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Evidence of chronic anthropogenic nutrient within coastal lagoon reefs adjacent to urban and tourism centers, Kenya: A stable isotope approach

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ABSTRACT

The source of anthropogenic nutrient and its spatial extent in three fringing reefs with differing human population gradients in Kenya were investigated using stable isotope approaches. Nutrient concentrations and nitrate-$\delta^{15}N$ in seepage water indicated that population density and tourism contributed greatly to the extent of nutrient loading to adjacent reefs. Although water-column nutrient analyses did not show any significant difference among the reefs, higher $\delta^{15}N$ and N contents in macrophytes showed terrestrial nutrients affected primary producers in onshore areas in Nyali and Bamburi reefs, but were mitigated by offshore water intrusion especially at Nyali. On the offshore reef flat, where the same species of macroalgae were not available, complementary use of $\delta^{15}N$ in sedimentary organic matter suggested inputs of nutrients originated from the urban city of Mombasa. If population increases in the future, nutrient conditions in the shallower reef, Vipingo, may be dramatically degraded due to lower water exchange ratio.

1. Introduction

Coral reefs are biologically diverse and economically valuable marine ecosystems that are vital for the socio-economic well-being of tropical coastal communities. Reef-based fisheries and income from tourism are essential to the economic prosperity of coastal communities in > 100 countries with coral reefs (Veron et al., 2009). Although nutrient supply is critical in supporting coral reef ecosystems and its productivity, excess nutrient input associated with anthropogenic activities such as sewage discharge has been suggested as one of the major factors threatening coral reefs (Lapointe et al., 2004; Fabricius, 2005; D'Angelo and Wiedenmann, 2014). The major source of anthropogenic nutrient input to near shore ecosystems could be attributed to sewage treatment facilities as well as untreated domestic sewage and municipal and industrial wastes entering the ocean via river, groundwater and storm runoff (Umezawa et al., 2002a; Derse et al., 2007; Dolenec et al., 2011). Consequently, the increasing influx of sewage to coral reef ecosystems due to increases in human populations and economic activities may affect the health of ecosystems in multiple ways, including by changing structural attributes, especially low or locally reduced hard coral cover by overgrowth of non-reef building organisms such as turfing and fleshy macroalgae (McCook et al., 2001; West and Van Woesik, 2001; Fabricius, 2005).

In East-African coastal cities sewage infrastructure is generally poorly developed and there has long been concern about increased sewage pollution in many nearshore reefs, mainly those bordering major town and tourism centers (Okuku et al., 2011). In Mombasa, the second city of Kenya, municipal sewage and wastewater from tourism hotels are estimated to be major sources of nitrogenous compounds to coastal waters, with lesser quantities from industrial effluent and livestock waste (Osore et al., 2003). While pollution concerns for coastal waters have increased (Crona et al., 2009), the links between high sewage-derived N loads and their influence on biological communities on adjacent coral reefs have been difficult to demonstrate, as suggested in other coral reefs (Lapointe, 1999; Hughes et al., 1999; Risk et al., 2009). For decades, studies have reported nutrient concentrations in the coral reefs near Mombasa city as one indicator of reef community dynamics (Obura, 2001; Carreiro-Silva and McClanahan, 2012). However, nutrients concentrations in coral reefs are often spatiotemporally variable or not detected due to intermittent input through the groundwater, rapid dilution by ocean currents and waves, and/or removal by plankton and macroalgae (Atkinson, 1988; Miyajima et al., 2007a; Garrison et al., 2007; Dailer et al., 2010). Without intensive sampling in time and space, therefore, water column nutrients alone are not

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effective for determining pulsing N sources or the time-averaged spatial extent of its impact on biological communities.

Stable isotope analysis using bioindicator species is an effective method to verify the extent of local nutrients in the coastal marine environment as it can serve as a tracer of both sources and long-term integration of nutrients in target organisms (Umezawa et al., 2002b; Derse et al., 2007; Kendall et al., 2007; Dailer et al., 2010). Benthic macroalgae have been shown to be reliable indicators of anthropogenic nutrient loading in aquatic ecosystems as they assimilate nutrients directly from the water column, whereas seagrasses also source nutrients from sediment interstitial water (Stapel et al., 1996), and corals are mixotrophs that partially depend on planktonic organic matter for their N demands (Reynaud et al., 2009: Treignier et al., 2009). Because the dissolved inorganic nutrients (DIN) continuously incorporated into algal tissues are averaged over their entire active growing period (approximately several weeks to months), macroalgal $\delta^{15}N$ values reflect the associated land-based nitrogen regime available in a given location (Umezawa et al., 2002b; Graham et al., 2015). Although specific species of benthic opportunistic macroalgae, such as *Padina* spp. and *Ulva* spp., are generally ubiquitous in many shallow coral reef environments, and enable us to compare targeted sites by sampling over large spatial scale (Umezawa et al., 2002b; Dailer et al., 2010), some coral reefs may lack these algae depending on the season. However, it has been reported that macroalgae having similar growth form exhibit similar $\delta^{15}N$ gradients as a function of distance from a source with specific $\delta^{15}N$ (Umezawa et al., 2002b). Even the $\delta^{15}N$ in sedimentary organic matter can be used in a complementary manner, over various time scales, as an indicator of the integrated effect of dissolved inorganic nitrogen (DIN) sources on shallow coral reef ecosystems, especially where microbenthic algae and macrophyte-derived organic matter are abundant (Umezawa et al., 2008a). Furthermore, in situ incubation experiments using macroalgal tissues in cages enable us to understand nutrient regimes at any location where natural biological samples are not evenly available (Constanzo et al., 2001; Umezawa et al., 2008b). Such information should help to improve our understanding of how anthropogenic nitrogen spreads in coastal waters and how it is subsequently utilized by primary producers, which is of great importance in assessing the extent of the impacts of anthropogenic vs 'natural' sources of nutrients in marine systems (Rogers, 2003; Kamer et al., 2004; Savage and Elmgren, 2004; Orlandi et al., 2014).

