Both these processes bring new nutrients into the surface layer of the ocean. Upwelling is the process through which deep nutrient-rich waters are brought up into the surface layer (vertical movement upwards), while freshwater input, horizontally, is mainly through rivers or surface runoffs during heavy rains (Ramessur 2011). This increases the nutrient concentrations, resulting in enhanced biomass concentration and productivity. In the WIO region, upwelling is known to occur along the Somali coast (McClanahan 1998), off the northern Kenya coast, Mascarene Plateau through obstruction of the South Equatorial Current (Galliene and others, 2004, Galliene and Smythe-Wright 2005), at specific offsets of the coastline in the Mozambique Channel, off the southeastern tip of Madagascar (Lutjehams 2006) and at the Madagascar Ridge (Poulton and others, 2009). In the Delagoa Bight, passing anticyclonic eddies influences water masses in the Bight, resulting in upwelling in the shelf area (Lutjeharms and Da Silva 1988, Kyewalyanga and others, 2007, Barlow and others, 2008, Sá and others, 2013, Fennessy and others, 2013); but also the inshore northward-flowing coastal current causes frequent upwelling due to interaction with the bottom topography (Lamont and others, 2010). For the Natal Bight, the Agulhas Current has been observed to result in a kinematically driven upwelling cell bringing cooler nutrient-rich waters into the shelf.

The WIO region is endowed with major rivers, which add nutrients to coastal areas, especially during the heavy rain season. Some of the main rivers from the mainland states that empty into the Indian Ocean include: Juba and Shabelle (in Somalia), Tana and Sabaki (Kenya), Pangani, Wami, Ruvu, Rufiji and Ruvuma (Tanzania), Zambezi, Maputo, Incomati and Limpopo Rivers (Mozambique) and Thukela, Great Brak, Breede, Klein, Mngeni, and Umfolozi Rivers (in South Africa). In waters very close to the shore, availability of nutrients due to anthropogenic input, surface runoffs and river input especially during the rainy season, results in high concentrations of phytoplankton. As such, phytoplankton tends to decrease from coastal waters towards deeper waters (Figure 16.3, Peter 2013, Ezekiel 2014, Sadally and others, in press). This implies that the coastal strip is richer than the open ocean in terms of productivity thereby supporting considerable number of food chains and food webs (Cloern and others, 2014). The coastal areas, especially in mangrove ecosystems and seagrass beds, act as nursery grounds and feeding areas for a number of marine organisms both benthic and pelagic.

Monsoon circulation

Primary productivity in the WIO region is subjected to two alternating and distinctive seasons, the southern and northern monsoons, which have a marked effect on air and water temperature, wind, rainfall and phytoplankton biomass (Figure 16.3). The prevailing winds during the monsoons are a particularly important influencing factor on water circulation, especially in the northern part of the WIO region. They affect the distribution of nutrients and marine organisms as well as biological processes, changing wave action, and affecting a wide range of human activities (Richmond 2011). From November to March, the prevailing trade wind is from the northeast, but more northwesterly in direction to the south of the equator. From June to September, the stronger southwest monsoon wind prevails. South of the equator, this wind is more southeasterly in direction (Richmond 2011). In Tanzanian waters, recent studies have shown that monsoon seasonality has a great influence on phytoplankton distribution and abundance (Peter 2013, Ezekiel 2014). Similarly, off the Kenyan coast, both primary and secondary productivity are strongly influenced by the monsoon seasons (McClanahan 1998). The

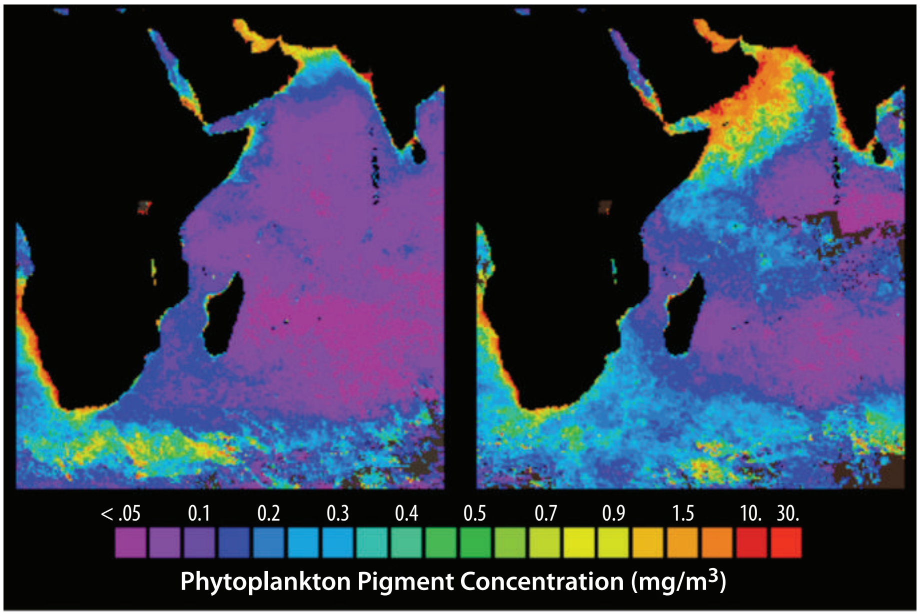


Figure 16.3. Monsoonal changes in the Indian Ocean directly affect phytoplankton biomass (Chl-*a* mg m^{-3}). Left panel shows a period of pre-monsoon calm (May-June composite); while the right panel shows strong summer southwesterly conditions with strong winds that generated upwelling of nutrient-rich waters, leading to the development of bloom conditions (September-October composite). (Source: http://disc.sci.gsfc.nasa.gov/education-and-outreach/additional/images/Monsoon.GIF).

southwest monsoons are characterized by heavy rainfall, strong wind energy, low temperatures and high clouds; the reverse is true for the northeast monsoon. Both primary and secondary plankton productivity are higher at the continental shelf compared to offshore as well as during the northeast monsoon over the southwest monsoon. This high production is caused by nutrient enrichment of the coastal waters by heavy surface runoff during the southwest monsoons from major rivers, Tana and Sabaki, and upwelling off northern Kenya. During the northeast monsoon the lower current speeds and higher salinities provide a comparatively stable environment for enhancing production at the shelf (Government of Kenya 2009).

ENVIRONMENTAL, ECONOMIC AND SOCIAL IMPLICATIONS OF TRENDS IN PRIMARY PRODUCTION

The trend

Primary production for the WIO region is not consistent, as it tends to vary from year to year driven by a number of factors (see above) that operate synergistically or antagonistically. For example, phytoplankton abundance (Chl-*a*), could be positively correlated with one factor (such as nitrate concentration) but at the same time negatively correlated to another such as temperature or salinity due to seasonality or input of surface runoff from terrestrial sources that might bring nutrients into the coastal areas (Peter 2013). Figure 16.4 shows average chlorophyll-*a* concentration for the WIO region, derived from satellite data over the last 12 years. The general trend has been to decrease with time, but it also shows a significant interannual variability. The general decrease is in agreement with the global trend in primary production, which appears to be decreasing and in doing so constraining fisheries catches (Chassot and others, 2010). Moreover, productivity in the WIO region is a bit low in the central part, but relatively higher in the northern (the Arabian Sea) and southwestern part of the region (Figures 16.2 and 16.3). Although the general trend for WIO region primary production is to decrease, there are some exceptional areas that have high productivity from influence of nutrient input via land-based sources and upwelling (see above). Therefore, it is somehow difficult to predict changes and trends in production for the entire region. The impact of climate change exacerbates any change that occurs due to other factors. Globally, primary production has been shown to increase in upwelling zones and sub-polar regions, while in the subtropical gyres the trend is to decrease (Behrenfeld and others, 2006, Chavez and others, 2010). In the following