In this study, we aimed to investigate the sources of anthropogenic N and their spatial extent in three inshore reefs along the Kenyan coast located along a human population gradient using a combination of $\delta^{15}N$ and N contents of macroalgae, seagrasses and sedimentary organic matter, and in situ incubation experiments using macroalgal tissue. The vulnerability of the reef ecosystem to anthropogenic nutrient was also evaluated in terms of its resilience based on reef-level hydrodynamics and topography.

2. Materials and methods

2.1. Study areas

Three study areas, which are characterized by different levels of anthropogenic pressure and different outflow patterns (Table 1) were selected along the Kenyan coast, located north of Mombasa city (Fig. 1d). Specifically, two sites are exposed to high but different sources of anthropogenic nutrient (Fig. 1a, b), while the third site was considered as reference as it is less exposed to anthropogenic nutrient (Fig. 1c): 1) Nyali, which is situated 2 km from the urbanized island of Mombasa and experiences sewage discharges from municipal/domestic and industrial sectors. In addition, the site is characterized by numerous groundwater seepage points occurring along the beach zone (Mwashote et al., 1999; Munga et al., 2006). 2) Bamburi, which is part of the north coast tourist center, has experienced a rapid expansion in tourism and hotel developments along its beach since 1971, mainly due to establishment of Mombasa Marine National Park (Mombasa MNP, protected area from all extractive uses including fishing) along Bamburi beach (UNEP, 1998; Obura, 2001). Bamburi lagoon is therefore known to be exposed to wastewater from these hotels through sewage pipe discharges and groundwater seepage emanating from septic tanks in nearby villages (Mwangi et al., 2001; Munga et al., 2006). The third site Vipingo is located 33 km from Mombasa city and is adjacent to few private/residential houses and small fishing community villages, thus serving as a reference site with relatively pristine conditions. The population density in Nyali area (7983 people/km^2) is almost 10 and 30 times higher than that in Bamburi (985 people/km^2) and in Vipingo (277 people/km^2), respectively (KNBS, 2010; Table 1). Actual anthropogenic nutrient loadings from Nyali and Bamburi can be higher than the values expected from population density, because these areas are characterized by numerous hotels along its beach zone (Table 1). The prevailing ocean currents in the study region is the East African Coastal Current (EACC) which flows from south to north throughout the year (Obura, 2001; Varela et al., 2015), and thus our studied sites are also affected by waterborne nutrient flowing northwards from the city of Mombasa (Fig. 1d). The nutrient transported with the ebb currents from the creeks are dispersed northward by the EACC beyond the fringing reef (Mwangi et al., 2001). Nyali and Bamburi are likely to be more exposed to this anthropogenic nutrient than Vipingo which is located much far away from these creeks.

2.2. Bathymetry and extraction of topographic features

The bathymetry of the study areas were estimated based on Collin et al. (2014) protocol using extracted Google Earth images. Firstly small but high resolution satellite images by Google Earth Pro (Google Inc.) were saved as RGB jpeg images, then a mosaic image was synthesized from the small images by Adobe Photoshop CC (Adobe systems Inc.). The mosaic image was imported to GIS software (QGIS, qgis.org) with some georeferenced points. As depth increases, reflectance from the sea floor decreases exponentially following the Beer-Lambert law. Therefore, a logarithm of the colour band intensities decreases linearly with increasing depth. The red band intensity with higher absorption

Table 1
Characteristics of potential nutrient sources at each watershed adjacent to the studied fringing reefs.

Area	Population	House holds	Hotels	Cottages	Area size (km^2)	Density (people/km^2)	Major economic activities Adjacent to the area	Outflow patterns
Nyali	308,141	90,577	9	3	38.6	7983	Hotels, golf course	Many underground seepage (> 10)
Bamburi	71,914	16,798	14	1	73.0	985	Hotels	Underground seepage (< 4), seasonal river
Vipingo	31,752	5872	0	2	114.5	277	Fishing, few farms	Few underground seepage (< 2)
Mombasa city	143,128	33,160	10	2	14.7	9737	Industries, restaurants	Sewage outfalls/pipes

The data was cited from "The 2009 Kenya Population and Housing Census (KNBS: Kenya National Bureau of Statistics).
The number of hotels was counted from Environmental Sensitivity Atlas of Coastal Area of Kenya (2006).