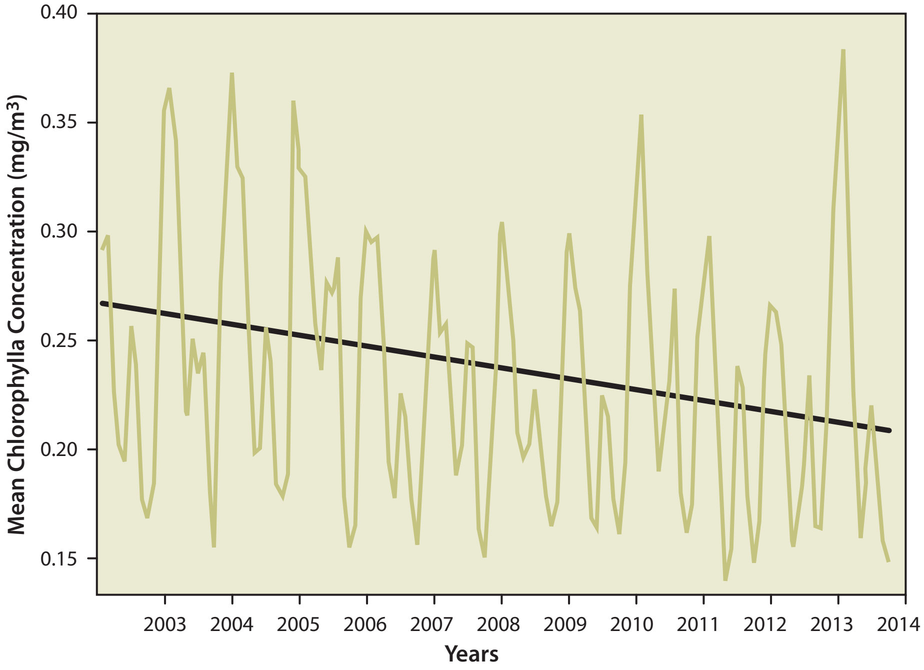


Figure 16.4. Monthly averages of chlorophyll-*a* concentration (mg m^{-3}) calculated for the Western Indian Ocean region covering a period from July 2002 to April 2014 The blue line shows monthly variations due to seasonal changes, but more importantly the red line shows a decreasing trend in the concentration with time. Data downloaded from NASA (National Aeronautics and Space Administration) – GIOVANNI Ocean Colour Radiometry online visualization and analysis – Global monthly products (http://www.gdata.sci.gsfc.nasa.gov/).

sub-sections, the environmental, economic and social factors that might have an impact on the trend in primary productivity of the WIO region are briefly discussed.

Environmental implications

The primary producers are linked to fisheries because they are at the base of the marine food webs. Furthermore, some fishes like parrot fish are herbivorous, thus feeding directly on marine plants (seagrasses, seaweeds). This implies that a change in the trend of primary production will also affect fish spawning, growth and/or reproduction. In temperate regions, the survival of fish larvae was clearly shown to depend on the timing of the phytoplankton spring bloom (Platt and others, 2003). In tropical regions, like the WIO region, coral reef ecosystems support a large number of fish and other marine organisms. Any impact to corals, such as bleaching events, will impact organisms that depend on the reef for food and shelter. Bleaching affects the survival and productivity of the symbiotic micro-algae (the zooxanthllae), which can lead to coral death. The death of the coral will have a direct impact on the corallivores (the fish who feed on corals, such as the orange-spotted filefish (*Oxymonacanthus longirostris*)) and others that depend on the health of the ecosystem. As a result, fisheries catch, especially artisanal fisheries, will be impacted. Considering a bottom-up approach, any factor that influences the base of the food web will have implications for higher trophic levels extending to the top predators (Cury and others, 2003). At the scale of LMEs, primary production was shown to limit average and maximum fisheries catches over both short (up to 5 years) and long (about 50 years) time scales (Chassot and others, 2010).

At smaller scales, especially in areas with high nutrient input, eutrophication (characterized by high growth of phytoplankton and macroalgae) may occur. The major causes of eutrophication is waste water input, which contain high levels of inorganic nutrients such as nitrogen and phosphate, or with high organic content, ie, high biological and chemical oxygen demand (UNEP/Nairobi Convention Secretariat, CSIR and WIOMSA, 2009, Chislock and others, 2013). In the WIO region, eutrophication at a large scale hasn't been shown. However, harmful or nuisance algal blooms have been identified in pollution hotspots of the WIO countries (UNEP/Nairobi Convention Secretariat, CSIR and WIOMSA, 2009). The only significant HAB events in the region have been reported in Kenya, Mauritius, Somalia, South Africa and Tanzania, and for each of these countries a good summary of the causes of HABs or nuisance algal blooms, the effect to the environment, to tourism and or to communities has been given, where Mauritius seems to have the biggest impact (ASCLME/SWIOFP 2012).

A simultaneous regional survey was conducted between 1998 and 2000 by the IOC-UNESCO HAB Programme in Kenya, Madagascar, Mauritius, Reunion and Tanzania. The results identified 60 potential HAB species, representing four different classes (ASCLME/SWIOFP 2012). The known environmental impacts of algal blooms include: reduced water clarity (by reducing light penetration) that is vital to light-dependent benthic species, effect on aesthetics and biodiversity, increased pH due to reduction of dissolved inorganic carbon because of increased photosynthesis, smothering of benthic communities during die-offs of algal blooms, modification of species composition and creation of anoxic conditions due to decomposition of organic matter, resulting in mortalities of marine species due to hypoxia (UNEP/Nairobi Convention Secretariat, CSIR and WIOMSA, 2009, ASCLME/SWIOFP 2012, Chislock and others, 2013).

Socio-economic implications

For coastal communities of the WIO region who depend mostly on coastal resources for their food and livelihoods, a decreasing trend in the regional primary production with direct impact on fisheries catches is not good news. In general, a global decreasing trend in primary production (Chassot and others, 2010) and the observed decrease in phytoplankton biomass in the WIO region in the last 12 years in particular (Figure 16.4), will have a significant impact in fisheries catches, which in turn will exacerbate the already existing problem of overfishing. Overfishing, which causes fish depletion has a direct impact on food security and livelihoods of coastal societies. Added to that, elevated levels of primary production resulting in algal blooms that include harmful and or the nuisance species would worsen an already worrying situation.

The HABs exist in both marine and fresh waters, and they do produce toxins which could poison domestic animals, wildlife, fish, benthic organisms and humans. The impact of HABs on coastal communities and their economy may be by loss of aesthetic values that greatly affect tourism and its associated benefits; loss of artisanal fisheries and aquaculture (see Box 16.2) and effects on seafood quality (Babin and others, 2008, Asplund and others, 2013).

BOX 16.2 HARMFUL ALGAL BLOOMS AFFECTING SEAWEED FARMS AND FARMERS IN ZANZIBAR

The algal farming in Paje, east coast of Unguja Island, Zanzibar. © José Paula.

Recently in Zanzibar waters, incidents of algal blooms have been observed and they are affecting areas where seaweed is being farmed – in Paje, the east coast and in Bweleo the southwest coast of Unguja Island. The farmers experienced irritation of the skin and mortality of the farmed seaweed *Eucheuma denticulatum* (Msuya 2013, Kyewalyanga Pers. observation). On the east coast, a toxic cyanobacterium *Lyngbya* spp. was identified as the cause, while on the southwest coast the identified alga was *Sarconema*, which was covered by microalgae film containing different species of microalgae and *Lyngbya* spp. The other microalgae included*: Nitzschia longissima, Licmophora abbreviate, Grammatophora marine and Podocystis spathulata* (Msuya 2013). The causes of this condition, which was not observed before 2011 are suggested to be nutrients load due to pollution (probably the primary cause) but the effect of climate change (increased surface temperature and erosion) might also be playing a significant role. The occurrence of these blooms affects the health of the environment (seaweed mortality) and public health (irritation of the seaweed farmers' skin). In addition, the mortality of the farmed seaweeds causes economic loss and impact on the livelihood of the surrounding village community. However, impact on other marine organisms especially benthic communities are yet to be identified.

The implication is the effect on food safety, food security and income-generating activities; and risk to human health from recreational contact with HABS and consumption of contaminated seafood that might even result into loss of life (UNEP/Nairobi Convention Secretariat, CSIR and WIOMSA, 2009).

Potential conflict between different sectors is another socio-economic factor associated with the formation of harmful algal blooms. For example, when establishments discharge untreated waste water, creating ideal conditions for development of harmful algal blooms that affect the environment as well as the surrounding communities. This would result in contravention of environmental regulations besides compromising food safety as well as public health of coastal communities.

Other factors affecting resilience at the base of the food web

Climate change is associated with increased irradiance, causing warming, which raises sea-surface temperature. Increased temperature causes stable water-column, resulting in stratification that might limit nutrient injection into the euphotic zone, needed for primary production. A large-scale study of primary production through remote sensing has shown that increase in sea surface temperature triggered a reduction in the global production of ocean phytoplankton since the early 1980s (Behrenfeld and others, 2006). Because an impact on the base of the food web will also affect higher trophic levels (Cury and others, 2003, Platt and others, 2003), a reduction in primary production would reduce fisheries catches and lead to overfishing in order to satisfy protein demand (Chassot and others, 2010). Another angle for which climate change impacts on ocean primary production is through ocean acidification (Cooley and others, 2009). Increased acidity in the ocean will impact on phytoplankton, especially those with calcareous shells such as coccolithophores (like *Emiliania huxleyi*) as well as macro-algae with similar structures, such as *Halimeda* sp. However, a direct link between ocean acidification and fisheries catch hasn't been shown for the WIO region. Besides climate change, anthropogenic activities such as increased coastal development to accommodate increased tourism (Sadally and others, 2014) as well as destruction of habitats and damming of the rivers, increases sedimentation in coastal waters thereby reducing light availability for photosynthesis to both phytoplankton and macro-algae.

BOX 16.3 THE USE OF SYSTEMS FOR MUNICIPAL WATER TREATMENT IN THE WIO REGION

There is a number of ways in which pollution from wastewater, which could lead to HABs, could be reduced in the WIO region. One of the assessments in the region (UNEP/Nairobi Convention Secretariat, CSIR and WIOMSA, 2009) revealed that four main municipal water treatment systems exist, though used differently in different countries, most likely dependent on the status of economic development of each country. These include central sewer systems, septic tanks and soak away, pit latrines and other systems. The distribution of the population in each of the WIO countries using the different systems can be summarized as (UNEP/Nairobi Convention Secretariat, CSIR and WIOMSA, 2009):

Percentage of the population on a central sewer systems ranges from a minimum of 0.3 per cent in Comoros to a maximum of 47 per cent in South Africa.

The percentage of the population with septic tanks and soak aways ranges from a minimum of 4 per cent in South Africa to a maximum of 87.6 per cent in the Seychelles.

Populations with pit latrines range from a minimum of 3.6 per cent in the Seychelles to a maximum of 94.4 per cent in the Comoros.

The percentage population on other systems (such as dry and chemical toilets) ranges from non-existence in Comoros, Kenya and Mozambique to a maximum of 31 per cent in South Africa.

This indicates that attempts to contain the municipal wastes do exist in each country in the region though the level of usage of particular systems vary depending on costs.

ACTIONS THAT COULD BE TAKEN FOR A MORE SUSTAINABLE FUTURE (RESPONSE)

The primary producers do adapt to natural changes in the environment, especially light, nutrients and temperature. They have various mechanisms such as varying proportions of chlorophyll-*a* and carotenoids, as described above. However, anthropogenic activities tend to exacerbate the natural factors/changes. Thus, we need to look at the human side to answer the question "What is being done and how effective is it?"

Eutrophication and harmful algal blooms (HABs)

To combat the effect of eutrophication, that causes HABs and other nuisance blooms, the countries of the WIO region are trying to reduce the input of wastewaters into the ocean or by treating the water to reduce contaminants and nutrients before its release into the environment. The estimated amount of municipal waste water (potentially entering the coastal zone of the WIO region) range from a minimum of 168 m^3 d^{-1} in the Comoros to a maximum of 255 000 m^3 d^{-1} in South Africa, other countries being somewhere in between (UNEP/Nairobi Convention Secretariat, CSIR and WIOMSA, 2009).

On HABs, it is known that potentially harmful algae exist throughout the region, and their effects (some acute) have been observed. Yet, only two countries have on-going monitoring programs; South Africa's west coast and Reunion Island (ASCLME/SWIOFP 2012). Other countries need to initiate similar monitoring programmes. For example, there was a public outcry in Seychelles' capital city of Victoria, when nutrient caused discolouration of the water surrounding the port, due to phytoplankton bloom (UNEP/Nairobi Convention 2014a). The Director General for Wildlife, Enforcement and Permits of Seychelles commented that the eutrophication was due to lots of nutrients that cause rapid algae growth and that this condition has been observed in previous years, occurring at the same time when it is hot and the ocean is calm. In a different case, as recent as March 2015, a discolouration of the water in Pemba Island (Tanzania) has been reported. The waters were red in colour and fish were dying. All activities in the sea (fishing, recreational, seaweed farming) hade to be altered until a study was conducted to identify the cause(s). These cases and that of Zanzibar (see Box 16.3) are strong evidence to prompt countries of the WIO region to initiate HAB monitoring programmes.

In other areas, nutrient input originates from mariculture activities. Effluents from mariculture farms may contribute significant nutrient loading into coastal waters, resulting in unwanted nuisance or harmful blooms. What is needed is to conduct sustainable aquaculture in which the effluent water is treated before being released into the ocean. Alternatively, mariculture systems considering integration of finfish, shellfish and seaweed (Mmochi and Mwandya 2003), are examples of good mariculture practices, in which both the solid and dissolved wastes are utilized within the closed system.

Climate change

For the WIO region, to combat the effect of climate change on primary production and other processes that affect marine resources on which human beings depend on (such as fisheries), scientists are directing research towards understanding mechanisms underlying ecosystem dynamics and fisheries dynamics "Ecosystem based management of fisheries". Research in the region is now multi-disciplinary and of trans-boundary nature, geared towards providing answers to managers and policy makers on how to conserve biodiversity and sustainable conservation, utilization and exploitation of coastal and marine resources (UNEP/Nairobi Convention Secretariat, CSIR and WIOMSA, 2009, ASCLME/SWIOPF 2012, SWIOFP 2012). Processes in the coastal zone, both natural and anthropogenic, are interlinked and complex, while some of them are trans-boundary. Nature takes care of itself, but human activities need to be regulated. Lack of political willingness in some cases and inadequate awareness complicate decision making in the management of coastal resources. There is need to take factors like climate change seriously and come up with adaptive and mitigation strategies. One good example is that of Mauritius, whereby the Ministry of Environment and Sustainable Development, together with other partners, have launched a sensitization campaign on climate change adaptation in the coastal zone of Mauritius (UNEP/ Nairobi Convention 2014b). The main strategic objectives of the campaign are to increase public access to information on climate change and to increase public awareness raising and education on climate change. This is a good strategy, which should be replicated by other WIO countries, especially Small Islands Developing States (SIDS), in order to reduce human impacts.

CONCLUSION

A considerable effort by the WIO states has also been put into designation of coastal and marine protected, conserved and reserved areas. A comprehensive list of existing parks, reserves or conservation areas of the WIO Countries, showing the name, designation, designation type (national, international), IUCN category, status (designated or proposed), year of status and management authority is presented in the SWIOFP report (SWIOFP 2012). The list shows that all countries (with the exception of Comoros, which has only one) have established a good number of marine reserves. Kenya has 15, Madagascar 14, Mozambique has 7, Mauritius 22, Reunion 18, Seychelles 13, Tanzania 25 and South Africa has 15. This is a good number of reserves in the region, totaling 129, and what is important is to make sure that each one has a good management plan and that rules and regulations are being enforced.

Although individual countries' efforts are commendable, oceanic primary production itself and its impacts (as discussed above) know no boarders. Therefore, integrated initiatives for the entire region are called for. The regional-wide, Strategic Action Plan (WIO SAP), with the vision '*People of the region prospering from a heathy Western Indian Ocean*' formulated three main quality environmental objectives, which are intended to be achieved by the year 2035 (UNEP/Nairobi Convention Secretariat 2009):

- Critical WIO habitats will be protected, restored and managed for sustainable use;
- Water quality will meet international standards; and
- River flows will be wisely and sustainably managed.

These environmental quality objectives are intended to ensure that the marine and coastal ecosystem will function well and that goods and services will be assured for sustainable socio-economic development in the WIO region. The vision has five principles, namely i) equity, ii) sharing responsibility and management, iii) harmony between resource users and nature, iv) an informed society and v) life style adjusted to sustainability (UNEP/Nairobi Convention Secretariat 2009). If all the countries of the region, regardless of the stage of development, would abide to the principles and also participate in implementing the agreed management targets and actions for each of the above objectives, uncertainties in the future of decreasing fish catch due to decreasing primary producers would be highly reduced.

RECOMMENDATIONS

The States of the WIO region need to honour their commitment in many signed protocols related to conservation and management of coastal and marine environment, such as the Nairobi Convention Protocols (www.unep.org/NairobiConvention/The_Convention/index.asp): Protocol for the Protection of the Marine and Coastal Environment of the Western Indian Ocean from Land-Based Sources and Activities (adopted: Nairobi, 31 March, 2010); Protocol Concerning Protected Areas and Wild Fauna and Flora in the Eastern African Region (adopted: Nairobi, 21 June 1985) and the Protocol Concerning Co-operation in Combating Marine Pollution in Cases of Emergency in the Eastern African Region (adopted: 1985). In addition, a new protocol on Integrated Coastal Zone Management is in preparation and is nearing completion.

Initiatives in dealing with changing environments should not be dealt with at national or regional scales only; they need to start at community (village) levels. Knowledge and awareness are important; people should be empowered and allowed to play an active role in effective governance and management of natural resources. All these require financial resources. Governments should strive to set aside appropriate finances to allow implementation and enforcement of technologies and practices that will minimize impact of human activities in the marine environments of the WIO region.

On the scientific side there are gaps in the knowledge in primary production in the WIO region. Most scientific work has concentrated in the Agulhas LME area – South Western Indian Ocean region. Significant efforts need to concentrate in the northern part of the region as well, in the Somali Current LME area. Furthermore, of the available regional literature on primary production, more work has been done in understanding their distribution, abundance, physiology and related subjects. There is inadequate literature relating to the variation or trends of primary production to the environmental, social and economic implications to the societies of the WIO region. Thus, studies like these need to be conducted to better understand the impact of variation in primary production on the well-being of coastal communities.

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